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Article

CO_2 Employment as Refrigerant Fluid with a Low Environmental Impact. Experimental Tests on Arugula and Design Criteria for a Test Bench

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Abstract: In order to define design criteria for CO_2 refrigeration systems to be used for agricultural products and foodstuff storage, a variable geometrical system was realized, with the goal of meeting a wide range of environmental and process conditions, such as producing low environmental impact and maintaining the highest Coefficient of Performance (COP), at the same time. This test-bench, at semi-industrial scale, was designed as a result of experimental tests carried out on Arugula. The storage tests showed that all samples stored in cold rooms with R.H. control showed a slight increase of weight but also small rot zones in all the boxes due to an excessive accumulation of water condensation; thus, the system may not have achieved conditions that RH requires in a given range, without reaching saturation condition. At the same time, the use of CO_2 must be adequately tested along its thermodynamic cycle, during steady state and/or transient conditions, imposing variable working conditions that can simulate plant starting phase or some striking conservation process, like those that characterize sausages. The designed plant will allow studying these specific performances and evaluate COP variation, according to environmental and plant operating conditions.

Keywords: refrigeration; natural fluids; arugula; CO_2 plant applications; variable geometry plant

1. Introduction

Engineering applications in the food industry are interdisciplinary. Various aspects have to be taken into consideration, including not only technical variables but also the physiology of the products, the health and hygiene aspects and the environment impact on these applications.

Innovation in machinery engineering is very often the result of studying how to use, adapt, and link proven technologies together, in order to obtain unique solutions that can improve the performance and efficiency in the field to which they are applied.

The recent international plans to reduce, as much as possible, the impact on the environment of the refrigeration systems is driving research on the possible use of new natural and ecological fluids. In fact, UE Directives tend to equate the benefits associated with the use of natural refrigerants and low environmental impact with those relating to the employment of traditional fluids. Since the introduction of the Montreal Protocol (1994), EU Legislation has gradually banned the use of CFC in 1994, HCFC in 2000 and since HFC will probably be banned starting from 2015.

In this context, the main objective of this paper is to provide a refrigeration system operating at low environmental impact with CO_2, in order to study the use of this fluid in some phases necessary for the production of particular products and, more generally, for food refrigeration and storage. The experiments were carried out in pilot plants to verify if the studied solutions can really be suggested to companies, in relation to the quality and the peculiarity of food as well as to the costs and environmental impact.

1.1. Law and Technical Aspects Regarding Greenhouse Gas Emissions of Refrigerant Fluids

European Regulations establish criteria and operational standards to regulate the construction, use and maintenance of equipment containing fluorinated greenhouse gas (Table 1).

Coming into force on 1 January 2017, refrigeration systems and heat pumps charged with HFC may be placed in equipment only if the HFCs are considered within the (transferable) quota system, established by Regulations [1–3]. Member States have until 1 January 2017 to provide measures for an adequate system to sanction at national level.

Table 1. Main Regulations regarding greenhouse gas emissions of refrigerant fluids.

Regulation (EC) n.	Year	Standard/requirements
842	2006	Containment, use, recovery and destruction of fluorinated greenhouse gases listed in attachment I; labeling and disposal of products and equipment containing those gases; communication of information on those gases.
516	2007	Leakage checking requirements for stationary refrigeration, air-conditioning and heat pumps.
1797	2007	Leakage checking requirements for stationary fire protection system containing certain fluorinated greenhouse gases.
303–306	2008	Minimum requirements and conditions for mutual identification for the certification of companies and personnel in regard to: stationary refrigeration, air-conditioning and heat pumps, stationary fire protection system and fire extinguishers, containing certain fluorinated greenhouse gases.
307	2008	Requirements for training programs for personnel in regards to air-conditioning systems containing certain fluorinated gases.
517	2014	Conditions placed on the trade of products and equipment that contain fluorinated greenhouses gases; conditions for use of greenhouses gases; limits placed on the trade of hydrofluorocarbons; institution of a quota market for the trade of hydrofluorocarbons; prevention of emissions, leakage checks, installation of leak detection (automatic) systems, registry, of F-Gases.

How long before it appears that, irrespective of deferments and repeals, the tendency is that of introducing a fair amount of obligations and restrictions, so that users will be forced to employ either HFO (Hydrofluoroolefins: ecological refrigerants) or natural fluids [3–5]?

Therefore, two research paths arise.

(1) Studying the creation of new synthetic refrigerant fluids that can satisfy plant and environmental needs; and
(2) Studying how to adapt plants and machinery to the new fluids, in particular natural ones.

This is true for air conditioning systems, fire extinguishing systems, heat pumps, refrigeration plants, deep-freezing plants and all other industrial applications.

A refrigerant fluid should have many properties all together but if they cannot all be fully satisfied, then each fluid has its field of use.

The main thermodynamic properties, both physical and chemical, which a refrigerant fluid must have in order to conveniently be used in plants are:

- high latent heat value during phase transition at evaporation temperature, which, combined with a high density, guarantees the necessity of suitable capacity at the same required refrigerating power;
- capacity to evaporate and condensate at temperatures and pressures that are suitable to the field of use;
- solubility, in the gaseous phase, and miscibility, in the liquid phase, with lubricating oil; and
- ratio between condensation and evaporation pressure, which should not be too high, so as to reduce the consumption of energy used for compression.

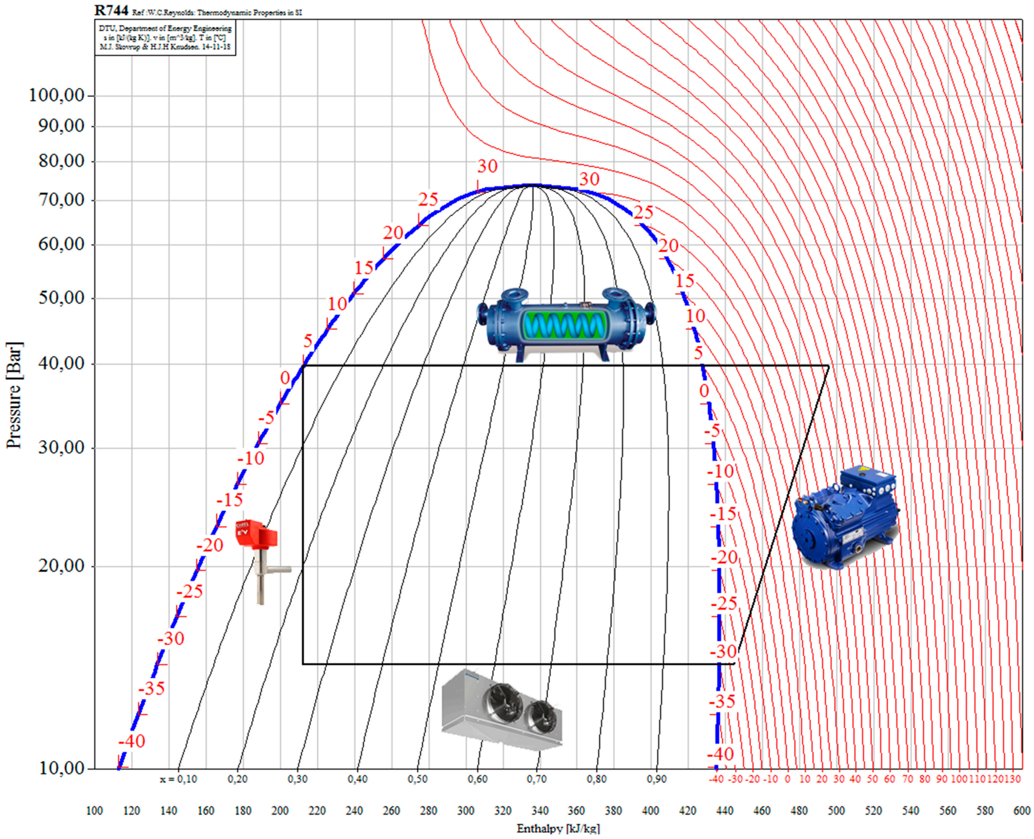
In this context, Carbon Dioxide (R744: CO_2) is less energy efficient than traditional fluids, but with properly designed plants, it can be used as a refrigerant fluid (Table 2; Figure 1). Its GWP is almost equal to 1, considering that it is possible to obtain CO_2 as recycled or recovered component from industrial by-production; it has volumetric refrigerating effect, at low temperatures, greater than the other fluids; therefore, at the same refrigerant efficiency (COP), the compressor flow rate can be lower, the plant can be smaller and also the TEWI index can be lower [6,7].

