

**UNIVERSITÀ DEGLI STUDI DI PADOVA**

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

CORSO DI LAUREA MAGISTRALE IN CHEMICAL AND PROCESS ENGINEERING

**Tesi di Laurea Magistrale in  
Ingegneria Chimica e dei Processi Industriali**

**Technical analysis and Energy optimization of industrial  
refrigeration systems in food processing applications**

Relatore: Prof. Sara Spilimbergo

*Laureando:* Andrea Franceschetti

A.A. 2025/2026

# Abstract

This thesis, developed in collaboration with Pastificio Rana S.p.A., focuses on the analysis and optimization of industrial refrigeration systems and the thermal efficiency of production facilities, with particular emphasis on pasteurization and cooling processes. The study addresses the growing challenges associated with seasonal temperature variations, which strongly influence the performance of refrigeration units and the overall energy consumption of the plant. The investigation highlighted several critical issues, including degradation of the pasteurizer insulation and the presence of direct steam leaks. Using thermal imaging, convection and radiation are calculated, and from these the energy balances are derived. It was estimated that the system currently dissipates 180,000 kWh per year of thermal energy into the surrounding environment. Based on these findings, several corrective actions were proposed, such as replacing damaged insulation panels, performing maintenance on the pasteurizer steam lines, and installing solar-control window films in office areas to reduce cooling demand. These interventions are expected to significantly improve both energy efficiency and operational stability. Overall, this work demonstrates how a detailed thermodynamic analysis combined with targeted maintenance strategies can lead to tangible energy and economic benefits in industrial food processing facilities.

## **Declaration of usage of generative AI and AI-assisted technologies**

- Writing text

The author reviewed and edited the Thesis as needed and take full responsibility for its content.

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# **Introduction**

Industrial refrigeration systems play a key role in food processing industries by ensuring suitable operating conditions, product quality, and production continuity. During the summer season, however, these systems often experience a noticeable reduction in efficiency due to high ambient temperatures. Elevated external temperatures increase energy consumption and reduce cooling performance, mainly because of the higher thermal load on condensers and compressors. As a result, the overall coefficient of performance (COP) decreases, making the system more energy intensive. This thesis aims to analyse and improve the performance of the refrigeration units installed in the production plant. The study focuses on evaluating the operating COP, analysing heat exchange processes, and identifying optimization strategies to enhance energy efficiency. Attention is given to the effect of ambient temperature on compressor performance, the potential benefits of improved thermal insulation, and the assessment of the plant's overall energy consumption. In addition, the work explores possible technological and operational improvements, including the use of advanced materials or surface coatings to reduce heat losses. The main objective of this study is to propose practical and energy-efficient solutions that reduce both environmental impact and operating costs, while maintaining high levels of reliability and process stability. The present work is structured into three main chapters. The first chapter provides an overview of the industrial context and the production processes analysed and the infrastructure of the plant. The second chapter focuses on the description of the refrigeration and air-conditioning systems, outlining their operating principles, configuration, and role in the overall thermal balance of the facility. Finally, the third chapter presents the thermal analysis and energy evaluation, including the calculation of heat losses, the assessment of system inefficiencies, and the proposed technical solutions aimed at reducing energy consumption and environmental impact.

## **Chapter 1**

### **Plant descriptions**

The main objective of this work is to identify and map areas in which the system shows inefficiencies or operational criticalities. Attention is given to energy performance, as it represents a key factor in evaluating system efficiency and in defining strategies to improve

overall performance. The research was conducted using a rigorous methodological approach based on standardized procedures for data collection, processing, and analysis. This approach allows for an accurate representation of the current operating conditions of the systems and supports the development of technical proposals for optimization and future improvements. To complete the analysis, a general description of the plant is provided, including all production lines, to offer a comprehensive overview of the facility and its specific operational requirements. The company is structured to cover all stages of the production process and operates in full compliance with applicable procedures and regulations. Figure 1.1 represents an example of the methodological framework applied to the acquisition of raw materials, illustrating a detailed and regulated structure in accordance with current standards.

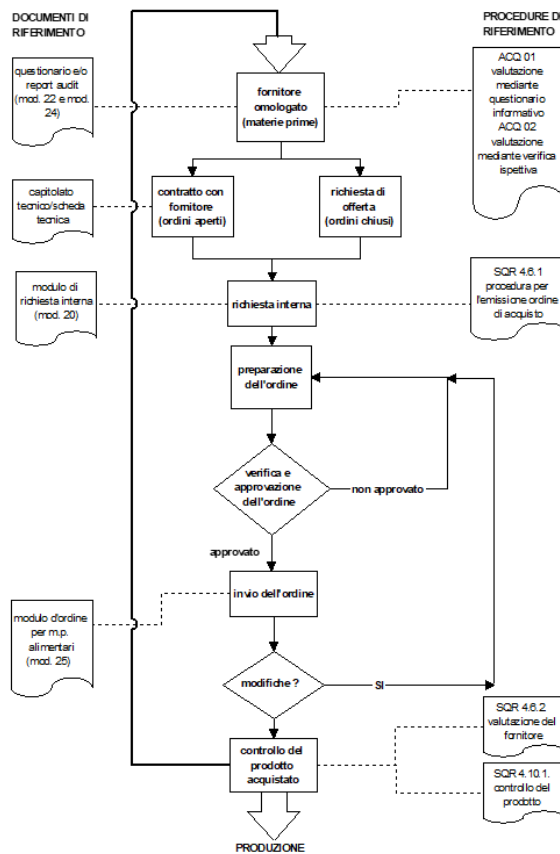


Figure 1.1: Example of reference procedures followed for the acquisition of raw materials.

## 1.1 Climate contest

The current climatic context is extremely fragile, marked by a progressive rise in global average temperatures, increasingly intense weather events, and greater seasonal variability. In this scenario, the protection of the environment must follow Legislative Decree No. 152 of April 3, 2006 (Consolidated Environmental Act). The refrigeration systems play a crucial role not only

in ensuring the stability of industrial processes, but also in maintaining product quality and production continuity. External temperature fluctuations have a direct impact on the cooling loads required and on the operating conditions of the refrigeration units, making it essential to continuously optimize system parameters to ensure energy efficiency, operational reliability, and environmental sustainability. Moreover, the evolving regulatory framework concerning energy efficiency and the reduction of greenhouse gas emissions is driving the adoption of more sustainable technological solutions, such as the use of natural refrigerants (e.g., ammonia) and integrated heat recovery systems. As a result, the management of refrigeration units has become a key factor not only in achieving optimal industrial performance but also in supporting the industry's contribution to global environmental goals and the ongoing energy transition.

## 1.2 Regulatory framework

At the same time, the analysis focuses on food safety aspects regulated by strict standards, highlighting the complexity of production operations. The HACCP system [9] (Hazard Analysis and Critical Control Points) is useful to identify, assess, and control hazards affecting food safety throughout the production chain. Introduced into European legislation through Directive 93/43/EEC and made mandatory by Regulation (EC) No. 853/2004, HACCP represents a cornerstone of modern food safety management. Its implementation is useful across all food industry sectors from production and processing to distribution and retail ensuring that each stage is properly monitored and compliant with hygiene regulations. Although HACCP does not explicitly govern refrigeration systems, they play an essential role in maintaining safe conditions. Proper design, operation, and maintenance of refrigeration units therefore remain fundamental to meeting HACCP hygiene requirements.

The HACCP system is based on seven core principles:

1. Hazard Analysis: Identification of microbiological, chemical, and physical hazards that could compromise food safety.
2. Critical Control Points (CCPs): Determination of key process stages where hazards can be prevented, eliminated, or reduced.
3. Critical Limits: Definition of measurable limits (e.g., temperature, microbial load) that ensure control at each CCP.
4. Monitoring: Continuous verification that CCPs remain within acceptable limits, enabling immediate corrective actions.

5. Corrective Actions: Steps taken to address deviations and prevent unsafe products from reaching the market.
6. Verification: Evaluation of the system's effectiveness through inspections, testing, and regular review.
7. Record Keeping: Documentation of procedures and monitoring results to demonstrate compliance and traceability.

One of the fundamental parameters is temperature control, therefore the cooling system must be designed and planned with particular care to ensure compliance with specific temperatures. Each production area operates at different temperature levels depending on its function, but after packaging, products are generally stored at temperatures below +6°C. The temperature danger zone for microbial growth ranges between +10°C and +65°C, where mesophilic and thermophilic microorganisms can proliferate, with an optimal growth range of 20/45°C. Therefore, the cooling phase from 65°C to 10°C must be completed within 2/3 hours to ensure food safety. The higher temperature is reached after the pasteurization unit and so the temperature must be abated in the next phase. To abate the temperature, the following measures are recommended to ensure safe treatment:

- Avoid stacking or compacting products.
- Use a forced-air cooling tunnel to accelerate heat removal.
- Maintain air temperature below 0°C (ideally -1 to -2°C) depending on cooling time.
- When possible, insert a temperature probe at the core of the product to verify that the correct internal temperature has been reached.

### 1.3 Energy objectives

One of the fundamental aspects of the work concerns the assessment of the potential for energy savings resulting from the analysis of refrigeration units and auxiliary units. Through an examination of the operating conditions and the thermodynamic behaviour of the system, optimization strategies aimed at reducing consumption and improving the coefficient of performance (COP) are identified. The objective is to promote more conscious and sustainable energy management, with positive impacts both economically and environmentally. Moreover, the proposed strategies must be feasible, as a real system is complex and the use of advanced solutions requires significant investments.

## 1.4 Flow diagrams

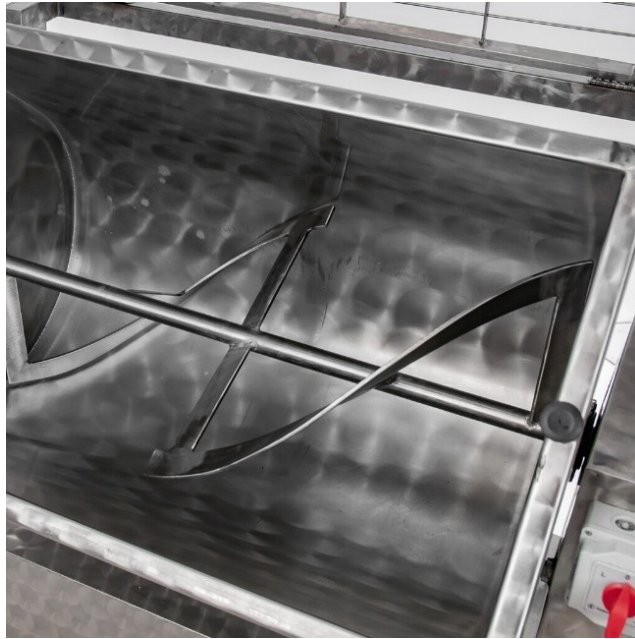
To facilitate the understanding of the plant architecture and the sequence of production operations, block flow diagram has been developed to schematically represent the general structure of the production line. This diagram is qualitative in nature because they do not include measurement data or experimental results but only serve as introductory visual tools that help illustrate the organization of the main process phases and the relationships among the different production areas. Within this process, two main operational macro-areas can be distinguished, each organized according to specific food safety, contamination control, and hygienic management criteria:

- **High-Protection Area (Closed Product Handling Zone):** This area includes operations related to the sealing and closing of the product, such as packaging, labelling, and final cooling. It is a controlled-risk environment where the product cannot be exposed to ambient air. The primary goal is to maintain high hygienic conditions to prevent any risk of post-process contamination.
- **Low-Risk Area (Open Product Preparation and Processing Zone):** This macro-area covers the initial stages of the production process, including dough preparation, filling, and pasta forming. During these phases, the product remains unpackaged and exposed, which increases the microbiological risk. Such risks are minimized through strict hygiene procedures, temperature and air quality control, and frequent cleaning cycles of work surfaces and equipment. Finally, to provide a clearer and more comprehensive understanding of how the production process is structured, the following flow diagram illustrates the sequence of operations and the interactions between the different processing areas. Figure 1.2 represents the flow diagram provides a schematic overview of the filled pasta production line, highlighting the key operations that make up the process from the preparation of ingredients to the final packaging of the product. The diagram is taken from the company's internal archives.



specifications for each of them. The following subsections present the machinery required for the process. Each phase is described, from the initial operations to completion and the production of the finished product.

