

DESIGN OF A CO₂ PLATE FREEZER TEST FACILITY WITH -50 °C EVAPORATION TEMPERATURE

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ABSTRACT

Food waste presents a global challenge to food security and sustainability while contributing to substantial emissions and energy consumption. Efficient cooling and freezing systems using natural refrigerants offer a sustainable solution to reduce food loss and waste in the food supply chain, particularly by preventing the loss of raw materials. Plate freezers are essential components in modern automated production and processing facilities for freezing processed foodstuffs. This study aimed to design a test facility for a real-sized industrial plate freezer that can be integrated into a dedicated CO₂ refrigeration system in the laboratory infrastructure. With CO₂ liquid circulation inside the plates, the unit can deliver over 100 kW of cooling capacity at an evaporation temperature ranging from -30 to -50 °C. Additionally, a numerical model was developed for the proposed freezing system and the freezing performance was investigated for different evaporation temperatures.

Keywords: Refrigeration, Carbon Dioxide, Plate Freezing, Freezing Time, Evaporation Temperature

1. INTRODUCTION

Freezing is a widely used technology for preserving fish and meat in industrial processing and long-term storage. Proper freezing technology in fish and meat processing and transport can significantly reduce food loss and waste in the supply chain, thereby lowering the consequent greenhouse gas (GHG) emissions and energy consumption. Plate freezers are essential components in modern automated production and processing facilities. These freezers consist of vertical or horizontal stacks of hollow plates, which cool the product through contact with cold surfaces. Plate freezers offer operational flexibility, allowing for batch, semi-continuous, or continuous processing. They are also categorized as quick freezers, capable of efficiently freezing large quantities of meat or fish.

In recent years, environmental safety concerns have led to the phase-out or impending ban of many synthetic refrigerants. Consequently, freezing systems using natural refrigerants with very low or zero Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) values have become promising long-term alternatives, attracting significant interest. Plate freezers using CO₂ as the refrigerant can achieve evaporation temperatures as low as -50 °C with a rapid temperature decrease (Dopazo & Fernández-Seara, 2012; Verpe et al., 2018). Additionally, CO₂ is environmentally friendly, non-toxic, and non-explosive, enhancing its appeal for food processing applications. Furthermore, CO₂ plate freezers exhibit high heat transfer rates and require infrequent defrosting of heat transfer surfaces, leading to lower operational costs and better product quality due to minimal dehydration. Consequently, CO₂ plate freezer technology holds significant commercial potential, appealing to both food manufacturers and customers who seek efficient, safe, and sustainable freezing solutions.

This study aimed to design a test facility for a real-sized industrial plate freezer, which can be integrated into a dedicated CO₂ refrigeration system in the laboratory infrastructure. With CO₂ liquid circulation inside the plates, the unit can deliver over 100 kW of cooling capacity at evaporation temperatures ranging from -30 to -50 °C. Additionally, a numerical model was developed for the proposed freezing system, allowing for the numerical investigation of its freezing performance under various operational conditions.

2. DESIGN OF THE PLATE FREEZING TEST FACILITY

In this study, a plate freezing system was designed for integration into an existing CO₂ refrigeration system in the laboratory infrastructure, applicable to fish freezing on onboard fishing vessels and fish and meat processing. The unit can deliver over 100 kW of cooling capacity at evaporation temperatures ranging from -50 °C to -30 °C. This test facility will be used to investigate and optimize the performance of the freezing system and its components.

2.1. CO₂ plate freezing system description

The existing CO₂ heat pump system features three suction lines with different suction temperatures and one supply line. A horizontal plate freezer is incorporated into this CO₂ system, functioning as a flooded evaporator. The P&ID of the designed plate freezer test facility is shown in Figure 1. The main components of the test facility include a subcooler, a separator, a pump, a plate freezer, a compressor, and an expansion valve (V3). The compressor is utilized in the defrosting circuit. During the experiments, various parameters will be monitored by the measuring instruments, including freezing time, the evolution of CO₂ evaporation temperature, the center temperature of the frozen product, energy consumption, and the production capacity of the designed plate freezing system. These parameters will be further analyzed to minimize emission footprints, energy consumption, and investment costs. Additionally, the test facility features a defrosting circuit that uses hot gases to defrost the plates at the end of the freezing process, ensuring efficient and continuous operation.