Table 2. Main thermodynamic, physical, chemical and environmental properties of CO_2 as refrigerant fluid.

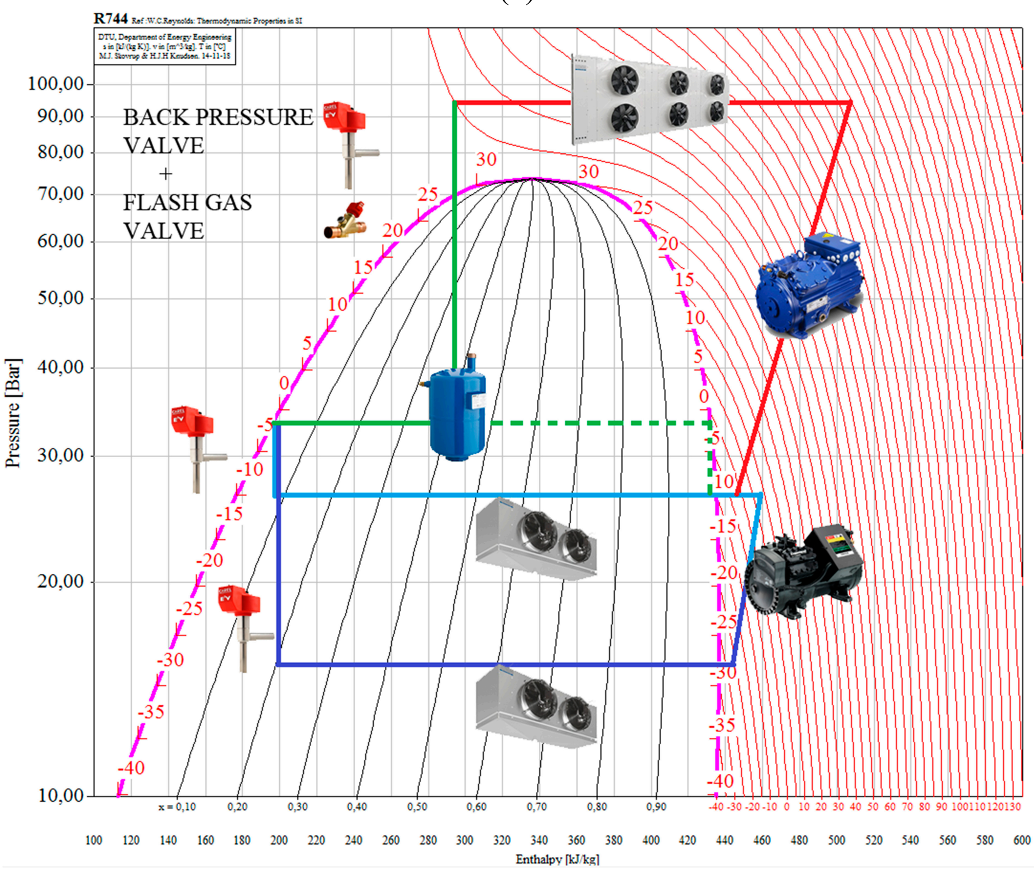
Harmless to the ozone layer
GWP = 1 (considering CO2 as recycled or recovered component from industrial by-production)
Non-flammable and non-toxic except in the case of high concentrations and poorly ventilated rooms
Compatible with all common materials
Corrosive only in the presence of water, except for stainless steel
Volumetric refrigerating effect at low temperatures greater than other fluids
Lower compressor flow rate, but higher pressure (even at low temperatures)
High thermal conductivity, both in liquid and steam phases
High specific heat guarantees
High thermal exchange coefficients in heat exchangers
Critical temperature of 31 °C
Subcritical refrigeration cycle comparable to that of other fluids

At the same time, refrigerant fluid must have safety properties:

- low toxicity and flammability in air;
- chemical inertia to the most commonly used materials in refrigeration circuits;
- low ODP (Ozone Depletion Potential); and
- low GWP (Global Warming Potential) or TEWI (Total Equivalent Warming Impact), a more complete version of GWP, which depends on the type of fluid and on the plant. In fact, apart from taking into consideration the direct effect the fluid has when released into the atmosphere (following its use in the plant), it also qualifies its indirect effect, which is caused by carbon dioxide emissions created by the production of the energy consumed by the plant during lifecycle. Then it is evident that, optimizing energetic consumption of a refrigeration plant means reducing TEWI [3–5].



(**a**)



(**b**)

Figure 1. Solution for CO_2 plant*:* (**a**) subcritical cycle, eventually in cascade plants (primary one: ammonia or R134a); (**b**) transcritical cycle.

CO_2 has a critical temperature of only 31 °C, which determine some limitations in terms of energy efficiency in those areas of the world characterized by temperatures close to or above this value. [8–10]. The subcritical refrigeration cycle (Figure 1a) is comparable to that of other fluids; it is widely used as a low temperature one in cascade plants, while the primary one generally works with ammonia or R134a [11–16]. In plants that work with transcritical cycle, at high pressure heat exchanger outlet, the liquid CO_2 is separated from the gaseous one and conveyed to the expansion devices, while the steam part, named flash gas, is recovered and conveyed by the compressor suction (Figure 1b) [10,16–18].

1.2. Control of Temperature and RH during Food Storage

Cold storage is recognized as one of the most used techniques to maintain quality of fresh and processed food product. The needs, in terms of temperature and relative humidity, strongly vary according to the kind of product [19,20].

