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Field assessment of the performance of a state-of-the-art CO_2 integrated system for supermarket with distributed HVAC terminals in the shopping area

Giacomo TOSATO[a], Silvia MINETTO[a], Armin HAFNER[b], Antonio ROSSETTI [a], Sergio MARINETTI[a], Sergio GIROTTO[c]

[a]Consiglio Nazionale delle Ricerche, Istituto per le Tecnologie della Costruzione, Corso Stati Uniti 4, 35127 Padova (Italy)

[b] Norwegian University of Science and Technology, Department of Energy and Process Engineering, 246, Kolbjørn Hejes vei 1, Trondheim (Norway)

[c] Enex Srl, Via Veneto, 12, 31038 Padernello di Paese TV (Italy)

1 ABSTRACT

Pushed by sustainability drivers, commercial refrigeration is now strongly oriented towards CO_2 based systems, and, amongst them, integrated solutions are gaining market share, as they offer an environmental friendly, all-in-one solution serving the entire supermarket thermal energy needs.

The EU H2020 Project MultiPACK aims at proving integrated CO_2 systems performance in the South European Climate by field measurements.

In this paper, the most recently installed MultiPACK unit is presented: its major peculiar lies in the fact of combining a state of the art CO_2 layout, including parallel compression, expansion by ejectors and overfed evaporators, with distributed heating and cooling terminals for localized AC in the shopping area.

Winter and summer operations are presented, taking care of both refrigerating unit and display cabinets performances.

Keywords: Refrigeration, Carbon Dioxide, Compressors, COP, Evaporators, Energy Efficiency.

2 INTRODUCTION

CO_2 refrigeration systems currently represent the preferred choice in the European market, with near 14.000 installation in Europe in early 2018, according to Shecco, 2018, and they are quickly spreading also to other regions, including warm and hot countries. Different layouts have been developed, to provide the market with suitable solutions, according to the local climate or specific utililsation and needs. While integrated solutions including heating by heat recovery have been first proposed since the beginning of CO_2 revival, as by Neksa, 1998, nowadays units providing refrigeration, air conditioning and heating are offered to the market. Their success is related to their cost and performance competitiveness, as demonstrated by Karampour and Sawalha, 2018. A widespread effort is taking place to document field performance of CO_2 systems and to develop suitable models to predict annual performances, as presented by D'Agaro et al, 2019.

Such as demonstrated by the project SuperSmart (Minetto et al, 2018), non-technological barriers can hinder the diffusion of energy efficient solution in the HVAC&R sector. For this reason, the EU funded project MultiPACK has the main goal of assuring the market about feasibility, reliability, energy efficiency of CO_2 integrated systems and promoting a fast transition to low environmental impact solutions. The confidence raising is performed by installation and monitoring of fully integrated state-of-the art systems in the South European Climate.

In this paper, a system developed and installed in North Italy within the project MultiPACK is presented; data from the field demonstrate its performance in summer and winter operations, including AC and heating functionalities. Field data also show the impact of evaporator superheat reduction on cabinets performance and prepare for next steps, that will include the evaporator overfeeding and evaporation temperature increase.

3 SYSTEM LAYOUT

The system lay-out includes all the characteristics of a MultiPACK unit, i.e. integration of all functions, refrigeration, space heating and cooling and hot water production, in the same appliance, while adopting the state-of-the-art technology for CO_2 refrigeration, i.e. parallel compression, ejectors for expansion work recovery, minimized superheat for evaporators with suction pressure receiver and liquid ejectors for possible liquid recirculation. With respect to other MultiPACK sites (Minetto et al., 2019, Hafner et al, 2020), the peculiarity of the presented system lays in the specific heating and AC set up, which includes distributed indoor units in the shopping area and a centralized Air Handling Unit (AHU) which is activated for summer dehumidification. Technical details of the system are fully described in the following sections.

3.1 Schematic of the unit

The system overall layout is presented in Figure 1. The unit is based on a booster concept with parallel compression and expansion work recovery by means of ejectors for both vapor pre-compression and liquid recirculation, if needed.

Semi-hermetic compressors are installed, three at each rack: Medium Temperature MT (1), Low Temperature LT (3), Auxiliary (2). For each rack, one out of the three compressors is inverter driven, to allow a smoother capacity modulation.