### 1.5.1 Mixer dough formation



*Figure 1.3: Mixer for dough formation*

The first phase is the mixing and dosing of the raw materials. This operation is done with mixers for dough formation that is shown in Figure 1.3 and operates intermittently. Raw materials are loaded and dosed through internal dispensers, which are set up via a control program on the display. At the end of the cycle, a uniform dough is discharged, ready for subsequent processing stages.

**Dough sheeter machine:** The dough sheeter is used to obtain a dough sheet with the required thickness, which is essential for the formation of various pasta products. The machine operates through one or more lamination rollers that evenly compress and stretch the dough, ensuring a uniform texture. Figure 1.4 illustrates a typical example of this equipment.

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Figure 1.4: Dough sheeter machine

At the final part of the sheeter machine reported below in the figure 1.5, there is a series of moulds that allow obtaining the desired shape of the product and ensure a constant product flow.



Figure 1. 5: Moulds to obtain different shape of the products.

By varying the speed and the number of available moulds, we can achieve a higher or lower number of strokes, thus allowing us to adjust production based on the type of product required and market demand.

### 1.5.2 Pasteurization

Once the product is obtained it is necessary to make food safe. The steam pasteurizer performs the thermal treatment necessary to reduce the microbial load of the product to safe and regulatory levels. The process takes place inside a tunnel divided into three zones: preheating, heating, and pasteurization. In the preheating stage, the product temperature gradually increased to avoid thermal shock. During the heating and pasteurization stages, sterile steam is evenly distributed above and below the conveyor belt through spray ramps, ensuring uniform temperature distribution. Temperature and exposure time are carefully controlled to achieve microbial stability while preserving the sensory quality of the product. Steam tightness is maintained through a water seal, while extraction hoods remove excess humidity. The steam is generated from osmotic water treated through reverse osmosis to remove hardness and salts, ensuring sterile steam production and reducing scale formation. The process is energy-intensive due to continuous steam generation and precise thermal regulation but is essential for product safety and process efficiency. Figure 1.6 represents one of the numerous steam pasteurizers present in the plant. It can also be observed that, in the last section, an extraction hood is installed and regulated according to the performance requirements to be achieved.

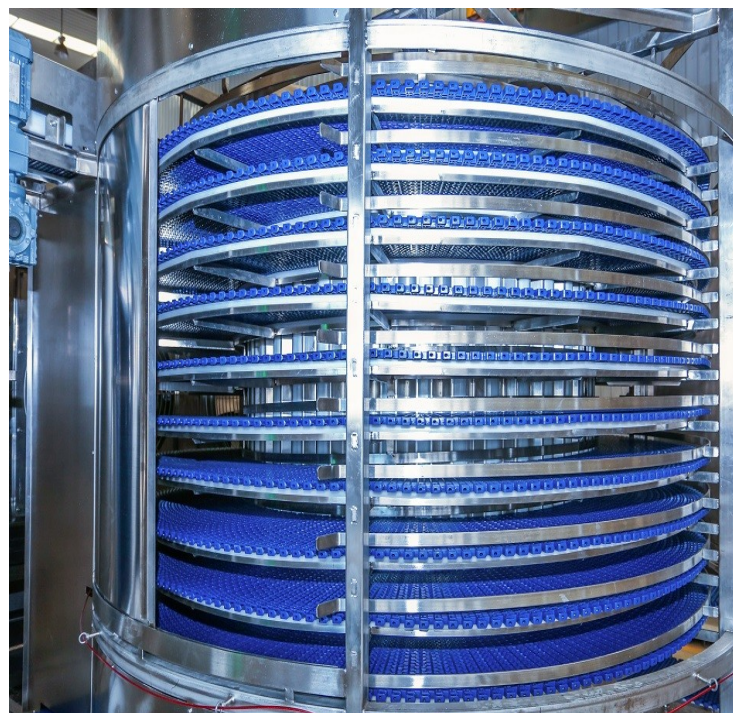


*Figure 1.6: Steam pasteurizer*

The internal insulation is made of mineral wool. The humidity must be checked because excess content of water increases the loss of efficiency of the insulating material by creating areas with higher thermal dissipation.

### 1.5.3 Cooling

After pasteurization, filled pasta must be rapidly cooled to prevent microbial growth and to preserve the product's quality attributes such as texture, colour, and flavour. The cooling process takes place inside a temperature-controlled chamber, where both temperature and humidity are continuously monitored and regulated. Figure 1.7 shows a cooling spiral system used to gradually reduce product temperature.



*Figure 1.7: Cooling spiral*

The system consists of a spiral conveyor chain, which allows the product to travel over an extended path within a compact space, optimizing heat exchange and ensuring uniform cooling. The plastic food-grade conveyor belt carries the pasta through the cooling chamber, where chilly air circulates this air is cooled by glycol water supplied from the external refrigeration plant. It is important to note that the refrigeration system itself is not an integral part of the machine; rather, it is externally connected and provides the necessary refrigerant to sustain the cooling process. The residence time of the product on the spiral conveyor is a key parameter, as it determines the effectiveness of temperature reduction to levels that inhibit microbial activity and ensure the desired shelf-life of the product. However, this phase is also energy-intensive, since removing the residual heat from the product requires a significant energy input.

For this reason, precise control of temperature, humidity, and belt speed is essential to achieve an energy-efficient and hygienically safe cooling process. Figure 1.6 and figure 1.7 represents the most energetic phase through all the system.

#### 1.5.4 Packaging



Figure 1.8: Packaging machine

The packaging phase as illustrated in the figure 1.8 represents one of the final and most delicate stages of the production line, as it is essential for preserving the quality, safety, and shelf life of fresh pasta. In this phase, automatic packaging machines are used to pack the product. After packaging, the product is transported via a conveyor belt to an automatic scale that checks the weight of each package, ensuring it falls within the predetermined tolerance limits, which are very tight to guarantee uniformity and precision. Subsequently, the packages pass through a metal detector, which detects any presence of metallic residues, thus adding an additional level of safety and quality control in the production process. In figure 1.9 is represented a typical layout of a process line.

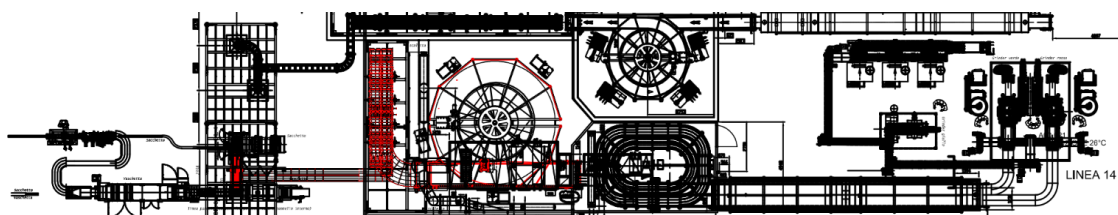


Figure 1.9: Example of a layout of a line

Additionally, each machine in the production line such as the pasteurizer and the sheeting machines has its own electrical power demand and thermal impact on the environment. While the pasteurizer introduces a significant heat load due to the high process temperatures required for food safety, the sheeters and other mechanical equipment contribute through frictional heat and continuous motor operation. These combined effects result in variable internal thermal loads, making it essential to optimize the refrigeration and ventilation systems to balance heat generation and removal efficiently. An optimized system not only ensures stable production conditions and consistent product quality, but also contributes to energy efficiency and operational sustainability, reducing unnecessary power consumption and minimizing the overall environmental impact of the facility.

# Chapter 2

## Refrigeration cycle

Heating, Ventilation, and Air Conditioning (HVAC) systems and industrial refrigeration units are deeply interconnected components within modern food-processing facilities. While refrigeration systems are primarily responsible for providing the cooling capacity required by production processes, HVAC systems play a crucial role in controlling the indoor environmental conditions and managing the distribution of thermal loads across both production and auxiliary areas. For this reason, these systems cannot be analysed independently, as their performance and efficiency are strongly interdependent. In industrial environments, refrigeration cycles supply cold energy to multiple users, including air-handling units, process heat exchangers, and cooling tunnels. HVAC systems act as the interface between the refrigeration plant and the conditioned spaces, transferring cooling capacity through air treatment processes and directly influencing the overall thermal balance of the facility. Any inefficiency or additional thermal load within the HVAC system directly increases the demand placed on the refrigeration units, particularly during summer operating conditions. This chapter therefore provides an integrated analysis of HVAC and refrigeration systems, highlighting their combined contribution to energy consumption and thermal management.

### 2.1 Refrigeration system

In this context, the focus is shifted specifically to the industrial refrigeration system, which represents the core element supplying cooling energy to both production processes and HVAC units. After introducing the interaction between air-handling systems and refrigeration infrastructure, this section presents the operating principles of the refrigeration plant and the thermodynamic cycle on which it is based. Industrial refrigeration systems are among the most energy-intensive assets in food-processing facilities, and their performance directly affects both operational efficiency and environmental impact.

The refrigeration cycle is a thermodynamic process that allows heat to be transferred from a lower-temperature environment to a higher-temperature one, thanks to the use of a refrigerant and suitable equipment. The refrigeration cycle consists of four main phases, divided into:

- Compression: The low-pressure refrigerant (ammonia  $\text{NH}_3$ ) is compressed in a compression chamber, whose purpose is to increase the pressure and consequently the temperature.
- Condensation: The ammonia is condensed in a heat exchanger, releasing heat into the external environment.
- Expansion: The throttling valve expands the fluid, resulting in a decrease in temperature and pressure.
- Evaporation: Finally, it evaporates in another heat exchanger.