As for horticultural commodities, temperature has a profound effect on the rates of biological reaction, such as metabolism and respiration [21,22]. All fruits and vegetables have an optimal or ideal temperature of storage; this temperature should normally be kept within a range of about ±1 °C of optimal temperature for the commodities being stored. Temperatures below the optimal range for some fruits and vegetables can cause freezing or chilling injury, in fact most perishable horticultural commodities last longer at temperature near 0 °C. At temperature above the optimum, the commodity has a short storage life; in fact the rate of deterioration increases between two- and fourfold for every 10 °C rise in temperature [23,24]. Temperatures either above or below the optimal range for fresh produce can cause rapid deterioration due to the occurrence of several disorders [25]. Relative humidity (RH) can influence water loss, decay development, incidence of some physiological disorders, and uniformity of fruit ripening. Condensation of moisture on the commodity (sweating) over long periods of time is probably influences decay more than the RH of the ambient air. The optimum relative humidity during storage of fresh non-fruit vegetables ranges between 95%–98%, while for fruit and vegetables (except dry onions and pumpkins (70%–75%)) is best kept at about 90%–95% [26].

For most processed foods, the main aim of the refrigeration process is to prevent bacterial contamination, keeping the product in a static condition [9]. For products such as sausages and aged cheeses, before the final storage, a strict control of thermal hygrometric conditions (Table 3) is needed for the correct development of sensorial characteristics during the ripening process. Therefore, a flexible *refrigeration plant* equipped with accurate sensors for monitoring the cooling fluid and storage environment is needed.

The present paper refers to experimental tests carried out on Rocket leaves, chosen as a product model because of their high sensitivity to temperature fluctuation [26] and to dehydration [23] using a basic pilot industrial CO_2 refrigeration plant. This product was stored at different thermal hygrometric conditions, in order to monitor the performance of the plant, according to both environmental conditions and product storage needs. Then improvements were made in order to achieve better microclimate conditions in the cold rooms.

Table 3. Properties and conditions recommended for *Capocollo* of Martina Franca (typical Italian sausage).

Time	Temperature (°C)	Relative humidity (%)
	Draining	
Day 1	22	65
Day 2	21	70
Day 3	20	75
Day 4	19	80
	Drying	
Day 1	19.5	60
Day 2	17.5	65
Day 3	15.5	70
Day 4	14.5	75
Day 5	13.5	80
Day 6	12.5	80
	Aging	
Total time: 120 days	12.5	80
Storage	4	-

2. Experimental Section

2.1. Basic Experimental CO_2 Plant

The basic plant (Figure 2) constituted a single-stage compressor, followed by a gas cooler and an internal heat exchanger. At the exit of the latter element, a motorized *Egelhof* electronic valve (EV) is positioned (this first expansion carries out a fluid mixture with liquid and gaseous phases). Then, the direct branch can be opened to allow the refrigerant to flow directly into the evaporator or to flow first into the liquid receiver for a second expansion. In this second solution the surplus of the gaseous component is conveyed to the liquid-gas separator by means of the differential valve, while the liquid is carried into a second electronic expansion valve (EEV) based on a PWM control (Pulse Width Modulation). The last solution leads to a higher COP in double expansion than in a single (traditional) one [8,11,14,15,22,27]. Moreover, it is widely recognized that the optimal working condition of electronic expansion valves is achieved when only the liquid phase enters the valve: avoiding flash gas at the inlet of the valve, not only is the best working efficiency guaranteed due to a correct and homogeneous lamination, but also an increase in the service life.

Downstream of the evaporator, a liquid-gas separator is installed to separate the gaseous component from the liquid, if any is still present. The compressor (a two-stage compressor) sucks the gas only after passing through the internal heat exchanger. Parallel to the low-pressure line, there is a by-pass branch activated by a manual valve. The use of the liquid receiver, and then the double expansion, compared to the simple direct expansion, with the same refrigerant mass flow, improves the performance of the machine in terms of increasing the evaporator cooling capacity; equivalently, at the same required cooling power, the mass flow of fluid will be lower, compared to the case of single direct expansion.

Temperature measurements are carried out with copper-constantan thermocouples, while the pressure sensors are piezoelectric.

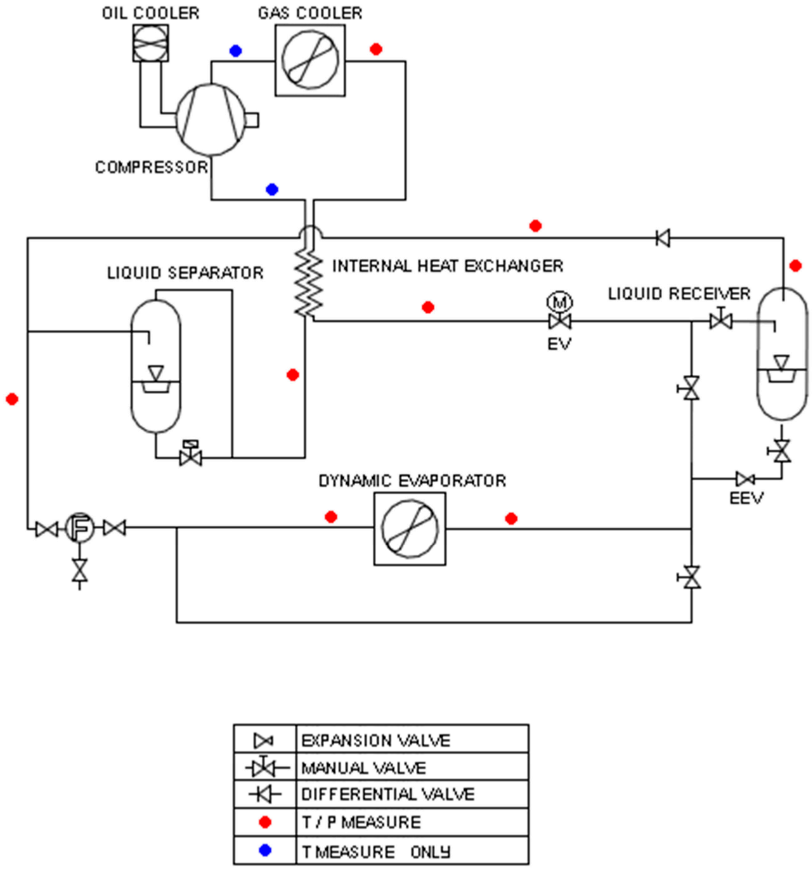


Figure 2. Basic experimental CO_2 plant.

Some considerations could be made about the COP of this type of refrigeration plants. Let us consider a basic two-stage cycle with liquid receiver (see Figures 1 and 2) operating with different fluids at the same temperature. In order to compare the efficiency of the different fluids operating within the same cycle type, it is standard to consider a theoretical (no friction loss in the pipes) subcritical cycle as shown in Figure 3 (only for CO_2: for other fluids, the thermodynamic cycle has the same shape). In our case, we used as design parameters those shown in the legend of Table 4 where the calculated results (COP and density—ρ—at the suction of the first stage) are summarized.