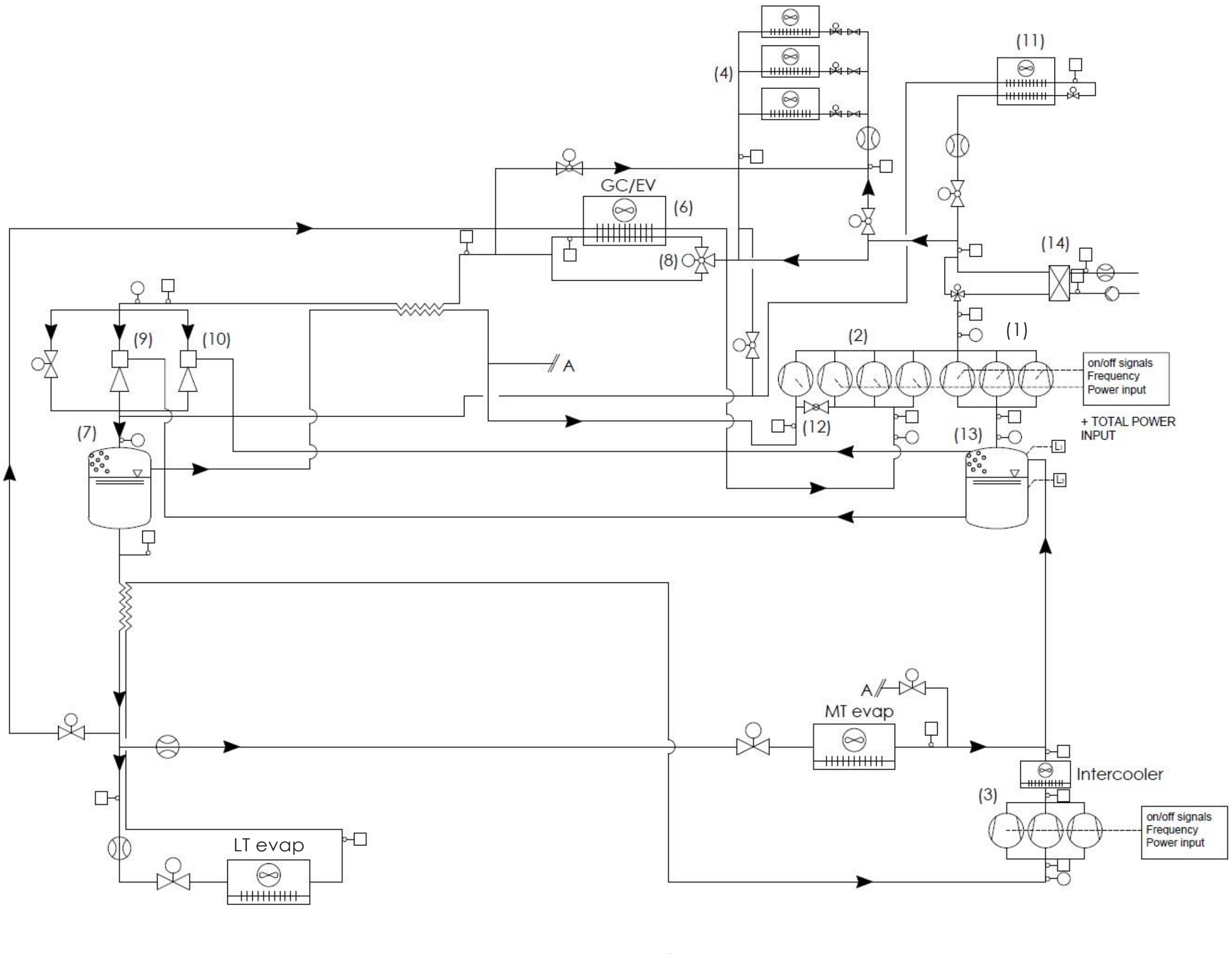

Figure 1: System layout

The unit also satisfies the heating and the cooling loads of the supermarket by means of indoor units (4), in which CO_2 directly flows in to the coils. In summertime, CO_2 expands from high pressure, downstream of the gas cooler, through the coils, to provide cooling effect, into the intermediate receiver; in wintertime it directly flows from the compressors discharge line, to reject heat into the shopping area. An Air Handling Unit AHU (11) that operates only in summer satisfies the dehumidification needs; the AHU is also able to provide post heating in summertime. If the heating demand exceeds the heat recovered from the refrigeration system, the heat pump mode is activated, i.e. the external evaporator (6), which is integrated with the gas cooler, is fed with liquid from the receiver (7). In wintertime, the gas cooler is by-passed, partially or totally, by means of a three-way valve (8), to promote heat recovery and to save external fan energy input. In heat recovery mode, the high pressure is set at 85 bar. Thanks to the solenoid valve (12), the auxiliary compressor dedicated to the heat pump functionality can work independently from those removing flash gas. In summertime, the cooling coils of indoor units are fed with two-phase refrigerant expanded through electronic expansion valves installed before each unit, which are air temperature controlled.

A liquid receiver (7) is located after the expansion devices, i.e. multiejector blocks (9) and (10), able to manage charge variations in the circuit and to provide sufficient liquid head to correctly feed MT and LT EEV located at each cabinet and cold room. In case of liquid flow back from MT evaporators, due to the adopted Electronic Expansion Valve EEV control, the liquid accumulated in the suction liquid receiver (13) is pumped back to the receiver (7) by liquid ejectors (10).

The domestic hot water demand is provided by a plate heat exchanger placed on high pressure side (14). Water passes through the heat exchanger, it is heated up to 60°C and stored in a water tank for further utilization.

3.1.1 Measuring devices

The system is fully equipped with measuring instruments, for pressure, temperature, refrigerant and water mass flow and compressor input power measurements. The location of the instruments is referenced in Figure 1. Temperatures probes are represented as squares while pressure probes as circles.