Figure 2.1 shows a diagram of the main stages of a refrigeration cycle. [4]

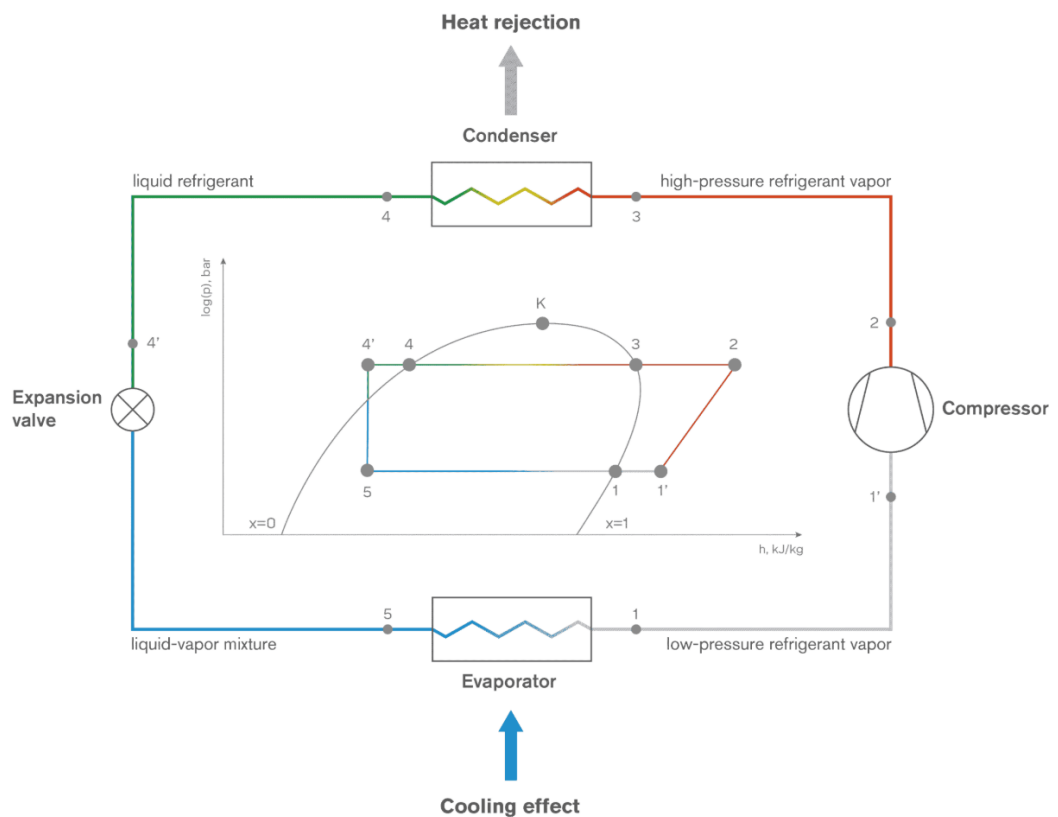


Figure 2.1: Refrigeration cycle

- 1 → 1': Vapor suction, an isobaric operation at low pressure. The refrigerant vapor enters the compressor as saturated vapor. There is a slight increase in enthalpy.
- 1' → 2: Vapor compression, an almost adiabatic phase  $Q = 0$  with a slight loss of entropy. The refrigerant exits superheated and at high pressure. This phase provides the mechanical work necessary for the cycle.

- 2 → 3: Condensation with an isobaric process where the high-pressure, high-temperature vapor releases heat to the external environment, resulting in the release of condensation heat that occurs at an almost constant temperature.
- 3 → 4: Liquid cooling, an isobaric process where the refrigerant liquid cools further below the saturation temperature with a decrease in enthalpy.
- 4 → 4': Passage from condenser to valve.
- 4' → 5: Expansion with a throttling valve, an isenthalpic process with a sudden pressure reduction. The reduction causes partial evaporation of the liquid, forming a liquid-gas phase.
- 5 → 1: The liquid-vapor mixture absorbs heat from the secondary fluid. The mixture enters at low pressure, and the operation is isobaric. The secondary fluid in this case releases heat and cools down.

The circuit continues to exchange heat until the required temperature is reached. It is also important to note that the refrigeration system operates in close interaction with the HVAC units and the pasteurization section. The thermal loads generated by the pasteurizer significantly affect the overall cooling demand, particularly during high production. Therefore, the analysis of the refrigeration cycle cannot be separated from the evaluation of these auxiliary systems, which contribute to the total energy balance of the facility.

The general equation 2.1, for evaluating heat exchange.

$$q = K \times A \times \Delta T \quad [2.1]$$

$q$  → Heat exchange [W]

$K$  → Global heat exchange coefficient  $[\frac{W}{m^2 \times ^\circ C}]$

$A$  → Heat exchange area [ $m^2$ ]

$\Delta T$  → Total difference of temperature between the two fluids [ $^\circ C$ ]

We also define the C.O.P, equation 2.2, as the coefficient of performance, that is, as the ratio between the heat extracted from the low-temperature zone and the energy supplied to the cycle.

$$C.O.P = \frac{Q_c}{W} \quad [2.2]$$

$Q_c$  : cooling capacity, amount of heat absorbed from the refrigerated space or process [J]

$W$  : work input, mechanical work supplied to the compressor to drive the cycle [J]

The C.O.P. expresses how efficiently a refrigeration system uses energy, a higher C.O.P [10]. indicates a more efficient system, as more cooling is produced for the same energy input. The performance of a refrigeration system is very much a function of the ambient temperature conditions, as these directly affect the thermodynamic balance between the evaporator and the condenser. The Coefficient of Performance will decrease with a rise in the outside temperature. This is since, during warmer periods, the condenser must operate at a higher pressure to reject heat to the environment. With an increase in the condensation temperature, the compressor must work harder to maintain the pressure gradient for the cycle, thus consuming more energy. In the meantime, when the evaporating temperature is low, whenever deep cooling is necessary the evaporator-condenser temperature difference is even greater, which further reduces the overall system efficiency. Consequently, under summer conditions, refrigeration equipment must operate against a larger thermal gradient, making the system less efficient and requiring more electricity. Conversely, when ambient temperature is lowered, the condenser can more easily reject heat, compression work is reduced, and COP is higher. For this reason, newer air-conditioning and refrigeration systems often employ adaptive control strategies, variable-speed compressors, or economizers that mitigate the seasonal reduction in performance. Condenser heat exchange maximization and temperature lift minimization between evaporator and condenser are essential to high COP maintenance and for guaranteeing stable and energy-efficient performance throughout the year.

For safety and environmental point of view particular attention is given to the choice of refrigerant and system configuration. In the analysed plant, ammonia (R717) [2] is used as the working fluid, due to its high thermodynamic efficiency and its classification as a natural refrigerant with negligible global warming potential. Ammonia-based refrigeration systems are widely adopted in medium- and high-capacity industrial applications, especially in the food sector, where reliability and efficiency are critical. Their increasing diffusion has also been supported by regulatory developments, such as Regulation (EU) No. 517/2014, which promotes the progressive reduction of fluorinated refrigerants. The following sections describe the main phases of the refrigeration cycle and the key components of the system, providing the basis for the subsequent performance and energy efficiency analysis.

### 2.1.1 Ammonia (R717)

To evaluate the impact of certain refrigerant compounds, we will introduce specific parameters to determine their effect on the environment. [1][7]

TEWI (Total Equivalent Warming Impact) is a key indicator that measures the environmental impact of a refrigerator, considering its contribution to the greenhouse effect. Unlike other parameters, TEWI evaluates both the direct impact, caused by refrigerant losses into the atmosphere, and the indirect impact, which concerns the carbon dioxide emissions related to the production of the electricity needed to operate the system. In this way, TEWI, provides a more complete and realistic view of the environmental performance of a refrigeration system throughout its entire operational life cycle. The equations 2.3, 2.4 illustrate the TEWI calculations [6].

[2.3]

$$TEWI = TEWI_{direct} + TEWI_{indirect}$$

$$2) TEWI = [GWP_{100} \times L \times n] + [GWP \times m_{RC} \times (1 - \alpha_{Re})] + [n \times E_{year} \times \beta] \quad [2.4]$$

- ❖ L= Leakage rate of system [ $\frac{Kg_{REFRIGERANT}}{year}$ ]
- ❖ n= operating life of system [*Year*]
- ❖  $\alpha_{Re}$ : factor of recovery/recycling 0-1 [-]
- ❖  $E_{year}$ : Energy consumption [ $\frac{KWh}{year}$ ]
- ❖  $\beta$ : CO<sub>2</sub> emissions per generated KWh [ $\frac{Kg \text{ of } CO_2}{KWh}$ ]

[ $GWP_{100} \times L \times n$ ] : Leakage losses

[ $GWP \times m_{RC} \times (1 - \alpha_{Re})$ ] : Recovery losses

[ $n \times E_{year} \times \beta$ ] : Indirect share

GWP (Global warming potential) indicates and compares the greenhouse effect of a gas with that of carbon dioxide (CO<sub>2</sub>), whose reference potential is set to 1. All GWP values are calculated over specific time horizons, typically 20, 100, or 500 years. A higher GWP value means that the gas traps significantly more heat in the atmosphere compared to CO<sub>2</sub> over the same period, making it more harmful in terms of its contribution to global warming and climate change. GWP calculation is presented in the next equation 2.5.

$$GWP = \frac{\text{Radiative Forcing of } CO_2}{\text{Radiative Forcing of the gas}} \quad [2.5]$$

ODP (Ozone depletion potential) is a numerical value that determines the extent to which a given gas contributes to ozone depletion in the atmosphere. The ODP indicates the ability of a

chemical substance to damage the ozone layer compared to the chlorofluorocarbon (CFC-11), which has a standard ODP of 1. An ODP less than 1 indicates that a substance has a lower potential for harm compared to CFC-11.

Table 2.1:

*Table 2.1: GWP and ODP for different refrigerants*

<b>Refrigerant</b>	<b>Chemical Name</b>	<b>GWP (100 years)</b>	<b>ODP</b>
<b>R717</b>	Ammonia	0	0
<b>R134a</b>	Tetrafluoroethane	1430	0
<b>R404A</b>	HFC blend	3922	0
<b>R22</b>	HCFC	1810	0.05

It's possible to observe the GWP values associated with various fluorinated compounds, such as hydrofluorocarbons (HFCs), which have been widely used as refrigerants in industrial and commercial refrigeration systems due to their chemical stability and operational safety. However, these substances have a remarkably high environmental impact, as many of them possess GWP values thousands of times greater than that of carbon dioxide (CO<sub>2</sub>). This means that, even in small quantities, their release into the atmosphere contributes disproportionately to global warming and the depletion of the ozone layer. However, the selection of a refrigerant cannot be based solely on environmental criteria. Operational safety and plant layout constraints also play a fundamental role in system design, especially in food production facilities characterized by high air circulation and the presence of personnel along the production lines. At the design level, a secondary fluid that transfers heat and cools down has also been selected. This choice stems from the fact of improved operational safety, as high air movement is required in the production lines, where the direct use of ammonia would increase the efficiency of the entire cycle but would lead to significant problems in the event of leaks or unit failures. In conclusion, as a choice, indirect use is preferable, keeping in mind the inefficiencies and losses of cooling capacity that this cycle entails; however, these are negligible compared to the safety benefits it provides. The following sections describe the main HVAC components, explaining their operating principles and how they distribute thermal loads within the plant, while also detailing the refrigeration cycle that supplies the required cooling capacity to these systems.