It has to be highlighted that:

- R22 is quite efficient, but it cannot no longer be used;
- R134A and R410A, substitutes of R22, are as efficient as R22; and
- R744 (CO_2) is a little less efficient than all the previous fluids ($COP_{R744} \approx 0.7\ COP_{R134A}$), but it is characterized by a quite higher density ($\rho_{R744} > 3\ \rho_{R410A}$) allowing the use of quite smaller compressors.

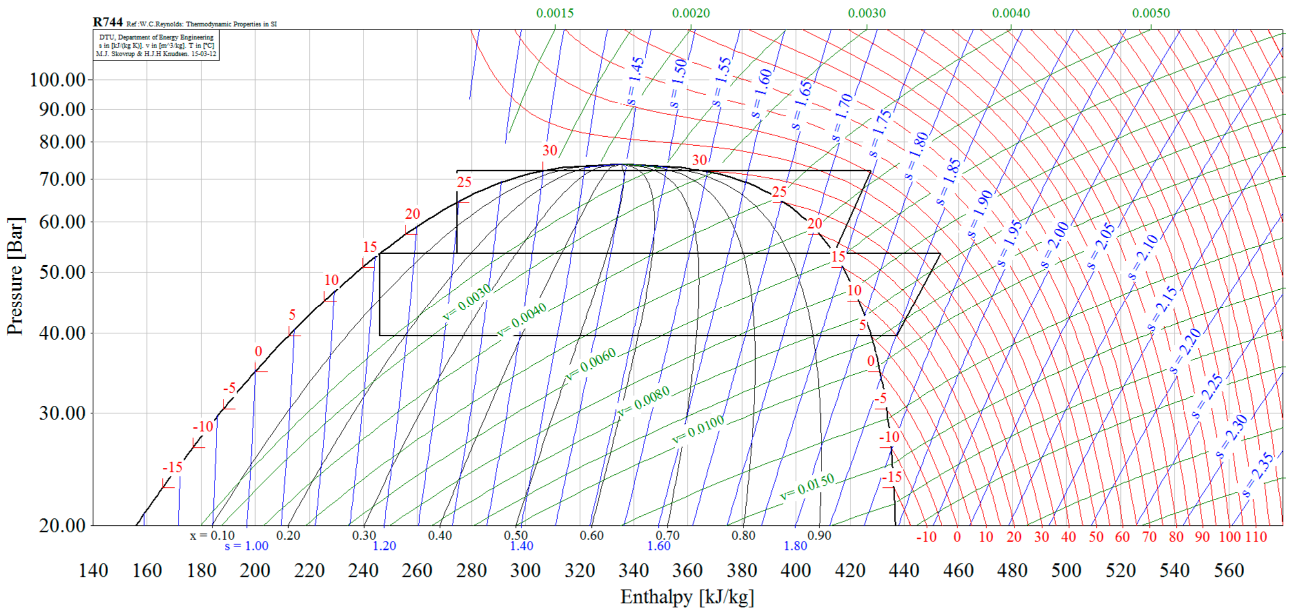


Figure 3. Basic CO_2 two- stage compressor cycle.

Table 4. Theoretical efficiency of a two-stage compressor subcritical cycle with the following design conditions: evaporation temperature = 5 °C; condensing temperature = 30 °C; $\Delta T_{SuperHeating} = \Delta T_{SubCooling}$ = 5 °C; and compressors isentropic efficiency = 0.7.

Fluid	COP	Density (ρ) (kg/m^3)
R22	7.22	24.0
R134A	7.31	16.7
R410A	7.03	33.8
R744	5.21	107

2.2. Experimental Tests

Twelve plastic arugula boxes (*Eruca sativa*), each one 3 kg, were used for the experiment; the first 8 of them transported to the Food Industries Machines and Plants Laboratory at the University of Bari and conserved in two cold rooms based on CO_2 as a refrigerant fluid (at 5 °C), in which there were pulverization humidifiers (isenthalpic) for relative humidity control (R.H. ≥ 95%). Three and four temperature and humidity sensors were placed, respectively, in Cold Room 1 and in Cold Room 2, at different heights on the vertical walls (Figure 4). Four boxes were placed in the first cold room provided with a static evaporator (Cold Room 1, dimensions 220 cm × 120 cm × 80 cm), the other four placed in the second environment having a bi-flow evaporator (Cold room 2, dimensions 220 cm × 120 cm × 80 cm). One of these sensors was used for control and the other ones were employed to evaluate temperature and humidity at different heights in each cold room. Humidity regulation was based on an on-off activation of humidifiers as a function of a hysteresis centered on the desired value and with a window of ±1.5%. During the experimental tests, normal storage conditions were simulated using a traditional R22 plant and a cold room without control over relative humidity. In fact, traditional industrial plants work without RH control during the storage of arugula or similar horticultural products. Therefore, the last 4 boxes of arugula were transported to the

Postharvest Laboratory at the University of Foggia and conserved in a R22 based cold room (CTRL Room) at the same temperature of 5 °C and without relative humidity control. The overall experiment duration was 11 days.