2.2. Components design

2.2.1 Subcooler

The CO₂ liquid from the supply line of the central CO₂ refrigeration system is initially at 14 °C and 50 bar. To ensure that only liquid CO₂ is throttled by the expansion valve (V3) before entering the separation tank, a subcooler was installed. This subcooler was designed to cool the CO₂ liquid from 14 °C to -33 °C. The cold stream is obtained by throttling the subcooled CO₂ by an automatic expansion valve (V2) to -38 °C and 10.8 bar, as shown in Figure 1. The expansion valve (V2) operates according to the setpoints of the temperature sensor (T1) and pressure sensor (P1) to control the superheat at the outlet (P4) and make sure only vapor CO₂ goes back to the -38 °C suction line of the central CO₂ system. The subcooling process is conducted under constant pressure. The cooling load is calculated based on the logarithmic mean temperature difference (LMTD) across the subcooler. The calculated LMTD is around 20 K and the required subcooling capacity for cooling CO₂ from 14 °C to -33 °C at 50 bar is 18 kW. The installed subcooler in the lab is shown in Figure 2.

2.2.2 Expansion valve (V3)

Through the expansion valve (V3), the liquid CO₂ is throttled from -33 °C and 50 bar to -50 °C and 6.8 bar. The electronic expansion valve (V3) was sized according to the maximum capacity of the lowest-stage compressors in the central CO₂ system. Three compressors operate in series at the lowest compression stage with a suction temperature of -48 °C and suction volumes of 18.4 m³/h, 28.9 m³/h, and 28.9 m³/h, respectively. The maximum suction volumetric capacity \dot{V}_{max} is a summation of the suction volumes of the three compressors. The volumetric efficiency (η) of the compressors is 0.6. Then the maximum mass flow rate (kg/s) can be calculated as in Eq. (1):

$$\dot{m}_R = \dot{V}_{max} \cdot \eta \cdot \rho / 3600 \quad \text{Eq. (1)}$$

The maximum freezing capacity is calculated as in Eq. (2):

$$\dot{Q}_{freezing} = \dot{m}_R \cdot (h_{out} - h_{in}) \quad \text{Eq. (2)}$$

where ρ is the vapor density (kg/m³), h_{out} and h_{in} are the enthalpies (kJ/kg) at the outlet and inlet of the plate freezer.

The expansion valve (V3) was sized based on a maximum mass flow rate of 0.23 kg/s and cooling capacity of 80 kW with an opening of 80%. The model selection was conducted by Coolselector software and Danfoss CMT08 model was chosen, as shown in Figure 2.