## 2.3 Internal components of HVAC

There are various technologies available for air treatment systems. Each system is designed for specific cooling or heating requirements and arranged according to the available space within

the plant. Therefore, all the different components may vary. In the sections below, all the various components are listed and described. Figure 2.2 shows a section of a HVAC unit.

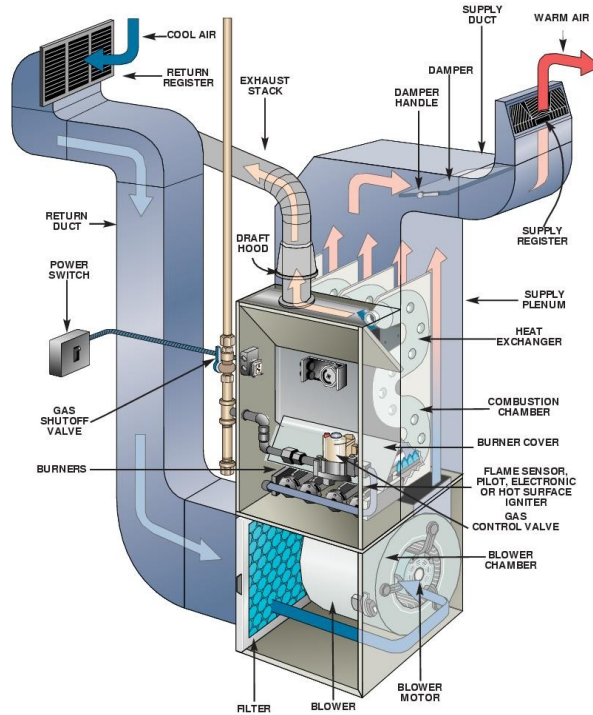


Figure 2.2: Internal components of HVAC

### 2.3.1 External case

The outer container serves the function of mechanically protecting the components and provides thermal and acoustic insulation to prevent unwanted pressure losses. Figure 2.3 shows an example of a machine located inside the plant.



Figure 2.3: External case of HVAC

### 2.3.2 Filtration system

Filtration: First stage aimed at ensuring adequate air quality. Outdoor air passes through a series of filters with different efficiency levels and purposes.

- Pre-filters: Removal of coarse dust particles ( $>10\mu\text{m}$ ). Composed of fiberglass and used as the first stage of filtration.
- Medium/High filters: Used for the removal of other particles with sizes ranging from 1-10  $\mu\text{m}$ . Rigid pocket filters shaped into numerous pleats are employed.
- HEPA filters: Used for the cleanroom where the finished product is packaged. They are used to remove minute particles, including bacteria. HEPA (High Efficiency Particulate Air) filters feature fibrous filtering surfaces and are built in standard modules. Filters are classified as HEPA when their efficiency ranges between 99.97% and 99.999%.

Figure 2.4 shows a V-shaped pocket filter. There are various shapes of filters that can be used. For the pre-filters in the current system, rigid flat pre-filters are used.



*Figure 2.4: V-shape pocket filter*

### 2.3.3 Cooling and heating coils

Inside an air handling unit, there are water coils that function to exchange heat between the treated air and a heat transfer fluid, depending on whether the air needs to be heated or cooled. From a construction point of view, a water coil consists of a coil of metal tubes through which

the heat transfer fluid circulates. The tubes are traversed by aluminium fins that increase the heat exchange surface and improve the efficiency of the process. The air coming from the ventilation section passes through the coil perpendicular to the flow of the fluid, allowing heat transfer through forced convection. Depending on the heat transfer fluid, we can have several types of coils:

- The heating coil is a hot-water heat exchanger used to warm the air within the system. The hot water is supplied by a central heating plant, where heat is typically generated through the combustion of natural gas. In some installations, high-pressure steam is used instead of hot water, transferring thermal energy to the air as it passes through the coil. This component ensures precise temperature control during colder periods and contributes to maintaining the desired environmental and process conditions.
- The cooling coil operates with chilled water supplied by a chiller or a dedicated refrigeration circuit. In this system, the cooling medium consists of a glycol–water mixture, typically using ethylene glycol in varying concentrations ranging from 10% to 40%, depending on the required operating temperature and system specifications. The glycol solution prevents freezing and enhances heat transfer efficiency, ensuring reliable and stable cooling performance throughout the process.

Figure 2.5 shows cooling and heating coils that are usually installed in easily accessible removable frames to allow for maintenance and periodic cleaning, which is essential to prevent efficiency losses.



*Figure 2.5: Cooling and heating coils.*

### 2.3.4 Humidification/dehumidification section

Essential for regulating the flow of water vapor in the incoming air to the production line. It allows excellent control and adaptation to different weather conditions, as the content in the external air varies. The humidification system used is a steam humidifier, in which saturated steam is injected directly into the air flow. For dehumidification, the cold-water coil is significant, where the air is cooled down to the dew point, causing the condensation of excess moisture. The condensate must be removed to maintain high machine efficiency. The management of these processes is automated through hygrometric probes that regulate the amount of steam or the degree of cooling necessary to maintain relative humidity within the required design values.

### 2.3.5 Heat recovery unit

Heat recovery units are an essential component, as they allow a portion of the thermal energy contained in the expelled air to be recovered to preheat or precool the incoming air. This results in significant energy savings and a reduction in the operating costs of the system. Heat recovery units can come in various types:

- Crossflow or plate units, where the exhaust air and the incoming air flow through separate channels divided by thin walls made of aluminium or plastic material, allowing heat exchange without contamination of the air streams.
- Refrigerant circuit or intermediate fluid units, where heat exchange occurs through an intermediate fluid (glycol water), pumped between the two sections. In this way, the thermal load on the cooling and heating coils is reduced.

### 2.3.6 Fan

Device that directly moves the airflow present in the system and allows it to be brought to the requested production line. They can be radial or axial depending on the different performance requirements. The rotation speed depends on the airflow handled during its cycle.

- Supply and return fans: placed at both the inlet and outlet of the AHU, they allow airflow management from the outside into the building.
- Exhaust and return fans: used simply for air recirculation or to expel stale air to the outside.

The air treated is distributed to the rooms through a network of ducts branching within the system. These ducts are designed and sized to reduce pressure losses and ensure smooth and uniform airflow. The duct materials can be of different types and include galvanized steel and durable plastic materials. The air is distributed through vents and grilles. The grilles for extracting stale air within the environment allow for a balance between incoming and outgoing air, without compromising the internal pressure. The ducts are not directly part of the treatment unit but are an integral part of the ventilation system, which branches out and distributes the various flows throughout the plant. Different types of ducts are used depending on construction needs. The plant features two types of ducting for air transfer. The insulated technical ducts are composed of several layers:

- Outer layer: Made of PVC resistant to dust, chemical attacks, and moisture. It ensures the mechanical strength of the duct.
- Inner layer: Made of insulation material such as synthetic fibre, intended to provide thermal insulation and prevent heat loss.

In some parts of the system, it is preferable to use coverings or flexible ducts made of technical fabric, like those shown in the photo. Fabric coverings are much more versatile and allow for easier maintenance.



*Figure 2.6: Textile duct*

Figure 2.6 represent a type of fabric duct. Insulation plays an essential role not only in increasing the energy efficiency of the ventilation system but also in preventing condensation, which is a rather frequent phenomenon in ducts that carry cold air or operate in humid environments.



*Figure 2.7: Insulated duct*

Figure 2.7, represent a different type of insulation, chosen based on the specific function of the ducts. The duct is used for direct cooling on the production line, which is why the insulation is designed to provide greater insulation capacity and minimize thermal exchanges with the surrounding environment.

#### 2.4 Technical scheme SH-206 S.F.

This section introduces the plant layout of chiller unit 1, which is part of the VUP. The plant contains several chillers since the cooling demand is high. Figure 2.8 illustrates the layout.



water, it is important to consider the concentration of salts that tend to form scale; therefore, anti-scaling products should be added. Exiting the condenser, the high-pressure refrigerant enters the expansion valve, resulting in a sudden pressure drop. At this stage, partial evaporation occurs, forming a liquid-gas mixture. The mixture enters a separator, which functions to supply the evaporator and to separate the liquid from the gas, which is then drawn into the compressor. The entire process takes place inside the cooling towers, which release water vapor into the atmosphere through a fan.

### 2.4.3 Evaporator

In the two-phase plate evaporator, the liquid enters at a high speed and evaporates through the plate heat exchanger from the bottom to the top, removing heat from the fluid flowing counter current on the other side, in this case glycol water. The outlet temperature at the end of the cycle is  $-14^{\circ}\text{C}$ . This configuration allows for a highly efficient heat exchange thanks to the large surface area provided by the plates and the turbulent flow conditions that enhance the thermal transfer coefficient. The upward flow of the refrigerant also helps separate liquid and vapor phases more effectively preventing the accumulation of liquid refrigerant at the bottom of the unit. Proper control of the refrigerant distribution across the plates is crucial to maintain stable operating conditions, avoiding issues such as dry-out or bad heat exchange, which could compromise the efficiency and reliability of the entire refrigeration cycle.

The glycolate water comes from a storage tank in which there is a perforated baffle. The tank can be divided into two zones: the first, where a pump takes the colder water and transports it to the production lines, where it heats up and returns to the second zone at a higher temperature, creating a temperature difference. In the second zone, there is an additional delivery pump that draws the hotter water and transports it to the evaporator, which, through exchange with ammonia, cools down and brings the temperature to the desired level before returning to the storage tank. This system is designed to maintain the temperature as stable as possible. The perforated baffle still allows for thermal exchange between the two sections. The temperature difference with this method is smaller and is around  $\Delta T = \pm 5^{\circ}\text{C}$ . If the perforated partition were not present, the temperature would be subject to greater fluctuations, leading to the stratification of liquids within the system. At the bottom of the tank, there is a drain valve for the removal of sludge formed during the various cycles.

# Chapter 3

## Thermal and energy analysis

This chapter provides a structured analysis of the operational data collected from the production lines, with the aim of evaluating the current performance of the systems and identifying key aspects that influence their overall efficiency. Within this context, particular attention is given to a known issue affecting the refrigeration system. Specifically, during the summer months, higher outdoor temperatures cause the glycol return temperature to increase, reducing the effective temperature gradient and requiring the refrigeration units to remove a larger heat load. This condition creates significant strain within the production area, as the required cooling capacity is not adequately encountered. The issue is particularly critical because the different zones of the facility must be kept at a controlled and constant temperature to prevent bacterial proliferation in the food being processed. At present, to avoid this thermal shortage, the cooling supply to the office area is suspended during peak conditions. While this prevents production downtime, it creates discomfort for the employees working in the offices. A crucial element in the refrigeration system is the glycol storage tank, which is undersized and unable to maintain a stable thermal buffer during the summer months, becoming heavily influenced by ambient conditions. This design choice was made due to structural limitations, as the floor slab beneath the production area could not safely support the additional load of a larger tank, which might have posed a potential risk of floor deformation or collapse. Based on the installed equipment in the facility (AHUs, compressors, and other units), we calculated the cooling demand required in the production zones and in the office building and compared it with the current cooling capacity to determine whether the existing system is sufficient.