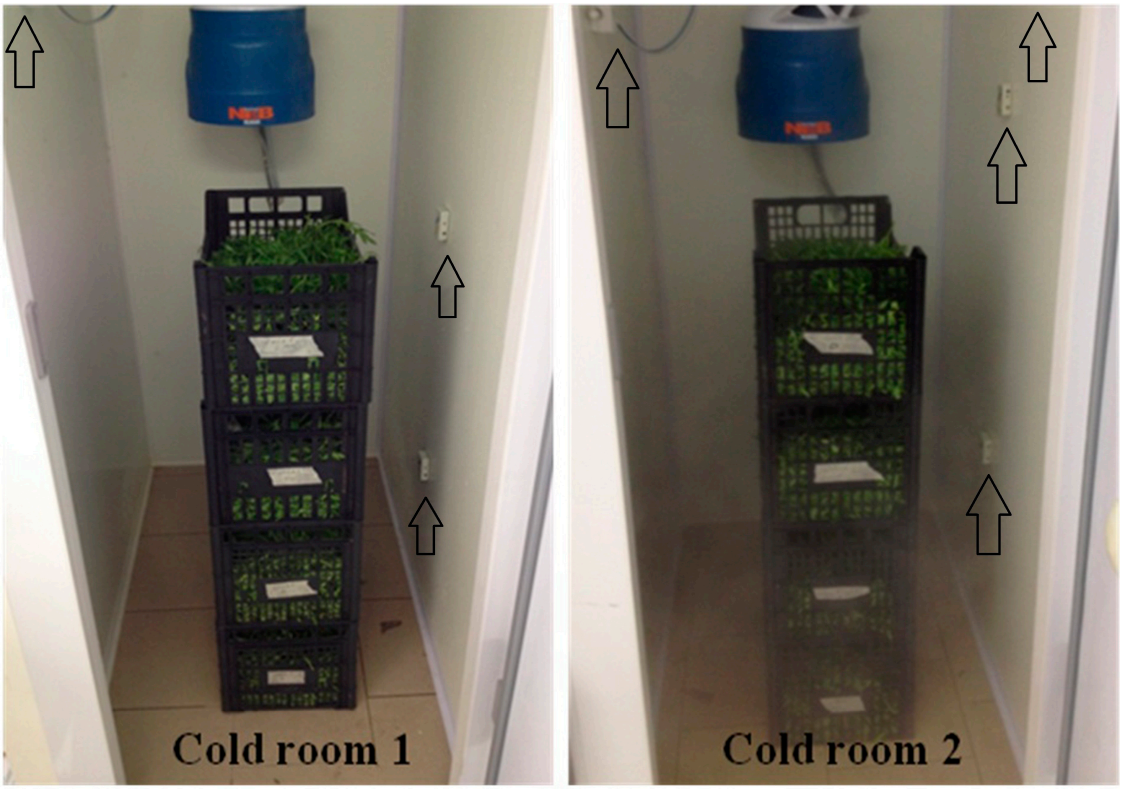


Figure 4. Rocket leaves at a temperature of 5 °C and with H.R. control: Cold Room 1 with H.R. ≥ 95% and a static evaporator; Cold Room 2 with H.R. ≥ 95% and a bi-flux evaporator in suction. Sensor positions are highlighted with arrows.

During storage in the modules with the CO_2 based plant (DISAAT Department), the following measurements were realized:

- CO_2 based plant test with proposals for improvements;
- system test used for data acquisition and significant CO_2 plant parameters control; and
- temperature stratification (CO_2 modules).

At the start of the experiment (time zero) and after 4, 7 and 11 days of storage in the 3 conditions described above, samples were analyzed for the following quality parameters:

- appearance (sensorial evaluation) using a scale from 5 (excellent) to 1 (very poor, inedible);
- color, valued through hyperspectral images acquired by a spectral scanner and later processed for the L*,a* and b* CIE parameter calculation using a specific software. Data were expressed as $\Delta E^* = [(L_0^* - L^*) + (a_0^* - a^*) + (b_0^* - b^*)]^{1/2}$ where L_0^*, a_0^* and b_0^* are the color parameters of the fresh sample; weight loss percentage over time; and shear strength to evaluate turgidity losses using a Instron Universal Testing Machine equipped with a Kramer shear cell, and measuring the maximum force required by 5 blades to advance through a 5 grams sample of arugula at 0.8 mm/s.

Statistical Analysis

Mean values of quality parameters during storage were analyzed with a 2-way ANOVA, with treatment and time of storage, as factors. Means were separated using the Tukey test ($p < 0.05$). The data were analyzed with SAS software. Different letters in column denotes significant differences at p-level < 0.05.

3. Results and Discussion

3.1. Results and Discussion of Experimental Tests

In Table 5 the main quality parameters are reported regarding the rocket leaves stored in the three different conditions. As expected, rocket leaves stored in a cold room without H.R. control (CRTL Room) suffered a significant weight loss during storage, whereas, on the contrary, the leaves placed in the two CO_2 cold rooms had a slight increase of weight due to the water condensation on the product. Regarding any color changes, shown as global color variation ΔE*, CTRL Room samples showed a higher increase of the b* value (data not shown) related to the yellowness of the leaves. Nonetheless, for texture evaluation, samples stored in CTRL Room and Cold Room 2, showed similar quality attributes; this is because the accumulation of moisture on the surface of the rocket leaves was more visible in the samples stored in Cold Room 1.

Table 5. Effect of storage condition (Cold Room 1 = cold room with H.R. control ≥ 95% and static evaporator; Cold Room 2 = cold room with H.R. control ≥ 95% and bi-flow evaporator in suction; and CTRL Room = R22 Cold Room without H.R. control) at 5 °C and length of storage on quality attributes of arugula.

	ΔE *		**Weight loss (%)**		**Texture (N)**	
Storage condition						
COLD Room 1	15.03	b	−2.33	b	165.16	b
COLD Room 2	15.37	b	−1.22	b	191.08	a
CTRL Room	20.77	a	8.86	a	212.41	a
Storage time						
4 days	8.22	C	1.12	AB	178.63	
7 days	20.64	B	0.61	B	190.97	
11 days	22.31	A	3.31	A	199.05	
Storage condition	****		****		****	
Storage time	****		*		ns	
Storage condition × storage time	****		ns		ns	

Asterisks indicate the significance level for each factor of the ANOVA test (ns, not significant; * p-level ≤ 0.05; ** p-level ≤ 0.01;*** p-level ≤ 0.001 **** p-level ≤ 0.0001). Different lower and upper case letters (a, b and A, B, C, AB) indicate statistical differences within storage conditions and time of storage, respectively, according to the Tukey's test ($p \leq 0.05$).

In this case, the presence of the static evaporator led to a higher depreciation of the product as evaluated sensorially (data not shown), which, in turn, caused a decrease of the texture of these samples, compared to the initial value (about 190 N). On the contrary, for samples stored in Cold

Room 2 and in the CTRL Room, the firmness remained quite stable or showed a slight increase as a consequence of the higher weight loss occurred in the CTRL Room.

Apart from the differences in treatments for the analyzed quality parameters, it must be underlined that in all samples stored in cold rooms with H.R. control, starting from the seventh day of storage, were small rot zones noted in all boxes that became more representative at the end of storage, after 11 days. This disadvantage could be due to an excessive accumulation of water condensation that resulted in a rapid loss of shelf-life, thus the need to optimize the system with a more accurate control of the humidity.

Temperature and relative humidity trends of the two CO_2 based cold rooms are shown in Figures 5 and 6. Measurements were obtained from both refrigerated modules and both product samples. Both modules reached the set temperature and humidity parameters in less than one hour. Immediately after this phase, it is possible to observe first a rapid temperature increase and RH decrease due to the insertion of the vegetables into modules and for the rest of time a maintained steady condition according to the expected set-points.