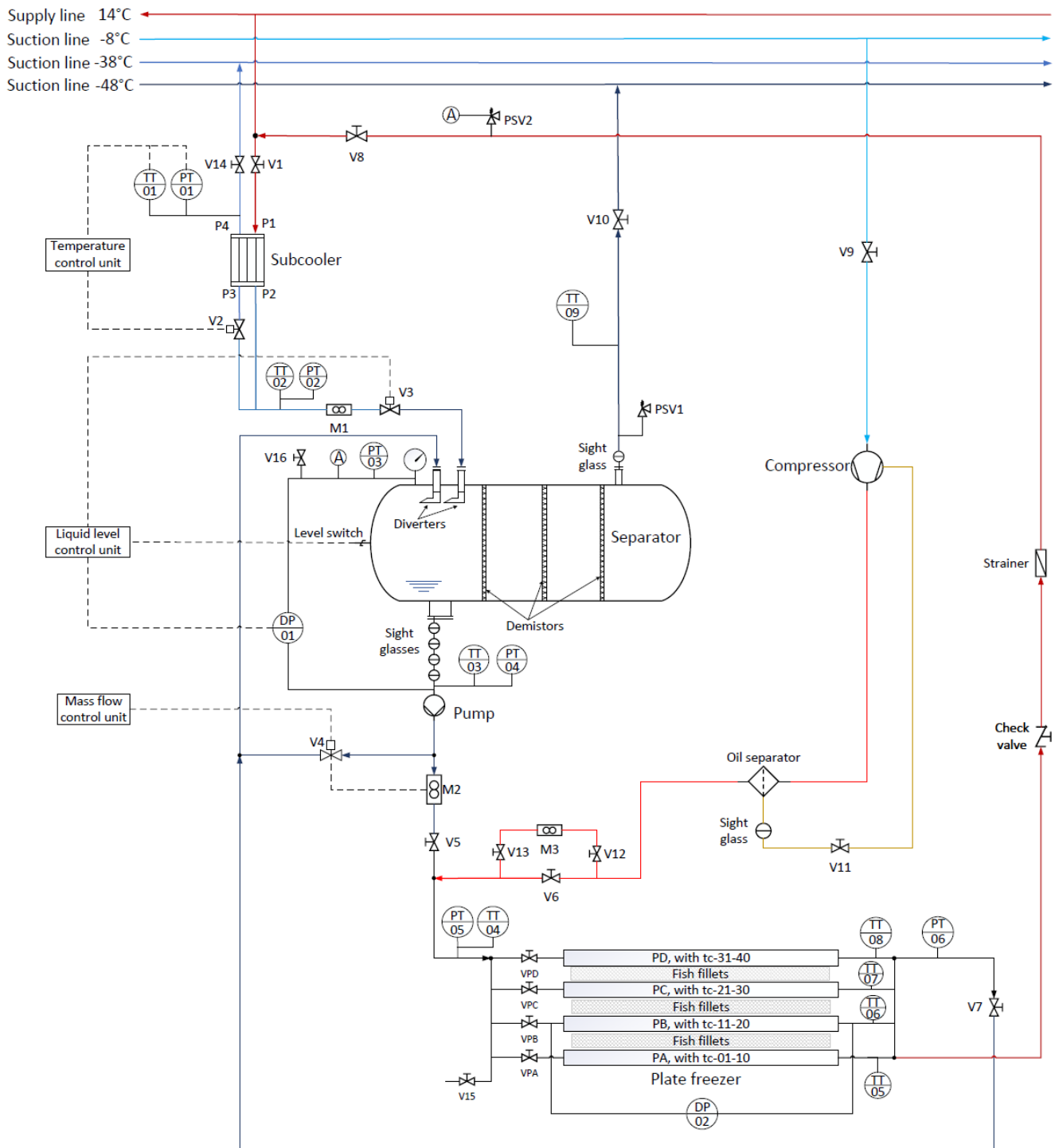


Figure 1: P&ID of the plate freezing test facility

2.2.3 Separator

The liquid and vapor two-phase separation is achieved in the separator in three stages. The first stage, known as primary separation, is accomplished using diverters located at the separator inlets, as shown in Figure 1. Larger droplets impinge on the diverter due to the momentum and then fall under gravity. The secondary separation occurs in the disengagement area between the diverters and demisters. Here, smaller droplets detach from the vapor flow and descend under gravity. The third stage involves demisting, where the smallest droplets are coalesced into

larger droplets in the demisters and then fall under gravity. As depicted in Figure 1, a horizontal separator with three demisters in series was selected. The sizing of the separator was determined using the method outlined by Svrcek and Monnery (1993). The calculated diameter of the separator tank is 500 mm, and the separator length is 1000 mm. Following the separation process, the liquid phase exits the separator through the outlet located at the bottom and is directed to the pump. The vapor phase exits the tank via the top vapor outlet and is routed back to the -48 °C suction line of the central CO₂ system.

As illustrated in Figure 1 and Figure 2, sight glasses have been installed in the middle of the separator shell and at the liquid outlet to facilitate monitoring CO₂ liquid level. The liquid column level has been set to be above 2.4 m. The control range of the liquid level spans from 0 to 400 mm above the set value of the liquid column. This range is covered by the effective observing length of the sight glasses at the liquid outlet of the separator. The CO₂ liquid level is regulated by the expansion valve (V3) based on the pressure difference between the top pressure of the separator and the pressure at the pump inlet, which is measured by a differential pressure sensor.