### 3.1 Plant cooling demand and system overview

This section focuses on the evaluation of the thermal performance of the system, analysing all sources of heat and dispersion identified within the plant. These thermal losses, as observed during the operational study, have a significant impact on the overall energy efficiency of the refrigeration units. Understanding and quantifying these effects is essential to identify potential improvements and to ensure a more stable and sustainable process. To initiate the thermal analysis, it is essential to first determine the cooling loads required by the plant, as they define the operating conditions of the refrigeration system. The facility is divided into two main sections: the NUP (Nuova Unità Produttiva) and the VUP (Vecchia Unità Produttiva), each

characterized by different production layouts and thermal demands. The cooling load calculation was performed by accounting for all major contributors to the refrigeration demand, including HVAC systems, cooling tunnels, and auxiliary thermal loads associated with the production processes.

### 3.1.1 NUP

The results of the thermal and energy assessment are presented in the figure below. The total cooling demand was estimated to be approximately 4 MWf, representing the overall refrigeration load of this production area. The diagram, figure 3.1, illustrates how the available cooling capacity is distributed among the different users, highlighting the contribution of each subsystem and providing a clear overview of the thermal load allocation within the plant.

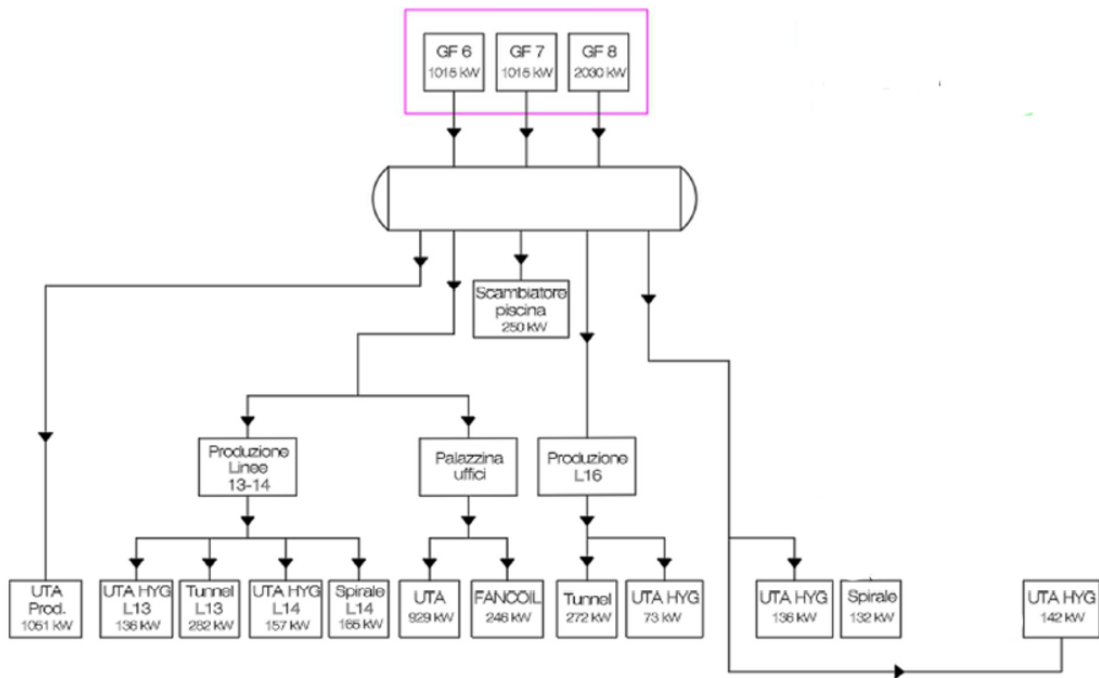


Figure 3.1: Nup cooling distribution.

### 3.1.2 VUP

The total installed power is equal to 4MWf. Figure 3.2 illustrates the diagram of how the cooling capacity is distributed across production.

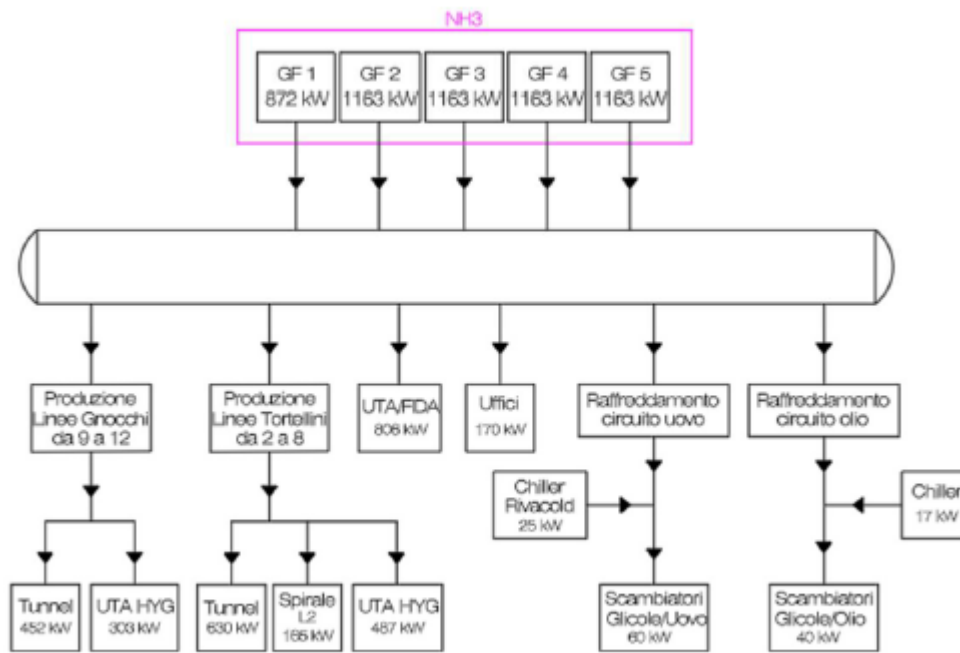


Figure 3.2: Vap cooling distribution.

### 3.1.3 Cooling demand

This section shows a real unit as an example for calculating the cooling required by the entire system. For simplicity, only one unit is described.

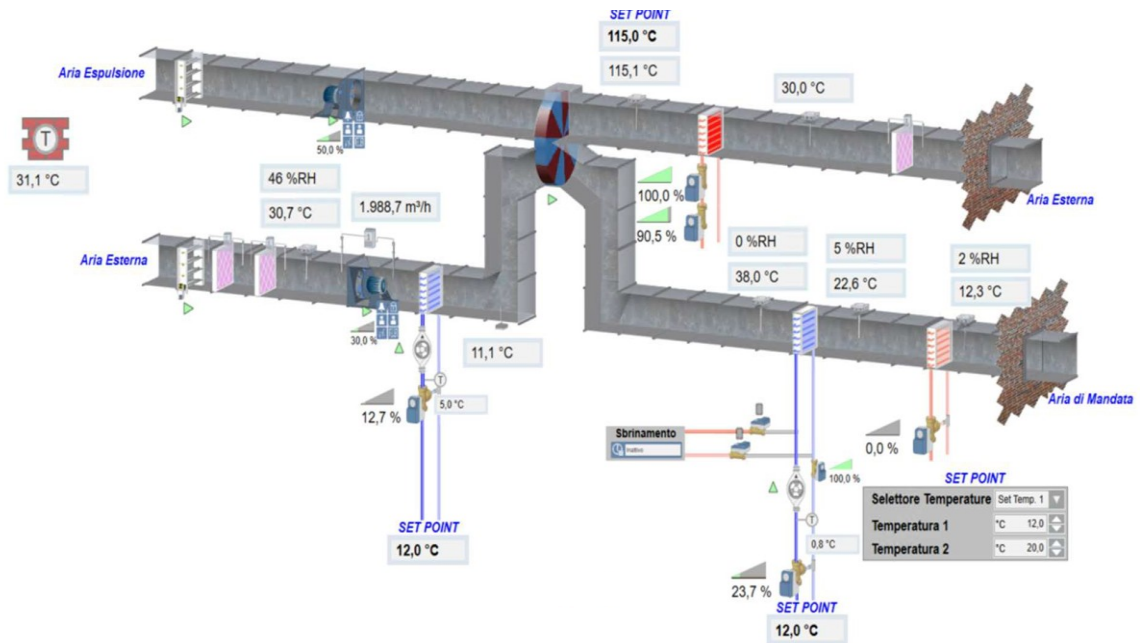


Figure 3.3: HVAC for production unit

Figure 3.3 illustrates the ventilation apparatus serving a production area of the plant. The unit is equipped with multiple heating and cooling coils, each specifically sized according to the thermal load requirements of the zone. The operational data was obtained from both the unit's technical data sheet and the field instrumentation installed on the system. Temperature measurements are performed through thermocouples positioned at strategic points along the air stream such as the supply, return, and post-coil sections to ensure accurate thermal monitoring. Pressure conditions, including recirculation and filter pressure drops, are monitored using differential pressure sensors integrated within the system. These instruments allow continuous supervision of airflow behaviour and system performance, ensuring that the air-handling unit operates efficiently and within its design parameters. Since these units contribute significantly to the total cooling demand, their inclusion allows for a more accurate thermal balance evaluation.

*Table 3.1: Supply heating coil*

<b>Power [KW]</b>	24,27
<b>Material</b>	AISI 304
<b>Surface[m<sup>2</sup>]</b>	4,67
<b>Air velocity [m/s]</b>	2,11
<b>Air flow [m<sup>3</sup>/s]</b>	5000
<b>Air pressure drops [Pa]</b>	9
<b>T<sub>in</sub>[K]</b>	268,15
<b>T<sub>out</sub>[K]</b>	279,15

*Table 3.2: Supply cooling coil*

<b>Power [KW]</b>	97,87
<b>Material</b>	AISI 304
<b>Surface[m<sup>2</sup>]</b>	79,39
<b>Air velocity[m/s]</b>	2,49
<b>Air flow [m<sup>3</sup>/s]</b>	5000
<b>Air pressure drops [Pa]</b>	207
<b>T<sub>in</sub>[K] air</b>	312,15
<b>T<sub>out</sub>[K] air</b>	285,15
<b>T<sub>in</sub>[K] fluid</b>	273,15
<b>T<sub>out</sub>[K] fluid</b>	278,15

The power of heating and cooling coil, table 3.1 and table 3.2, is understood as the exchanged thermal power. Furthermore, we note that the required thermal powers and surface are widely different since the main purpose is the cooling of the environment. Having defined the overall cooling demand and clarified the contribution of HVAC systems to the installed refrigeration capacity, the analysis now focuses on the evaluation of thermal losses within the plant.