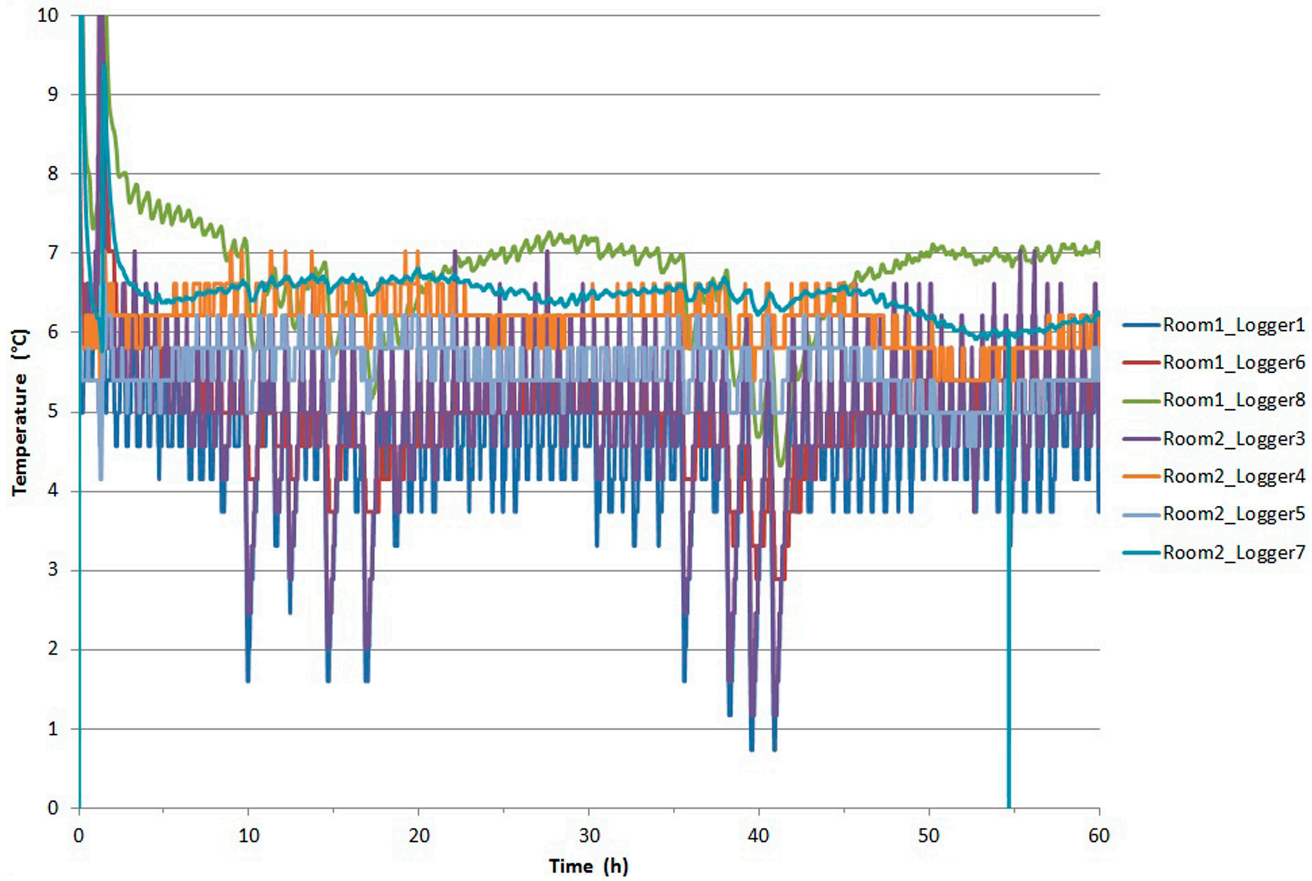


Figure 5. Temperature behavior in refrigeration modules working with a CO_2 plant during the early period of conservation (Temperature hysteresis: 2 °C).

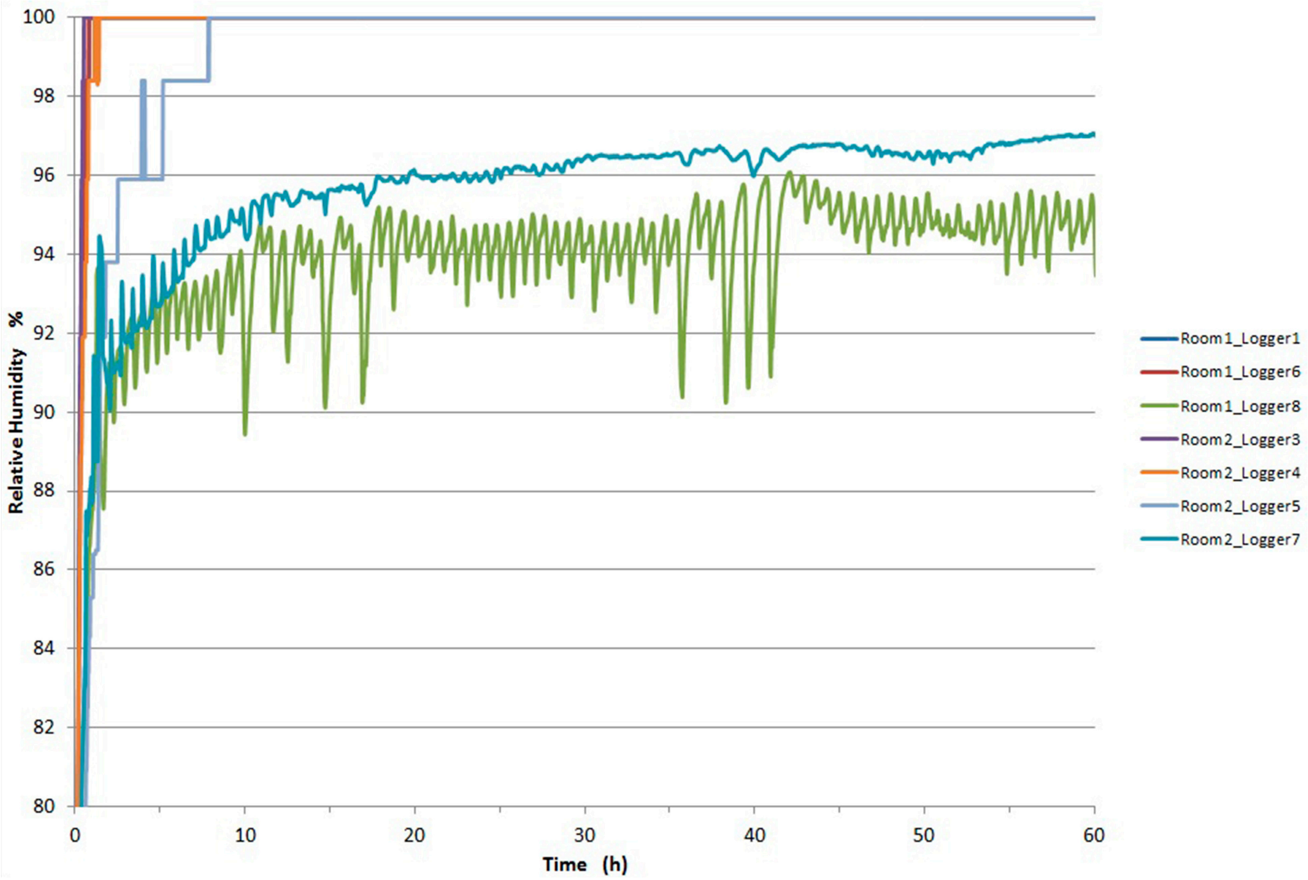


Figure 6. R.H. behavior in refrigeration modules working with a CO_2 plant at the early period of conservation (R.H. hysteresis: 2 ÷ 5%).

During the experiment, the following was highlighted.

(1) The correct behavior of the devices specially designed for the fluid used and conditioning needs have ensured the required plant performance, in relation to the recommended storage conditions, of the rocket leaves.

(2) With regard to thermodynamic problems that characterize CO_2 based plants, the condensing section of the refrigeration system has given extremely significant results including in the external temperature critical condition.