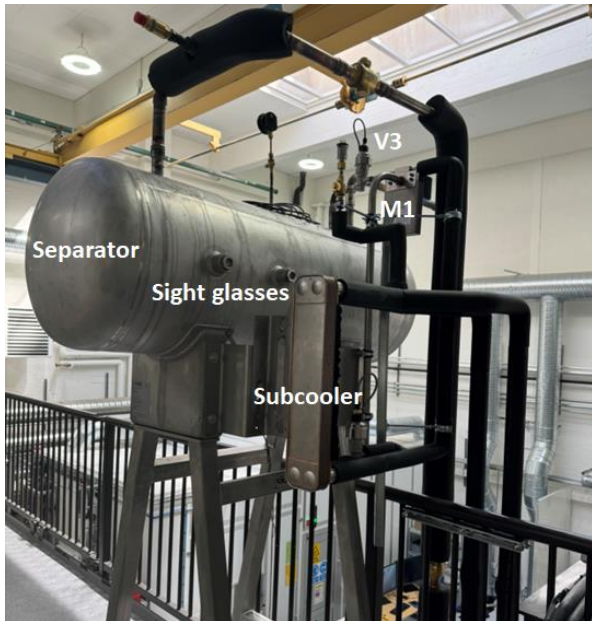


Figure 2: The separator and subcooler in the lab

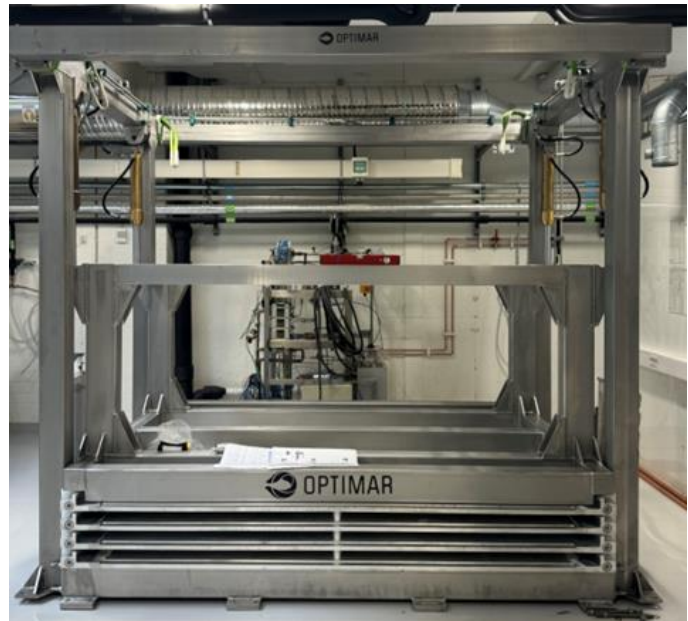


Figure 3: CO₂ plate freezer in the lab

2.2.4 Plate freezer

The liquid CO₂ at approximately -50 °C and 6.8 bar, is pumped from the separator into the plate freezer. Within each plate, CO₂ as the refrigerant flows through the coils and undergoes evaporation by absorbing heat from the product. The CO₂ plate freezer is manufactured by Optimar AS, with relevant technical data provided in Table 1. Figure 3 depicts the plate freezer installed in the lab. Following the evaporation process, the resulting liquid-vapor mixture is directed back to the separator. The mass flow to the plate freezer is monitored by a mass flow meter (M2) and controlled by a control valve (V4) equipped with a mass flow control unit, as shown in Figure 1. If the reading of M2 exceeds the set value, the opening of V4 will be increased to allow more refrigerant to return to the separator, and vice versa.

2.3. Instrumentation and data acquisition

The instrumentation of the test facility is detailed in Figure 1. The inlet mass flow rate of the separator and the liquid mass flow rate to the plate freezer are measured by mass flow meters M1 and M2, respectively. Each plate was equipped with 10 thermocouples to capture the temperature distribution across the plate surface. Additionally, each product block (fish fillets) is fitted with 10 thermocouples to measure the center temperature. Plate B, the second product plate from the bottom, is designated as the test plate. The pressure drop across Plate B is measured by a differential pressure sensor (DP-02). Each plate was also equipped with a PT-100 temperature sensor at the

refrigerant outlet to monitor the superheat. The control strategies of the test facility, as explained in the component design in Section 2.2, involve these measurements. The data acquisition and processing of the analog signals from all the measuring instruments are handled by National Instrument components with the LabVIEW software.