## 3.2 Data analysis methodology

The following section presents the methodology adopted to identify and quantify heat dissipation mechanisms, providing the basis for the subsequent thermal calculations and energy optimization measures. Pasteurizers using sterile steam were considered in this analysis, as their external surface temperature was significantly higher compared to more modern units. This condition is mainly due to the deterioration of the internal insulating layer over time.

### 3.2.1 Thermographic inspection

The temperatures were measured using a FLIR C3 thermal camera, a portable infrared tool capable of detecting the surface temperature distribution of an object without direct contact. The thermal camera operates by capturing the infrared radiation emitted by objects, which is proportional to their surface temperature, and converting it into a color-coded thermal image. In these images, warmer and cooler areas are displayed with distinct colour tones, making it possible to identify potential heat losses. During the measurement campaign, several thermographic acquisitions were performed at different points on the pasteurizer to identify zones with abnormal heat dispersion and evaluate the effectiveness of the thermal insulation. This approach was applied to determine an average temperature across the various sections, avoiding a single approximation over the entire heat-exchange surface. The procedure was conducted by maintaining a fixed distance of approximately one meter between the camera lens and the inspected surface, to minimize errors related to variations in the field of view and ensure more uniform measurements. To ensure the reliability of the measurements, an emissivity value of 0.53 was set, determined through several tests using a blackbody with known emissivity. In addition, an apparent reflected temperature of approximately 30°C was considered, obtained by measuring the surrounding environment with a contact thermometer and accounting for reflections from nearby walls and the ceiling. All these parameters were entered into the thermal camera before acquiring the images to ensure correct temperature readings. The thermal images were then analysed using the resolute FLIR Tools software, which allowed for point and average temperature extraction across the inspected areas. The results clearly show that deterioration of

the insulating layer leads to a significant increase in surface temperature, confirming reduced insulation efficiency and the need for maintenance to limit heat losses and improve overall operational safety.

### 3.2.2 Thermographic results

Thermographic images highlighted several localized areas characterized by significantly higher surface temperatures. In these areas, surface temperatures exceed 80°C, compared to approximately 30°C in sections where the insulation remains intact. Figure 3.4 and figure 3.5 show the colour scale of the thermal camera make it easier to confront the different temperature. Normal operation of the pasteurizer should indicate a uniform temperature across the entire surface.



Figure 3.4: Thermal acquisition



Figure 3.5: Confrontation 86°C vs 30°C

Figure 3.5 is the thermal acquisition of the surface of the pasteurizer. In the red circle, the surface temperature exceeds 86°C, as indicated by the colour scale on the right. In contrast, the

green circle highlights an area where the temperature is below 30°C. This marked thermal contrast confirms localized heat loss and reduced insulation performance. This hypothesis is further supported by visible oxidation patches on the metal exterior, indicating prolonged overheating and potential internal moisture accumulation. Figure 3.6 illustrates the visible oxidation of the upper face.



*Figure 3.6: Corrosion on the upper surface of pasteurizer*

Since the system operates with high-temperature saturated steam, moisture gradually penetrates the compromised insulation layer, increasing its thermal conductivity. Because the insulating material is fibre based, moisture absorption drastically reduces its thermal resistance and accelerates panel degradation. The thermographic analysis shows an average surface temperature of approximately 68°C, depending on the specific area examined, while the air temperature measured at 2 meters from the unit is approximately 30°C. This value is significantly higher than the typical ambient temperature in the production area (24/25°C), generating a thermal rise of about 5/6°C in the surroundings of the pasteurizer. This condition clearly indicates a non-negligible thermal contribution to the room, increasing the cooling load required to maintain optimal process conditions.

### 3.3 Dispersion mechanisms

This dispersion is primarily due to two mechanisms: thermal radiation and natural convection. The first mechanism, thermal radiation, represents the transfer of energy in the form of electromagnetic waves emitted by the hot surface of the pasteurizer toward cooler surrounding surfaces. This mode of heat transfer requires no medium and strongly depends on the absolute temperature and surface emissivity. In this case, despite the low emissivity of the metallic surface, radiation accounts for a huge portion of the thermal losses, especially in zones where insulation is degraded. The second mechanism is natural convection. In the absence of forced ventilation, heat exchange occurs through the buoyancy-driven motion of the surrounding air: the air in contact with the hot surface warms up, becomes less dense, and rises, establishing a slow but continuous convective flow. During the measurements, an anemometer confirmed that air velocity in the inspected zone was zero, indicating no relevant forced airflow. The air velocity measurements were performed using an RS PRO DT-8880 digital anemometer [13], a portable instrument designed for precise airflow monitoring. The device operates by measuring the air velocity through a built-in vane sensor and displaying the value in real time. It was used by positioning the probe perpendicular to the airflow direction at different points near the tested surface. The instrument has a measuring range from 0.01 to 25.0 m/s, ensuring accurate detection even at extremely low natural convection speeds. Therefore, heat transfer by convection can be assumed to be natural, characterized by a relatively low heat transfer coefficient compared to forced convection. The combination of radiation and natural convection accurately describes the overall heat loss from the pasteurizer surface. These losses directly affect the thermal efficiency of the system, as part of the energy generated for pasteurization is not used in the process but instead dissipated into the surrounding environment. As a result, the internal cooling systems are subjected to higher loads, reducing their efficiency and increasing overall energy consumption. Improving insulation is therefore an essential step to maintain thermal comfort and enhance system performance.

### 3.4 Radiation mechanism

Following the qualitative and quantitative thermal analysis, the study proceeds with the calculation of the thermal losses associated with each identified surface and operating condition. In the following section, the equations, empirical correlations, and heat transfer models adopted for the evaluation of convective and radiative heat losses are presented in detail [12]. Pasteurization dispersions are calculated as:

Thermal radiation in the equation 3.1:

$$Q = A\delta\varepsilon(T_s^4 - T_a^4) \quad [3.1]$$

$A$  : Heat exchanged area [ $m^2$ ]

$\delta$  : Stefan-Boltzmann Constant: 5.67037E-08

$\varepsilon$  : Emissivity: 0.53

$T_s$  : Superficial temperature [K]

$T_a$  : Ambient temperature [K]

This section presents calculations for radiation on the various surfaces of the pasteurizer. The top and side surfaces, as well as the extraction channels, are considered. The bottom surface is not considered, so we ignore it because it is in an inaccessible location for data collection.

### 3.4.1 Radiation of pasteurizer line 3

Upper face, table 3.3:

*Table 3.3: Upper face pasteurizer line 3*

Area [ $m^2$ ]	Q_ir[W/ $m^2$ ]	Q_ir[W]	Mean temperature [K]
6.804	57.86	393.68	315.15
2.754	54.18	149.23	314.15
2.3976	285.48	684.48	364.15
2.8512	291.20	830.28	365.15
0.9558	279.81	267.44	363.15

Also, we consider all the elements present in the pasteurizer that emit heat so below are reported the other components. The extraction channels are divided into different section to obtain more precise calculations. Two extraction channels of the pasteurizer in line 3, table 3.4 and table 3.5:

*Table 3.4: Extraction channel n.1 pasteurizer line 3*

1	Area [ $m^2$ ]	Q_ir[W/ $m^2$ ]	Q_ir[W]	Mean Temperature [K]
<b>Vert</b>	0.324	100.64	32.60	326.15
<b>Vert</b>	0.072	9.52	0.68	301.15
<b>Oblique</b>	0.48	43.37	20.81	311.15
<b>Trap</b>	0.5376	65.31	35.11	317.15
<b>Horizon tal</b>	0.09	96.57	8.69	325.15

Table 3.5: Extraction channel n.2 pasteurizer line 3

<b>2</b>	<b>Area [m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W/m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W]</b>	<b>Mean Temperature [K]</b>
<b>Vert</b>	0.324	225.61	73.10	353.15
<b>Vert</b>	0.072	100.64	7.24	326.15
<b>Oblique</b>	0.48	185.45	89.01	345.15
<b>Trap</b>	0.5376	200.19	107.62	348.15
<b>Horizontal</b>	0.09	215.31	19.37	351.15

### 3.4.2 Radiation of pasteurizer line 4

Upper face, table 3.6

Table 3.6: Upper face pasteurizer of line 4

<b>Area [m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W/m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W]</b>	<b>Mean temperature [k]</b>
0.5427	139.37	75.63	337.35
1.4742	140.73	207.46	337.65
1.5714	135.76	213.33	336.55
1.5714	149.43	234.81	339.55
0.4779	132.62	63.38	335.85
0.486	161.10	78.29	342.05
1.4661	149.43	219.08	339.55
0.5022	157.33	79.01	341.25

Three extraction channels of the pasteurizer in line 4, table 3.7, table3.8 and table 3.9:

Table 3.7: Extraction channel n.1 pasteurizer line 4

<b>1</b>	<b>Area [m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W/m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W]</b>	<b>Mean temperature [K]</b>
<b>Vert</b>	0.648	120.70	78.21	333.15
<b>Vert</b>	0.072	41.02	2.95	313.15
<b>Oblique</b>	0.48	41.02	19.69	313.15
<b>Trap</b>	0.5376	30.31	16.29	310.15
<b>Horizontal</b>	0.09	112.06	10.08	331.15

Table 3.8: Extraction channel n.2 pasteurizer line 4

<b>2</b>	<b>Area [m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W/m<sup>2</sup>]</b>	<b>Q<sub>ir</sub>[W]</b>	<b>Mean temperature [K]</b>
<b>Vert</b>	0.648	91.12	59.04	326.15
<b>Vert</b>	0.072	48.34	3.48	315.15
<b>Oblique</b>	0.48	52.05	24.98	316.15
<b>Trap</b>	0.5376	23.34	12.55	308.15
<b>Horizontal</b>	0.09	99.38	8.94	328.15

Table 3.9: Extraction channel n.3 pasteurizer line 4

<b>3</b>	<b>Area [m<sup>2</sup>]</b>	<b>Q_ir[W/m<sup>2</sup>]</b>	<b>Q_ir[W]</b>	<b>Mean temperature [K]</b>
<b>Vert</b>	0.648	91.12	59.04	326.15
<b>Vert</b>	0.072	48.34	3.48	315.15
<b>Oblique</b>	0.48	52.05	24.98	316.15
<b>Trap</b>	0.5376	23.34	12.55	308.15
<b>Horizontal</b>	0.09	44.66	4.01	314.15

### 3.5 Natural convection mechanism

This section presents calculations for natural convection on the various surfaces of the pasteurizer. For natural convection, the calculation is more complex than that of radiation, as it requires considering many more parameters. The convective heat flux  $Q_{conv}$ , equation 3.2, is expressed as [12]:

$$Q_{conv} = h_c \cdot A \cdot (T_s - T_\infty) \quad [3.2]$$

where:

- $Q_{conv}$ = heat transferred by convection [W]
- $h_c$ = convective heat transfer coefficient [W/m<sup>2</sup>·K]
- $A$ = heat exchange surface area [m<sup>2</sup>]
- $T_s$ = surface temperature [K]
- $T_\infty$ = ambient air temperature far from the surface [K]