There are 20 commercial type NTC 10 kΩ sensors. Pressure is measured with six commercial type piezoresistive pressure transmitters. In order to evaluate the total electric power input, three-phase electric power meters are located before each compressors rack to measure the power input to Low Temperature (P_{LT}), Medium Temperature (P_{MT}), and Auxiliary (P_{AUX}) compressors and one is dedicated to measuring power of Gas Cooler/Evaporator’s fan (P_{GC}). The status of every single compressor and the inverter frequency are also acquired. The liquid level in the liquid receiver is monitored in order to detect the status of the liquid ejectors since the activations of it depends on the liquid level in the receiver.

4 Coriolis mass flow meters are utilized to measure refrigerant mass flows (M). M_1 measures the hot gas mass flow to the internal cassettes, to determine CO_2 mass flow rate in heating and cooling mode; M_2 and M_3 measure CO_2 mass flow to MT and LT cabinets; finally, M_4 is used for measuring CO_2 mass flow that to the heating coils of the AHU unit in the cooling season.

A magnetic mass flow meter M_5, located on DHW water side, measures water mass flow to the dedicated plate heat exchanger; water temperature lift is measured by two NTC sensors.

3.2 Shopping area heating and cooling terminal units

With respect to the other systems developed within the project Multipack (Minetto et al., 2018; Minetto et al., 2019, Hafner et al, 2020), the comfort of the shopping area and service rooms is demanded to direct flow of CO_2 inside 24 localized ceiling terminal indoor units (IU), according to the experience described in Girotto, 2016. Figure 2 represents a picture of a terminal in the field.

Figure 2: Heating and AC terminal unit in the shopping area

Units are controlled by air temperature and can heat up air (winter) or cool it down (summer) as required. The installed system is very suitable for refurbished sites, especially in the case of low internal height, as it allows for distributed AC and heating, while not requiring bulky air distribution channels to entirely satisfy the building thermal loads, but only to comply with air change.

Figures 3a and 3b register CO_2 temperature to and from the indoor units, $T_{in\ iu}$,$T_{out\ iu}$, in typical winter (heating) and summer (cooling) operations. In summertime, indoor units coils are overfed, as shown in Figure 3a, when comparing $T_{out\ iu}$ to the saturation temperature of the receiver ((7) in Figure 1).