On the one hand, even if the acquired data and process parameter control system was suitable to maintain the storage conditions required by the tested protocol, especially for the RH condition (in terms of temperature and RH ≥ 95%), it is extremely critical to achieve the desired RH without reaching saturation condition. Indeed, from graphics, it is possible to observe that temperature and relative humidity trends remain within the set point limits with a certain hysteresis degree (for temperature case within 4–6.5 °C). This problem does not arise in plants operating with traditional fluids, as it is possible to easily set the dew point in the cold room, maintaining the global efficiency of the plant by means of a suitable sub-cooling in the condenser. On the other hand, working near critical temperature in the condensing-gas cooler section (as in CO_2 plants), could lead to a more difficult control of the dew point or to a relevant reduction of the global efficiency of the plant.

The studied "cool room–plant" can be considered quite flexible and close to being able to be transferred from prototype to industrial dimension. However, due to some previously mentioned aspects, some improvements were realized:

- control of the dew point immediately after the evaporative coil followed by an air heating system by controlling the evaporation pressure independently from the other components; and
- separate control of the pressure in the condensing–gas cooler section to achieve the optimal value of the global efficiency of the plant.

Therefore, the following plant changes have been made with the goal of an oriented industrial development for plant manufacturers and final users, oriented toward investments in environmentally friendly technology:

(a) solenoid valve insertion upstream of each evaporator with the possibility to stop a refrigeration circuit independently from the other, improving cold room flexibility;
(b) measurements of CO_2 concentration contained in the cold room air, with the aim to control the microclimatic condition during preparation of meat based products;
(c) system for internal air replacement of cooling rooms; and
(d) insertion of an air heating system to integrate the independent temperature and humidity control, which is helpful during drying and maturing phases for which only a refrigeration plant is insufficient, due to particular humidity values and specifics requirements on the base of the conserved product type.

3.2. Optimization of Plant Configuration

The adjusted experimental plant (Figure 7) requires a single compressor, followed by a high-pressure heat exchanger or gas cooler, whose aim is to transfer heat from the refrigerant to the external environment. It also includes a HBPEV (High Back Pressure Electronic Valve), controlling the pressure inside it according to the operating conditions. The carbon dioxide at the outlet of the valve is channeled into a liquid receiver whose aim is to separate the liquid phase from the gaseous one achieving an increase in COP even better than the old plant. In fact, another problem raised during the experimental tests is the difficulty in controlling vapor flux leaving the receiver due to the presence of a simple maximum pressure valve, which allows only pressure control. In the new plant, the controlled Back Pressure Electronic Valve allows both pressure and flux control.

The liquid phase is sent to three parallel branches—corresponding to three independent cold rooms—where an EEV (Electronic Expansion Valve), an evaporator, and an EBPEV (Evaporator Back Pressure Electronic Valve) are assembled. The back pressure valve allows the tuning of each evaporator pressure to the set value allowing each of them to be independent from the other, with different evaporation temperatures. Downstream of the EBPEVs, the fluid is channeled in a liquid separator from which the gas is withdrawn and sent to the compressor suction. The CO_2 stream leaving the gas cooler and the one sent to the compressor suction are conveyed in an IHX (Internal Heat Exchanger).

The communication between the liquid receiver and liquid separator is guaranteed by a BPFGEV (Back Pressure Flash Gas Electronic Valve), which keeps the pressure of the liquid receiver at a constant value, sending the excess saturated vapor to the liquid separator.

The system can work in both transcritical and subcritical conditions (Figure 1), thanks to the HBPEV and the high-pressure heat exchanger, which can work both as a condenser and as a gas cooler. When the external environmental conditions allow fluid temperatures far below its critical temperature (about 31 °C), heat transfer inside the heat exchanger is achieved by condensing the refrigerant. When the plant is working in subcritical conditions, the HBPEV does not intervene, remaining completely open. Conversely, for higher temperatures, the carbon dioxide inside the heat exchanger no longer passes from the vapor phase to the liquid one. The heat transfer in the heat exchanger is achieved by gradually cooling the gas without reaching the liquid phase. In this case, the HBPEV intervenes by adjusting the pressure in the gas cooler according to the temperature of the refrigerant leaving it, so as to improve the performance of the machine. All valves are controlled by a driver in which the adjustable parameters can be set, either using the display or through a serial connection. The compressor is controlled by an inverter in order to adjust the angular speed and consequently the flow rate of the refrigerant. Among the three evaporators, one is static (696 W, Δt = 10 °C) and the other two are dynamic (*i.e.*, forced ventilation: 1530 W for the first one and 5350 W—partitionable—forthe second one; Δt = 10 °C in both cases).

The dimensions of the three compartments are identical and equal to 2.2 m in height, 1.2 m in depth and 0.78 m in width.