Table 1. Technical data of the plate freezer

Plate number	4
Orientation	Horizontal
Dimensions including the frame	3150 x 2150 x 2580 mm
Plate dimensions	2480 x 1605 x 27 mm
Design pressure	50 bar
Filling volume	12 l per plate

3. NUMERICAL SIMULATION OF THE PLATE FREEZING SYSTEM

A dynamic numerical model of the CO₂ plate freezing system was developed by Dymola (Dynamic Modelling Library, version 2022, Dassault systems) (Systèmes, 2022) using Modelica language. Two commercial Modelica libraries were utilized for the simulations, namely TIL-suite 3.10.0 and TILMedia 3.10.0 which are provided by TLK-Thermo GmbH. The system model and component models were all established based on the designed plate freezing system introduced in Section 2.

3.1. Numerical model

A simplified simulation model of the freezing process is illustrated in Figure 4. To simplify the simulation, the pressure drops caused by friction in the system and heat losses to the surroundings were neglected. A plate heat exchanger model was employed to simulate the heat transfer in the subcooler. To simplify the simulation, the pressure drop across the subcooler was neglected. The evaporation heat transfer coefficient was calculated by the Longo correlation (Longo et al., 2015) and the single-phase heat transfer was calculated by Martin correlation (Martin, 1996).

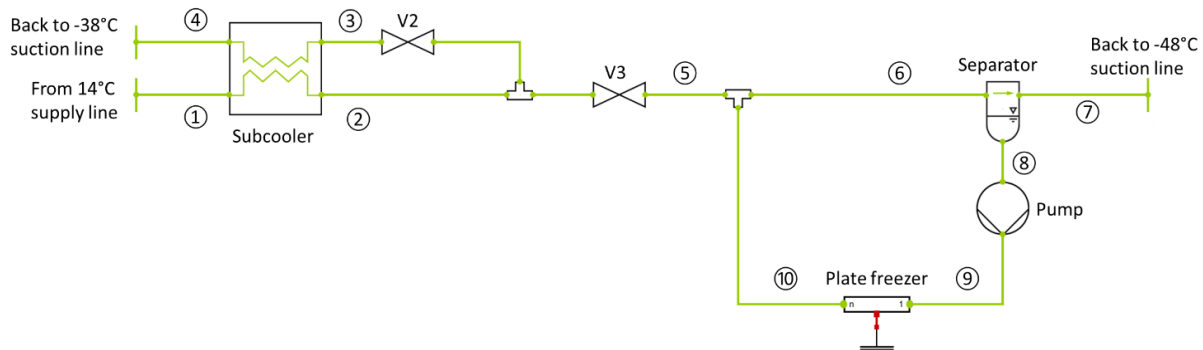


Figure 4: Simplified numerical model of the plate freezing system

The plate freezer was simulated by a tube exchanger with a capacitor heat boundary to model the heat flow from the product with an initial temperature of 18 °C. The evaporation heat transfer coefficient was calculated by the Gungor and Winterton (1987) correlation and the single-phase heat transfer was calculated by the Gnielinski (1975) correlation and Dittus and Boelter (1985) correlation. The pressure drop was calculated by Konakov (1946) correlation. Because the ice in the fish products forms over a range of temperatures rather than at a single temperature, a temperature-dependent effective heat capacity, which considers both the sensible and latent heat effects, was used in the simulation according to Schwartzberg (1976). Cod muscle was chosen as the frozen product by assuming homogenous material and regular shape and the parameters in Schwartzberg (1976) were used for the effective heat capacity calculation.

The liquid and vapor phases were assumed at thermodynamic equilibrium in the separator. The volume of the separator was 0.2 m³ and the initial filling level was set at 40%. The pump was running at a constant mass flow rate with an efficiency of 0.4. The expansion process was assumed to be isenthalpic and at the outlet of the expansion valve, the liquid-vapor two-phase flow was at a thermodynamic equilibrium state. The expansion valves V2 and V3 were controlled by PI controllers according to the superheat at stream point ④ and the freezer evaporation pressure, respectively.

3.2. Simulation results

The evolution of the product core temperature at different evaporation temperatures is illustrated in Figure 5 (a). During the simulation, the refrigerant mass flow rate through the plate freezer was maintained at 0.2 kg/s, and the product mass was 235 kg. The freezing times required to freeze the product from 18 °C to -20 °C were 83 min, 100 min, and 147 min for evaporation temperatures of -50 °C, -40 °C, and -30 °C, respectively.