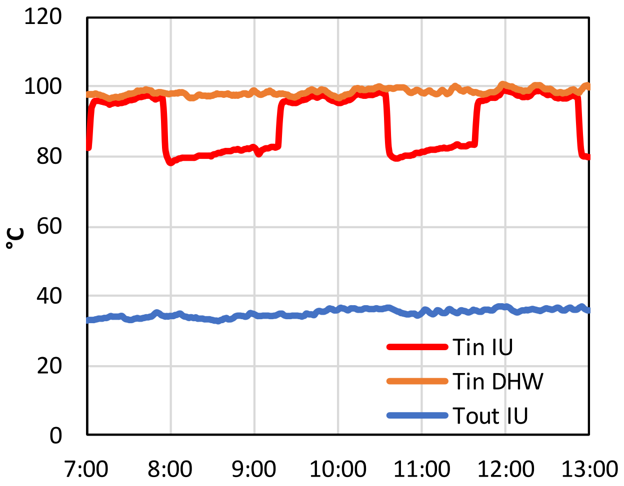

Figure 3a: Indoor unit return temperature (winter)

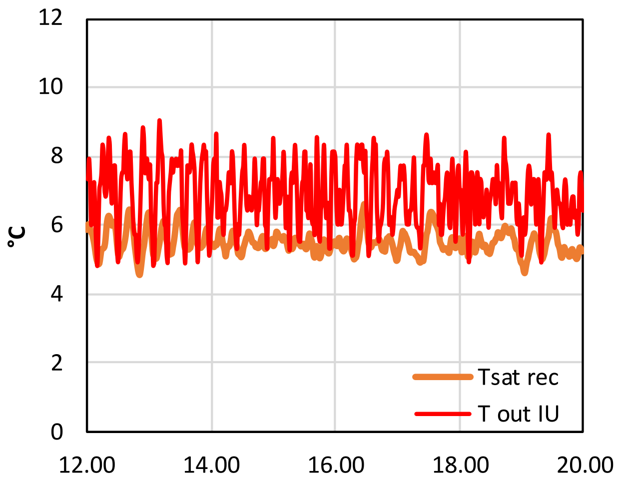

Figure 3b: Indoor unit return temperature (summer)

4 RESULTS FROM THE FIELD

Working conditions of the unit and performances are presented in Figures 4a-4f for summer (Figures 4a, b and c) and winter operations (Figures 4d, e and f), respectively taken on 16th August 2019 and 11th December 2019. According to the weather data registered at 2km distance from the site, the outdoor temperatures in the analysed periods are respectively 26.1°C (average), 23.2°C (min), 29.1°C (max) in summer and 4.7°C (average), 3.0 (min), 5.8(max) in winter. Moving averages over a 10-minute interval of the measured values are plotted in the graphs.

During the first semester, standard operating conditions for commercial refrigeration were set, to assess baseline performances.

In wintertime, the unit satisfies the cooling demand of the MT and LT cabinets, while heating the indoor environment. Heat recovery is performed by setting transcritical operations, as represented in Figure 4a. 6 relevant hours for heating operations are identified in winter and 8 hour period in summer. In winter, when the heating demand exceeds the heat recovery capacity, heat pump functionality is activated, by feeding the external evaporator, built in in the gas cooler frame (components (6) in Fig. 1), In Fig. 4a saturation temperature at MT, LT, Receiver ((7) in Fig.1) and outdoor evaporator ($T_{ev\ HP}$) are illustrated. The outdoor evaporation temperature depends on external air condition.