The heat transfer coefficient  $h_c$ , equation 3.3, depends on the airflow generated naturally and is determined as a function of the Nusselt number (Nu).

$$h_c = \frac{Nu \cdot \lambda}{L} \quad [3.3]$$

- $h_c$ : convective heat transfer coefficient [W/m<sup>2</sup>·K]
- $Nu$ : Nusselt number (dimensionless)
- $\lambda$ : thermal conductivity of air [W/m·K]
- $L$ : characteristic length of the surface [m]

For natural convection, the Nusselt number calculated as in equation 3.4 is correlated with the Grashof number ( $Gr$ ) and the Prandtl number ( $Pr$ ) through the empirical relationship.

$$Nu = C \cdot (Gr \cdot Pr)^n \quad [3.4]$$

- $C, n$ : empirical constants depending on surface orientation and flow regime.
- $Gr$ : Grashof number (dimensionless)
- $Pr$ : Prandtl number (dimensionless)

The Grashof number, equation 3.5, represents the ratio between buoyancy and viscous forces in the fluid and is defined as

$$Gr = \frac{g \cdot \beta \cdot (T_s - T_\infty) \cdot L^3}{\nu^2} \quad [3.5]$$

- $g$ : gravitational acceleration (9.81 m/s<sup>2</sup>)
- $\beta$ : thermal expansion coefficient of the fluid [1/K] ( $\approx 1/T_{film}$  for air)
- $T_s$ : surface temperature [K]
- $T_\infty$ : ambient temperature [K]
- $L$ : characteristic length [m]
- $\nu$ : kinematic viscosity of air [m<sup>2</sup>/s]

The Prandtl number, equation 3.6, represents the ratio between momentum diffusivity and thermal diffusivity and is given by:

$$Pr = \frac{c_p \cdot \mu}{k} \quad [3.6]$$

- $c_p$ : specific heat of air at constant pressure [J/kg·K]
- $\mu$ : dynamic viscosity [kg/m·s]
- $k$ : thermal conductivity of air [W/m·K]

Depending on the orientation of the surface, different empirical correlations are used to determine the Nusselt number and thus the convective heat transfer coefficient. For a horizontal plate with the hot surface facing upwards, the correlations are:

- Laminar regime:

$$Nu = 0.54 \cdot (Gr \cdot Pr)^{1/4}, 10^4 < Gr \cdot Pr < 10^7 \quad [3.7]$$

- Turbulent regime:

$$Nu = 0.15 \cdot (Gr \cdot Pr)^{1/3}, 10^7 < Gr \cdot Pr < 10^{11} \quad [3.8]$$

The downward surface is not considered because the temperature is equal to the Ambiental one, so the calculations is neglected. For a vertical plate, the most widely used correlation that smoothly transitions between laminar and turbulent regimes are:

- Laminar regime:

$$Nu = 0.68 + \frac{0.670 \cdot (Gr \cdot Pr)^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}}, 10^{-1} < Gr \cdot Pr < 10^9 \quad [3.9]$$

- Turbulent regime:

$$Nu = 0.15 \cdot (Gr \cdot Pr)^{1/3}, 10^9 < Gr \cdot Pr < 10^{12} \quad [3.10]$$

For an inclined (or oblique) plate, the behavior lies between the vertical and horizontal configurations. The Nusselt number can be estimated as

$$Nu(\theta) = Nu_{vertical} \cdot (\sin \theta)^{1/4}, 10^4 < Gr \cdot Pr < 10^{10} \quad [3.11]$$

After presenting the empirical correlations and the heat transfer models adopted for the analysis, the following section reports the thermal calculations carried out for the different localized areas of the pasteurizers. The exponent on the correlation  $(Gr \cdot Pr)^n$  indicates the flow regime: a value of 1/4 corresponds to laminar flow, while 1/3 corresponds to turbulent flow. For inclined surfaces, the effective buoyancy component acting in the direction of motion is reduced, which lowers the overall heat transfer coefficient compared to a vertical plate.

### 3.5.1 Natural convection pasteurizer line 3

Upper face pasteurizer line 3 in table 3.10:

Table 3.10: Natural convection of upper face pasteurizer line 3

Length [m]	$\Delta T$ [K]	Nu	h [W/ (m <sup>2</sup> s)]	Q [W]
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4,20	16,00	709,70	4,45	484,55
1,70	16,00	287,26	4,45	196,13
1,48	58,00	384,17	6,84	950,82
1,76	59,00	459,46	6,88	1156,77
0,59	59,00	154,02	6,88	387,78

Extraction channel pasteurizer line 3 in table 3.11:

*Table 3.11: Natural convection of extraction channel pasteurizer line 3*

Length [m]	$\Delta T$ [K]	Nu	h [W/ (m <sup>2</sup> s)]	Q [W]
0,20	23,00	21,86	2,88	21,45
0,12	3,00	8,96	1,97	0,42
0,28	16,00	25,69	2,42	17,54
0,26	22,00	26,32	2,67	3,97
0,80	18,00	58,15	1,91	16,54

### 3.5.2 Natural convection pasteurizer line 4

Upper face pasteurizer line 4 in table 3.11:

*Table 3.11: Natural convection of upper face pasteurizer line 4*

Length [m]	$\Delta T$ [K]	Nu	h [W/ (m <sup>2</sup> s)]	Q [W]
6,96	40,00	1596,17	6,04	2724,50
3,07	40,00	704,06	6,04	1201,76

Extraction channel pasteurizer line 4 in table 3.12:

*Table 3.12: Natural convection of extraction channel pasteurizer line 4*

Length [m]	$\Delta T$ [K]	Nu	h [W/ (m <sup>2</sup> s)]	Q [W]
0,20	30,00	40,15	5,29	51,40
0,12	12,00	21,77	4,78	4,13
0,28	16,00	44,16	4,15	30,15
0,26	28,00	52,94	5,36	10,15
0,80	10,00	86,29	2,84	13,64

### 3.6 Natural convection vs Radiation

The figure 3.7 shows the individual contributions of thermal radiation and natural convection for each pasteurizer. This graphical representation allows a clear comparison between the two

heat transfer mechanisms, highlighting their relative impact on the overall thermal dispersion of each unit.

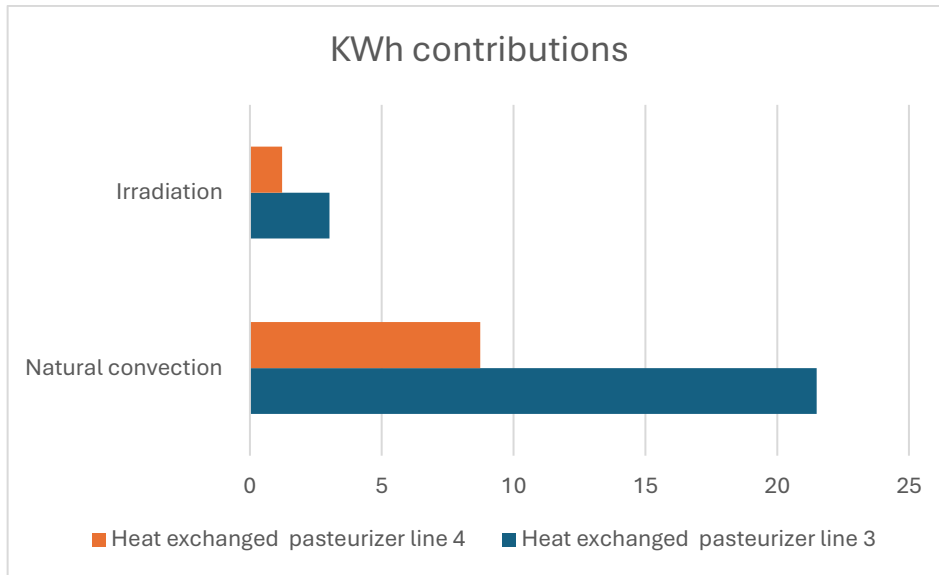


Figure 3.7: Confrontation contributes of natural convections and irradiation.

As we can see the natural convection values are much higher than the radiation. In practical applications, the convective heat transfer coefficient  $h_c$  increases with both the temperature difference between the surface and the surrounding fluid and with the characteristic length of the surface. This result indicates that the dominant mechanism responsible for heat loss in the analysed configuration is natural convection, mainly due to the significant temperature difference between the pasteurizer surfaces and the surrounding air. Consequently, reducing the surface temperature through improved insulation would significantly decrease the overall thermal load released into the production environment. Table 3.13, illustrate the total energy dissipated over a year.

Table 3.13: Total energy exchanged

	<b>Line 3</b>	<b>Line 4</b>
<b>TOTAL ENERGY EXCHANGED [KWh/year]</b>	140836,8	37657

### 3.7 Direct steam leak

The value of total heat exchanged in the two pasteurizers are totally different. The presence of direct steam leaks (pasteurizer line 3) represents an additional source of inefficiency: each kilogram of steam released into the environment loses its entire enthalpy, increasing both

operational costs and the thermal load that the HVAC system must remove. These leakage points require corrective maintenance, and their elimination provides a further energetic and economic benefit. Figure 3.8 shows a direct leakage of steam.



*Figure 3.8: Direct steam leakage*

Overall, the proposed intervention provides a twofold advantage:

1. A reduction in the thermal power released into the environment, leading to lower energy consumption of the air-conditioning system.
2. A reduction in sterile steam consumption, achieved through greater thermal stability within the pasteurizer.

The combination of these two factors defines total achievable energy saving and serves as the basis for estimating the payback period of the investment. Both the direct and indirect steam losses are equal to  $S_L = 28.12 \text{ Kg/h}$ . For the calculation of the heat dissipation through the office building windows, the total cooling energy was estimated based on the sum of all installed refrigeration capacities within the system, resulting in a value of approximately 1.2 MW of cooling power. This evaluation considered the contribution of operating HVAC units in the office area. By considering the total installed cooling capacity, it was possible to obtain a realistic estimate of the overall thermal load.

### 3.8 Proposed solutions

Based on the analyses conducted, different interventions were proposed to achieve higher efficiency in the system. These solutions aim to reduce thermal losses, improve the stability of the refrigeration process, and decrease the overall energy consumption of the plant. The following subsections present the main optimization measures together with their expected technical and economic benefits.

#### 3.8.1 Insulating layer

One of the proposed solutions is to replace the pasteurizer insulation, combined with corrective maintenance aimed at eliminating the direct steam leaks identified during inspection. The economic assessment of this intervention was conducted using actual costs for energy and sterile steam, with the latter produced at a pressure of 5,8 bar. Enhancing the insulation leads to a significant reduction in heat losses to the surrounding environment. Under current conditions, this lost heat constitutes an additional thermal load for the air-conditioning system, which must remove the extra energy released by the machine. The difference between the heat emitted by the pasteurizer in its current state and the heat estimated after insulation replacement therefore represents the first source of energy savings, as it corresponds to thermal energy that the refrigeration system will no longer need to dissipate. The second contribution to overall energy savings derives from the reduced consumption of sterile steam required to maintain the internal temperature of the pasteurizer. A deteriorated insulation layer causes greater thermal instability inside the machine, forcing the system to compensate for heat losses by supplying larger amounts of steam at 5.8 bar. By improving the insulation, these losses are minimized, leading to lower steam demand. Consequently, the recovered heat from better insulation translates directly into a reduction in thermal energy supplied via sterile steam, resulting in proportional economic savings.

$$\text{Steam price} = 0.031 \frac{\text{€}}{\text{Kg}}$$

$$\text{Cost of electricity} = 0.141 \frac{\text{€}}{\text{KWh}}$$

The values of steam price and the cost of electricity are obtained through the archives of Pastificio Rana spa.