The freezing process can be divided into three distinct periods. The first period is the cooling down of the product to the freezing temperature. It took around 18 min at the evaporation temperature of -50 °C. The second period is the freezing of the water content and it took approximately 44 min at the evaporation temperature of -50 °C. In this period, the product temperature remained constant due to the large fusion latent heat of the water content. The third period is the further cooling down of the frozen product to -20 °C and it took about 21 min. The freezing rate was higher in this period because the specific heat capacity of the frozen product is lower than that of the fresh product. Increasing the evaporation temperature significantly prolonged the freezing time during the second period and also raised the minimum reachable temperature. By decreasing the evaporation temperature from 30 °C to 50 °C, the freezing time was reduced by 43.5%, which aligns with the results of Verpe, Bantle et al. (2018).

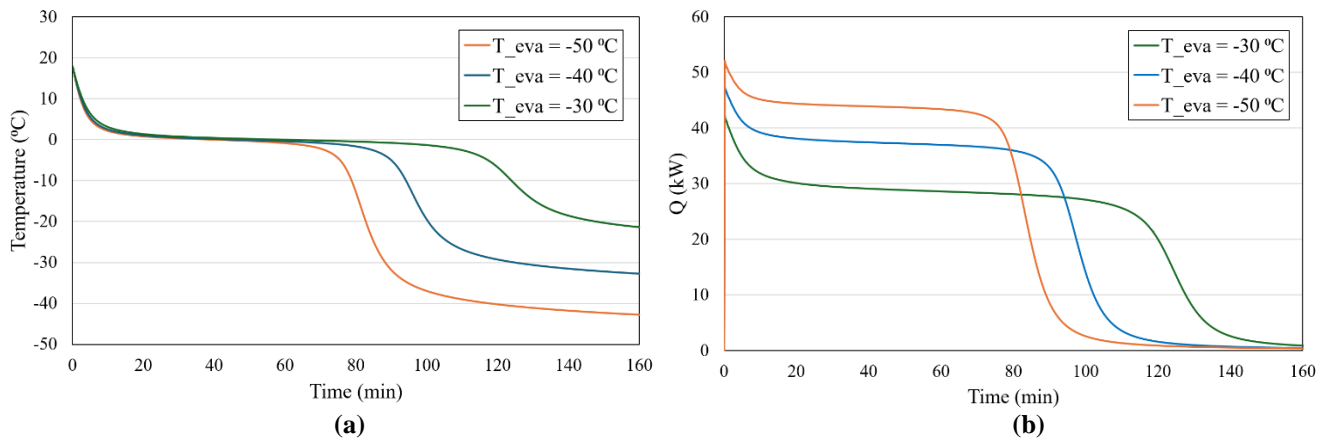


Figure 5: (a) Evolution of the product core temperature with different evaporation temperatures. (b) Evolution of the freezing load with different evaporation temperatures

The evolution of the freezing load at different evaporation temperatures is illustrated in Figure 5 (b). The thermal load was higher at lower evaporation temperatures, resulting in shorter freezing times. Additionally, the freezing load was higher at the beginning of the freezing process when the temperature difference between the refrigerant and the product was high. This led to a rapid heat transfer from the product to the refrigerant. The freezing load was nearly constant in the second freezing period due to the almost constant product temperature. Then the freezing load decreased in the third period as the product temperature approached the refrigerant temperature. The diminishing temperature difference reduced the heat transfer rate.

The feeding CO₂ liquid mass flow rate to the plate freezer was controlled by adjusting the pump speed. As illustrated in Figure 6 (a), the freezing time decreased significantly as the feeding CO₂ mass flow rate increased from 0.13 kg/s to 0.3 kg/s, particularly during the second freezing period. This reduction in freezing time occurred because the increased CO₂ mass flow rate enhanced the freezing capacity, enabling more efficient heat transfer and faster reduction of the product temperature.