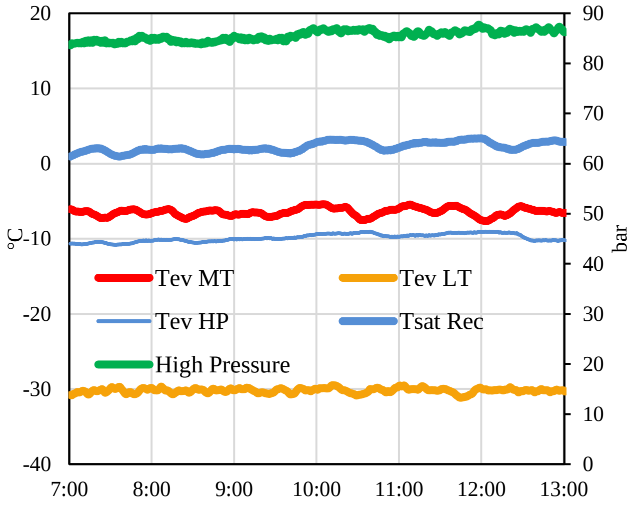

Figure 4a: Winter operating conditions

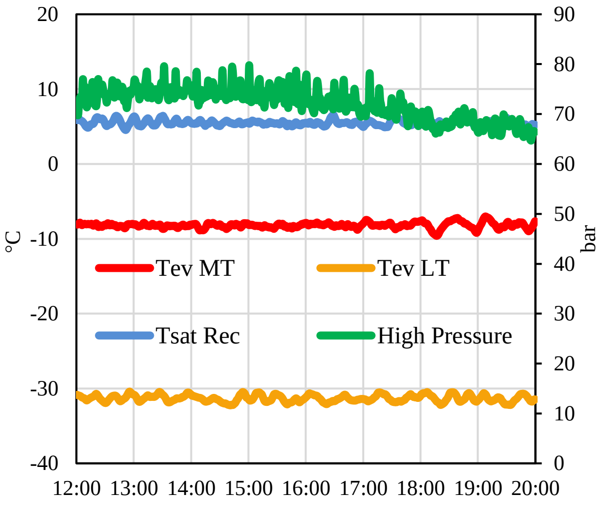

Figure 4d: Summer operating conditions

The refrigeration unit set points change in terms of evaporation and receiver pressure from winter to summer, as it can be seen by comparing figures 4a and 4f. The saturation temperature at AC evaporators is set at about 5°C. The resulting pressure difference for vapour ejectors in summertime is 12 bar. Liquid ejectors are never activated indicating that no liquid returns to the MT liquid receiver neither in summer nor in winter, due to the operating conditions which have been tried so far and that will be illustrated in section 5.

Fig. 4b shows that the Auxiliary power input is actually relevant to the overall system consumption, as auxiliary compressors are activated for the heat pump mode; although heat is recovered locally in the shopping area, GC fans are on as they serve the heat pump evaporator. Summertime power inputs are displayed in Figure 4e, with auxiliary compressors serving the AC mode and parallel compression.

Finally, useful refrigeration, heating and AC effects are presented in Figures 4c and 4f for winter and summer operations respectively.