The electric power, equation 3.12, calculated is equal to:

$$P_{el} = \frac{Q}{COP} \quad [3.12]$$

$Q$  : Heat exchanged [KWh]

$COP$  : Coefficient of performance

The C.O.P is calculated, table 3.14, with all the nominal values of each electric component and it's equal to  $COP = 2.47$  [10]

Table 3.14: Calculation of COP

	<b>Energy consumption [KW]</b>	<b>Time of functioning [h]</b>	<b>Daily energy consumption [KWh]</b>	<b>Annual energy consumption [MW/year]</b>
<b>Compressor engine</b>	250	24	6000	1.91
<b>Oil pump engine</b>	4	24	96	0.03
<b>Oil resistance</b>	1	24	24	0.007
<b>Evaporative condenser fan engine (high speed)</b>	30	24	720	0.23
<b>Evaporative condenser fan engine (low speed)</b>	7.5	24	180	0.06
<b>Evaporative condenser water pump engine</b>	2.2	24	52.8	0.02
<b>Evaporative condenser water resistance</b>	5	24	120	0.04
<b>Glycol pump engine</b>	22	24	528	0.16
<b>TOTAL</b>	321.7	24	7720.8	2.45

To obtain the total refrigeration cost in the equation 3.13 and the steam loss in the equation 3.14:

$$\text{Refrigeratiuon cost} = P_{el} \times h \times \text{Cost of electricity} \quad [3.13]$$

$$\text{Steam loss cost} = Q \times h \times H \quad [3.14]$$

$h$  : Hour worked over a year = 6240h

$H$  : Specific enthalpy heat at 5.8 bar

The total steam dissipated for direct leakage in the process, table 3.15, present only in pasteurizer of line 3 is equal to:

Table 3.15: Cost of direct leakage of steam

Steam losses [Kg/h]	Steam cost [€/year]	Refrigeration cost [€/year]	Total [€/year]
21	4060,30	5309,504	9369,81

Instead, the total cost for both pasteurizer of line 3 and 4 are estimated, the values include the direct and indirect leakage of steam so are higher respect the one in the table above. Reported in the table 3.16:

Table 3.16: Total euros loss

	3	4
<b>Refrigeration cost [€/year]</b>	9429.61	3530.8
<b>Steam cost [€/year]</b>	5635.67	2700.09
<b>Total cost [€/year]</b>	15065.29	6230.89

Furthermore, the practical feasibility of the repair work was also evaluated, including the involvement of an external specialized company. The installation of new insulating panels for instance, a 25 mm layer of rock wool capable of maintaining a surface temperature of approximately 27°C reduces this thermal loss. Considering the surface area occupied by the pasteurizer and the unit cost of the selected insulating material estimated at €250/m<sup>2</sup>, including installation and labour the total cost of implementation was determined.

Table 3.17 shows the values related to the pasteurizers in lines 3 and 4:

*Table 3.17: Cost of realization of the intervention*

	<b>Area tot [m<sup>2</sup>]</b>	<b>Cost of realization [€]</b>
<b>Line 3</b>	21.96	5490.65
<b>Line 4</b>	26.17	6542.5
<b>Total</b>	48.13	12033.15

### 3.8.2 Protection film

To reduce the energy impact associated with the office area, a solution was proposed involving the installation of solar-controlled window films designed to absorb and reflect solar heat. The main issue occurs during the summer season, when the existing glazing allows a significant amount of solar radiation to enter the building, increasing indoor temperatures and, consequently, the cooling demand. The application of thermal films limits heat transfer to the indoor environment by dissipating part of the solar energy on the external surface of the glass. This improvement not only enhances thermal comfort in office spaces but also allows part of the cooling capacity saved to be redirected to the production area when needed. The analysis presented in this section is based on real performance data provided by an external supplier, which indicates an estimated energy saving of approximately 30% in the office zone. Direct experimental tests were not carried out, as the evaluation was conducted before the start of the summer season. Therefore, the expected benefits were estimated through local thermal analysis and a comparison between treated and untreated glass surfaces. A preliminary test was performed by applying the selected film to a representative window section and measuring surface temperatures using a thermal imaging camera. The thermal behaviour of the treated area was then compared with that of the untreated one, allowing an estimation of the total solar energy absorbed by the glass before and after the application. The difference between these two conditions represents the potential energy savings associated with the reduction of the summer thermal load. The selected film, OPTILITE 75 XTRA [11], was chosen because it is specifically designed for applications where preserving the original appearance of glass surfaces is required. (Topfilm, s.d.). According to its technical data sheet, the key features include:

- Reduction of indoor temperature by up to 6°C during peak daytime hours and around 3°C at night, significantly decreasing the cooling system load.

- Solar factor (g-value or SHGC): This parameter expresses the percentage of total solar energy (direct and absorbed/re-emitted) that passes through the glass.
- A standard untreated glass has a g-value of 0.75–0.85, meaning that 75–85% of solar heat penetrates indoors.
- With the OPTILITE 75 XTRA film, this value is significantly reduced, lowering the total solar energy transmitted inside. A lower g-value directly translates into less internal heat gain and consequently lower air-conditioning energy consumption.

Another important parameter is the solar reflectance, which indicates the fraction of incident solar energy reflected by the surface. Higher reflectance values mean more effective rejection of solar radiation, reducing both heat ingress and glare. All the parameters are reported in table 3.18. The glare reduction property, also reported in the data sheet, measures the film’s ability to reduce visual discomfort caused by excessive brightness. This contributes to improved indoor comfort, particularly in office environments exposed to direct sunlight.

*Table 3.18: Technical data sheet*

<b>g</b>	<b>Total solar energy rejected [%]</b>	<b>Total solar energy absorbed [%]</b>	<b>Glare reduction [%]</b>
0.53	57	56	15

Finally, the table 3.19 represents all the values after the intervention:

*Table 3.19: Total saved after the intervention*

<b>Total office energy [MW]</b>	<b>Energy saving [%]</b>	<b>Total energy saved [MW]</b>	<b>Cost of saved electricity[€/year]</b>
1.2	30	0,36	50.760

### 3.9 Environmental impact

To complement the thermal and energy analysis, an evaluation of the environmental impact associated with the proposed improvements was carried out. The objective of this section is to quantify the reduction in CO<sub>2</sub> emissions achieved through the energy savings obtained from the optimization measures applied to the refrigeration systems and the pasteurization units.

The calculation of the avoided emissions was based on the total annual energy savings, expressed in kilowatt-hours, using an emission conversion factor of 0.4 kg CO<sub>2</sub> per kWh. This factor represents the average carbon intensity of electricity generation in the national energy

mix and provides a realistic estimate of the environmental benefit associated with reduced energy consumption.

The results obtained for the two production lines analysed are summarized in table 3.20 and 3.21 represent the annual electrical energy savings achieved for each production line because of the proposed efficiency measures, together with the corresponding avoided CO<sub>2</sub> emissions.

- Line 4

*Table 3.20: CO<sub>2</sub> saved emissions line 4*

<b>Energy savings KWh/year</b>	<b>Emission Kg CO2/Year</b>
25561,56	10224,62

- Line 3

*Table 3.21: CO<sub>2</sub> saved emissions line 3*

<b>Energy savings KWh/year</b>	<b>Emission Kg CO2/year</b>
140885,93	56354,37

Overall, the implementation of the proposed interventions not only enhances operational performance but also significantly reduces the plant’s environmental footprint, reinforcing the importance of energy efficiency as a key component of sustainable industrial development.

### **3.10 Conclusion**

The analyses conducted in this thesis demonstrate the strong interdependence between refrigeration system performance, thermal insulation quality, and overall energy efficiency of the production plant. The results indicate that the degradation of the pasteurizer insulation constitutes one of the main sources of thermal losses within the production area, leading to increased cooling demand from the HVAC system and higher steam consumption. Thermal imaging surveys and on-site measurements identified surface temperatures exceeding 80 °C in several locations, compared with an expected value of approximately 27 °C for adequately insulated components. The replacement of the existing insulation with new 25 mm thick rock-wool panels, together with the repair of the identified steam leaks, allows for a substantial reduction in heat losses. The estimated energy recovery, equal to approximately 152,000 kWh per year, results in lower operating costs and improved process stability. From an operational perspective, annual cost savings of approximately €21,000 are achieved. Furthermore, the reduction of thermal loads in the production environment indirectly decreases the energy

demand of the refrigeration system, which currently operates with a seasonal coefficient of performance (COP). In parallel, the installation of solar-control window films in office buildings is expected to mitigate overheating during the summer period, leading to a reduction in indoor temperatures of up to 6 °C and a decrease in HVAC energy consumption of about 30%, according to manufacturer specifications. Furthermore, the implementation of solar films allows for energy savings of approximately 30% with a reduction in the cost of refrigeration of approximately €51.000. This intervention supports the broader objective of optimizing energy distribution across the facility while maintaining appropriate thermal comfort for employees. From a wider perspective, this work emphasizes the importance of an integrated approach to energy management in industrial environments, where refrigeration, steam generation, and air-conditioning systems are closely interconnected. The proposed actions, supported by quantitative analyses and economic evaluations, represent a practical and replicable strategy for improving energy efficiency in industrial food processing facilities. In conclusion, the objectives of the study were achieved through the identification of the main inefficiencies, the quantification of their impact, and the definition of realistic corrective measures. The implementation of these interventions is expected to enhance thermal performance, reduce energy consumption, and improve the overall environmental sustainability of the production site. On line 4, an annual energy saving of 25.561,56 kWh/year is obtained, corresponding to an avoided emission of approximately 10,22 t CO<sub>2</sub>/year. For line 3, the higher installed capacity and operating hours result in a significantly larger saving of 140.885,93 kWh/year, equal to approximately 56,35 t CO<sub>2</sub>/year. These values highlight the substantial environmental advantages that can be achieved through targeted efficiency improvements. In addition to the direct economic benefits resulting from lower energy consumption, the reduction in CO<sub>2</sub> emissions contributes to the company's broader sustainability goals, aligning with the European Green Deal and industrial decarbonization objectives. Overall, the proposed technical solutions lead to a significant reduction in energy consumption, resulting in an estimated decrease of approximately 67 tonnes of CO<sub>2</sub> emissions per year. This reduction is achieved through the combined effect of lower thermal losses, decreased cooling demand, and improved system efficiency. Beyond the economic benefits, these results highlight the strong environmental impact of targeted energy optimization measures, reinforcing the role of thermal management as a key lever for sustainability in industrial food processing plants.

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