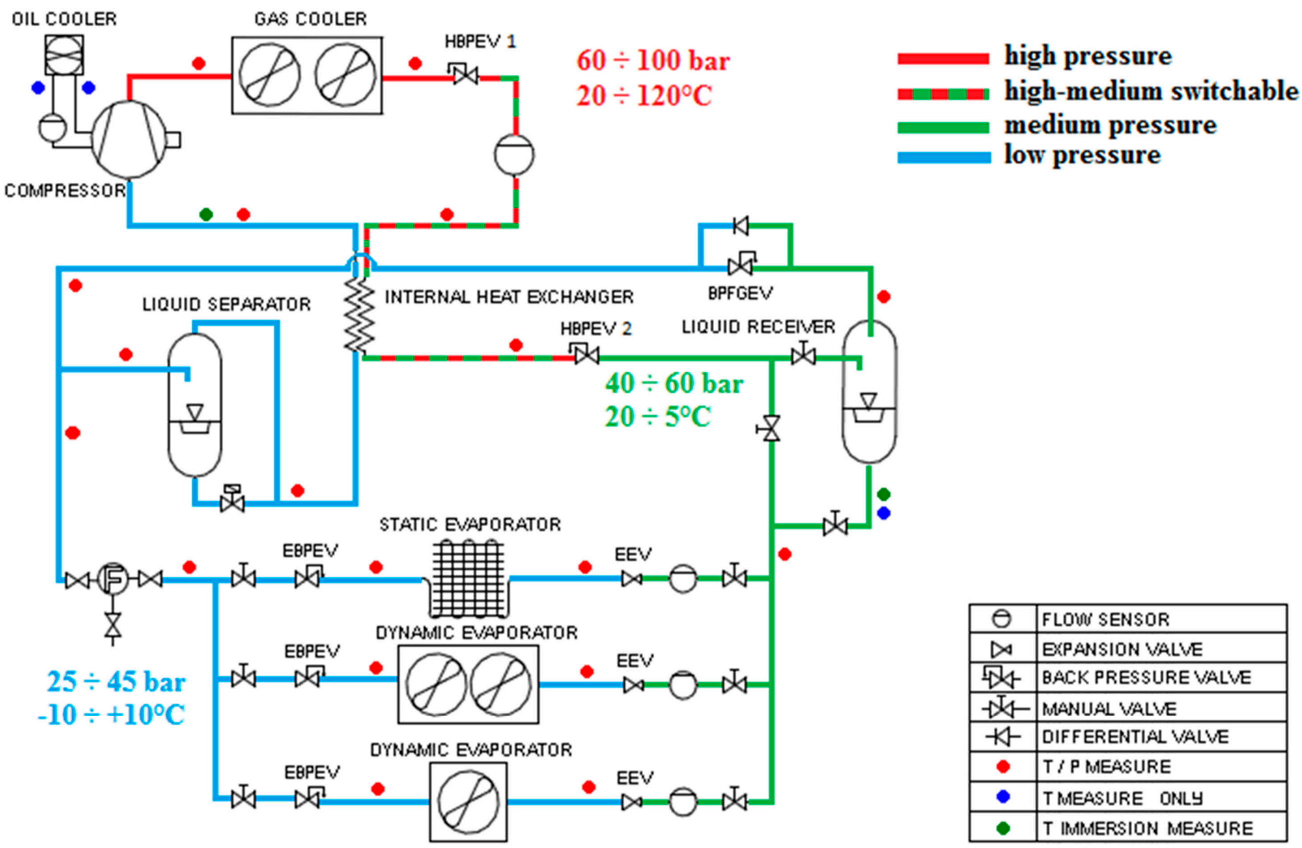


Figure 7. Adjusted experimental plant, distributed measurement points, and subcritical and supercritical working capability.

The plant is characterized by the presence of many measurement points where a simultaneous acquisition of temperature (PT1000 contact class B ±0.3 °C) and pressure (piezoelectric of 0.5% FS) is performed. PT100 immersion (class A by ±0.15 °C) were also installed near the contact sensors downstream of the liquid receiver and at the compressor inlet. This choice was made because of the difficulty of placing a large number of immersion sensors. Therefore, in order to assess, at least in a first approximation, the temperature difference between the actual fluid and that measured on the outer surface of the pipes, it is necessary to have two probes (contact and immersion) in the same position (Figure 7).

CO_2 mass flow meters are installed immediately downstream of the HBPEV and upstream of each of the three EEV, using two models of Coriolis meters: the first one with FSI of 5600 kg/h and the second one of 3700 kg/h. In both cases, the accuracy is ±0.15%. On the cooling circuit of the compressor there is a gear flow meter with pulse output (0.25–10 L/min ±3% FSI).

Inside the three cold stores it is possible to measure air temperature (PT1000 Class B, 0–50 °C ± 0.3 °C), relative humidity (0–95% ± 5% HR www.spluss.eu/en) and carbon dioxide air content (0–2000 ± 100 ppm) with a NDIR sensor (Non Dispersive Infrared). The last measure was necessary because of CO_2 variability as a result of the metabolic activity of bacteria and mold present on the stored food (Figures 5 and 6).

The acquisition and digitization of analog signals from the sensors was carried out using two NI PCI-6024E due to their analog-to-digital features and an NI cDAQ-9172 equipped with signal conditioning modules for both current and voltage analog inputs. The hardware is completed with a DAC module for the digital-to-analog conversion and some modules operating as a low side switch, for the control of power loads. The whole monitoring and control program was developed in a LabVIEW environment (from National Instruments: www.ni.com). The GUI management software consists of four main parts: the first one allows turning off unused rooms, to set the desired temperature and humidity inside the used cold rooms and to control the dynamic evaporator fan when required. This first section also allows starting a data acquisition process and to identify and count over pressure events in high and low pressure heat exchangers. A push-button is present for emergency stop in case of critical situations.

The second part of the interface allows overall system representation, displaying all the variables from the sensors at the points where it is actually positioned. It is even possible to activate and deactivate the actuators and change the default values of the reference variables, such as pressure and overheating set points, for a real time evaluation of the machine performance. Using RS-485 serial communication and Modbus protocol, the software can make "handshake" connections with valve drivers and compressor inverters ensuring maximum flexibility of this application.

In the third and fourth parts of the program interface, it is possible to visualize the trend over time of each measured variable, of the refrigeration cycle in the pressure-enthalpy plane and of the COP, by means of CoolProp 4.5.2 subroutines, respectively [16].

In order to keep temperature and humidity close to the set values in each of the cooled rooms, two FSM (finite state machines) were implemented, while the control was realized simultaneously using the evaporative cooling unit and a heat source. The first one guarantees both ambient refrigeration and dehumidification, by vapor condensation present in the air, at the heat exchange zone of the evaporator. Heat source can be effectively used during drying action of cooling unit to compensate inevitable temperature drops when it is working in the target zone. The possible decrease of humidity is then corrected by means of the second FSM, which activates the humidifier positioned inside the refrigerated room.

During normal operation of the plant, the software allows saving all the values from the sensors, including those related to the control variables and parameters displayed on the interface, for later post-processing. Any malfunctions, defects or dangerous conditions, such as cases of over-pressure, are efficiently handled by the program that stops the compressor and opens the HBPEVs and BPFGEV to even out the pressure differences in the various parts of the plant. In the latter case, the operation is suspended until any risk is ceased, then the application is automatically restarted. Concerning abnormalities in communication with the acquisition system, with the valve drivers or the inverter driver, the program is suspended until a new user intervention. A buffer battery capable of powering the valves in case of power failure has also been prepared: if this happens, an automatic procedure is activated to fully open HBPEVs and BPFGEV avoiding some parts of the system remaining at a pressure that is too high.

4. Conclusions

Internationally-oriented policy towards the minimization of the impact of refrigeration systems on the environment are forcing the operators to implement industrial solutions based on the use of a new generation of ecological fluids, either natural or synthetic.

The use of carbon dioxide as a refrigerant, whose technology is sufficiently established, is increasing in Europe. It is very cheap and harmless to the environment, but it should be used in specifically designed plants, considering that the storage of agricultural products and foodstuff has particular and stringent needs in terms of temperature and relative humidity.

In this work, a pilot plant able to meet a wide range of specifications and to work in different environmental conditions was studied. The refrigerating unit was designed, with the aim of flexibility and versatility, so as to work not only to refrigerate a cold room, but also as a test bench to evaluate its performance in specific applications of food conditioning and refrigeration.

The experimental tests carried out on Arugula resulted in the realized variable geometry plant, which is able to develop the following objectives:

- COP maximization, to obtain the minimum energetic impact with a uniform cold produced;
- high pressure heat recovery;
- map plant fluid evolution in a multi-dimensional space variable, which can be monitored and controlled; and
- optimization of the plant, also in function of TEWI index.

These solutions are requisites to identify, for the storage studied processes, the most suitable values of the parameters characterizing the thermodynamic cycle, as well as to define design criteria for CO_2 refrigeration systems characterized by low environmental impact, which purpose could meet the needs of foodstuff in the storage field.

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Author Contributions

All the authors contributed equally to this work.

Conflicts of Interest

The authors declare no conflict of interest.

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