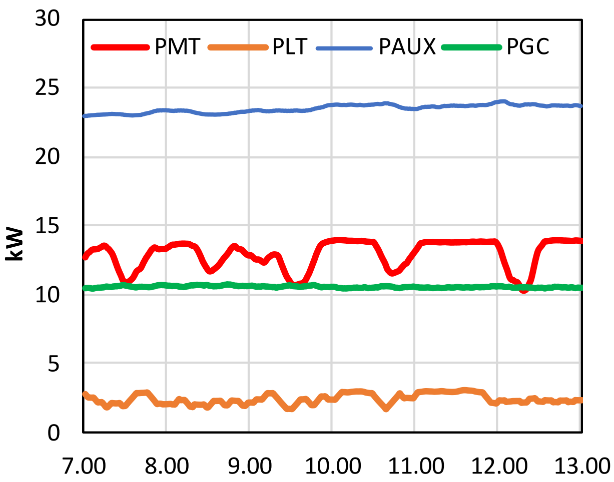

Figure 4b: Winter power input

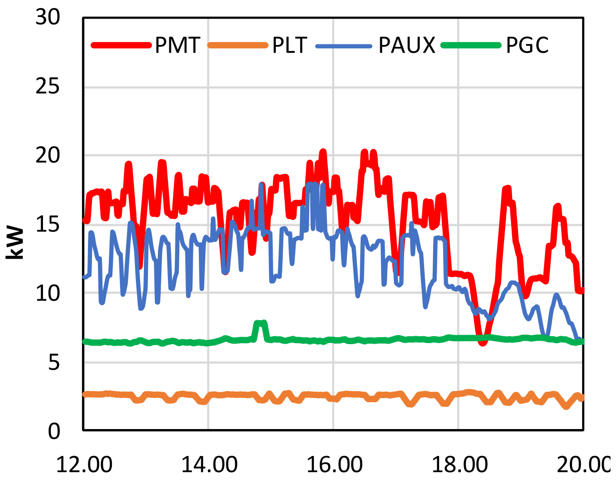

Figure 4e: Summer power input

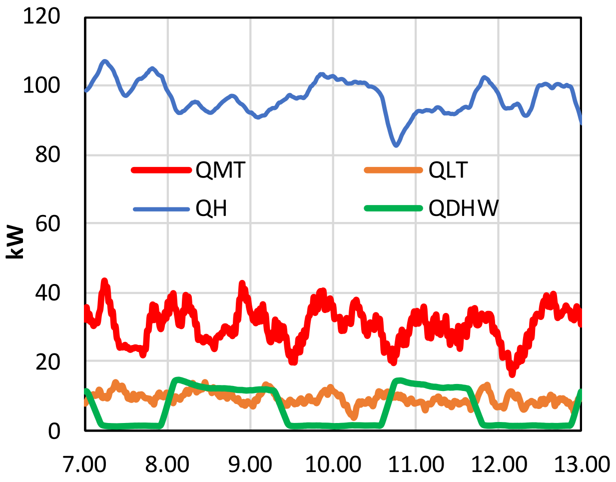

Figure 4c: Winter thermal power

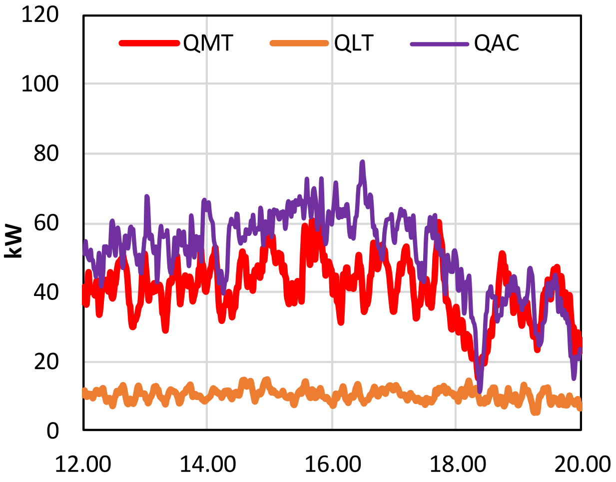

Figure 4f: Summer thermal power

For the summer and winter reference period represented in figures 4a-4f, the overall energy efficiency ratio is calculated as $EER = \frac{\sum_{t=ti}^{t=tf} Qi}{\sum_{t=ti}^{t=tf} P_{in}i}$, taking into account also P_{GC}, i.e. the power input to GC and external evaporator fans, thus evaluating a total EER. The second law efficiency was also calculated (Blust et al, 2019, Minetto et al, 2019), in order to weight the different loads occurring at the same time at different temperature levels. In wintertime, when heat recovery is on, the gas cooler is partially or totally by-passed, thus the impact of outdoor temperature on EER is very limited; 4.7 °C outdoor was taken as a reference in the considered period for second law efficiency evaluation, according to the average value collected by the closest available weather station. On the contrary, the above stated summer EER is evaluated at 28.3°C gas cooler outlet temperature and the ambient temperature was assumed to be 26.1°C for the calculation of the second law efficiency, also as given by the weather station. Reference temperature values for Carnot factors calculation were 26°C for AC, 21°C for heating, 0°C for MT , -20°C for LT and 40°C for DHW.

Overall results are summarised in Table 1, where first and second law efficiencies are calculated using average values over the entire period represented in Figures 4a-4f, i.e. 6 and 8 hours respectively in winter and summer respectively.

5 CABINETS PERFORMANCES

The performances of cabinets were analysed in terms of internal air temperature, cycling according to set point and expansion valve operations. PWM EEV were used to feed evaporators. To build up a baseline, traditional parameters set up was applied during the first period, i.e. standard superheat control, while improvements in the valve control to meet MultiPACK objectives are undergoing and preliminarily presented in this section.

MultiPACK seeks for optimal evaporator usage, i.e. overfeeding and superheat removal, which has widely proved to be able to allow for much higher evaporation temperature and consequent energy saving (Minetto and Fornasieri, 2011), with special relevance in CO_2 systems (Minetto et al., 2014).

A MT cabinet was selected as reference, a vertical glass door case VC4 according to EN ISO 23953-1:2016, dedicated to dairy products.

Figure 5a shows how the Superheat SH set point was changed on 23rd December 2019 from 8.00 am to 20.00 p.m, while Figure 5b displays the trend of set and measured evaporation temperature; while the set evaporation temperature refers to the cooling unit, the measured value is given by the cabinet control system, i.e. it is locally evaluated by commercial control system.