As depicted in Figure 6 (b), the vapor quality at the outlet of the plate freezer decreases during the freezing process following the same trend as the product temperature. In the third period, the vapor quality drops rapidly as the temperature difference between the product and the plates diminishes quickly. The circulation rate, defined as the ratio of the circulated refrigerant mass flow rate to the vapor mass flow rate exiting the freezer, changes throughout the process. Since the plate freezer operates in batches, the thermal load is not constant but decreases over the course of the freezing process. Consequently, with a constant feed liquid mass flow rate, the circulation rate of the plate freezer increases throughout the entire freezing process. Furthermore, the vapor quality was observed to be higher at lower feeding CO₂ mass flow rates, indicating that the circulation rate was lower when the feeding CO₂ mass flow rate was reduced.

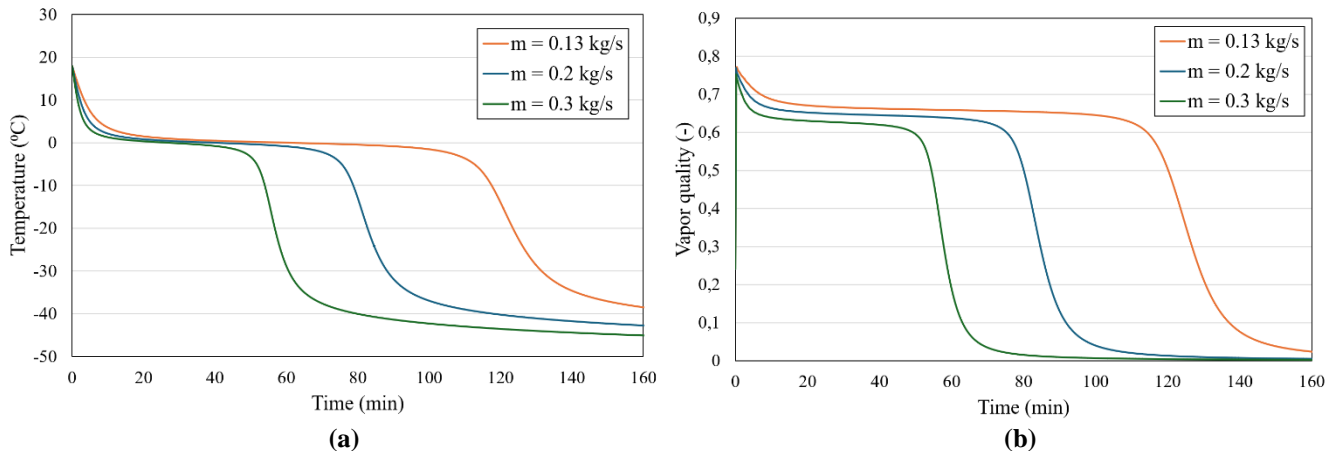


Figure 6: (a) Evolution of the product core temperature with different CO₂ mass flow rates. (b) Evolution of the vapor quality at the outlet of the plate freezer with different CO₂ mass flow rates

4. CONCLUSIONS

In this study, a plate freezing system was designed for application in fish and meat processing. A real-sized industrial horizontal plate freezer was implemented into an existing CO₂ heat pump system, functioning as an evaporator. The unit can deliver over 100 kW of cooling capacity at evaporation temperatures ranging from -50 °C to -30 °C. The test facility will be employed to test and optimize the freezing performance of the plate freezing system. Additionally, a numerical simulation was conducted to analyze the freezing times at different evaporation temperatures and with different CO₂ mass flow rates. The results showed that the freezing time to freeze 235 kg cod muscle from 18 °C to -20 °C was 83 min. By decreasing the evaporation temperature from 30 °C to 50 °C, the freezing time can be reduced by 43.5%. Moreover, with a constant feed liquid mass flow rate, the circulation rate of the plate freezer increased throughout the entire freezing process. Increasing the feeding CO₂ liquid mass flow rate can further decrease the freezing time and increase the circulation rate. Upon completion of the test facility construction, a comprehensive experimental study will be conducted. The numerical model will also be validated and refined based on the experimental results.

ACKNOWLEDGEMENTS

This study has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588 – project ENOUGH.

NOMENCLATURE

h	enthalpy (kJ/kg)	\dot{V}_{max}	maximum volumetric capacity (m ³ /h)
\dot{m}_R	refrigerant mass flow rate (kg/s)	η	volumetric efficiency (-)
$\dot{Q}_{freezing}$	freezing capacity (kW)	ρ	density (kg/m ³)
T_{eva}	evaporation temperature (°C)		

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