Table 1. Average performance values.

Q [kW]	**MT**	**LT**	**HP / AC**	**DHW**
Summer	40.8	10.2	51.4	-
Winter	30.3	9.5	96.4	6.3
Power input [kW]	**MT**	**LT**	**AUX**	**GC**
Summer	15.2	2.5	12	6.6
Winter	12.9	2.3	23.5	10.5
T [°C]	**MT** T_{ev}	**LT** T_{ev}	**AUX** T_{sat}	**HP** T_{sat}
Summer	-8.2	-31.3	5.5	-
Winter	-6.5	-30.0	2.3	-9.9
EER [-]				
Summer	2.8			
Winter	2.9			
η_{ex}[-]				
Summer	0.19			
Winter	0.19			

The reduction in superheat set point forces the EEV to a higher opening degree (Figure 5c), with a general benefit in terms of cabinet air temperature (Figure 5b) and more thermostat cycles. The advantage in terms of air temperature is observed even when the suction temperature is increased (starting from -5.5 up to -2.8°C), with not perceivable impact on air temperature (Figure 5d).

This result confirms that, when the superheat is properly reduced, the evaporation temperature can be significantly increased while maintaining the performance in terms of air temperature. The evidence out of this experimental campaign is the fact that the performance (air temperature) is colder at low superheat and high evaporation temperature (2.0 K, -2.8°C), rather than high superheat and low evaporation temperature (8.0 K, -5.5°C). This conclusion can be explained by the circumstance that the evaporator exit temperature must of course be lower than the evaporator air inlet, i.e. the bottleneck is represented by the evaporator exit condition, thus resulting in working operations with higher cabinet air temperature in the case of high evaporator outlet.

In addition, monitored cabinets display a total time with open valve much shorter when the superheat is low rather when it is high and evaporation temperature is low (53% vs 81%), thus confirming better performances in terms of air temperature.

Similar behavior was observed in other cabinets, both for diary and meat products, with lower impact for those cabinets where the superheat was originally set at 5°C.

Further activity will include set point reduction for all cabinets and evaporation temperature increase up to -2.5°C of the cooling unit, with measurement of energy consumption reduction at unit level.

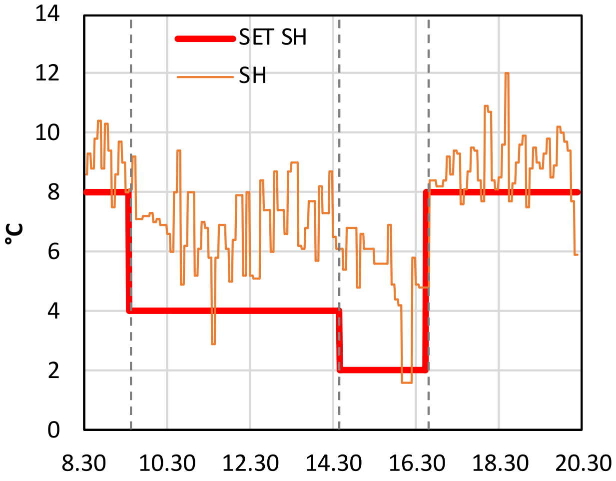

Figure 5a: Superheat SH

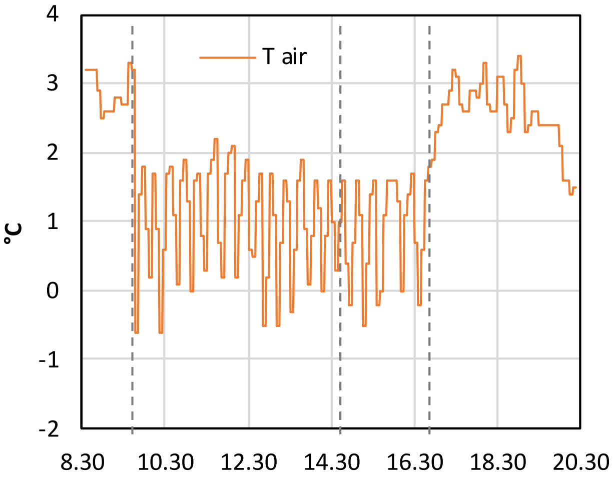

Figure 5b: Air temperatue

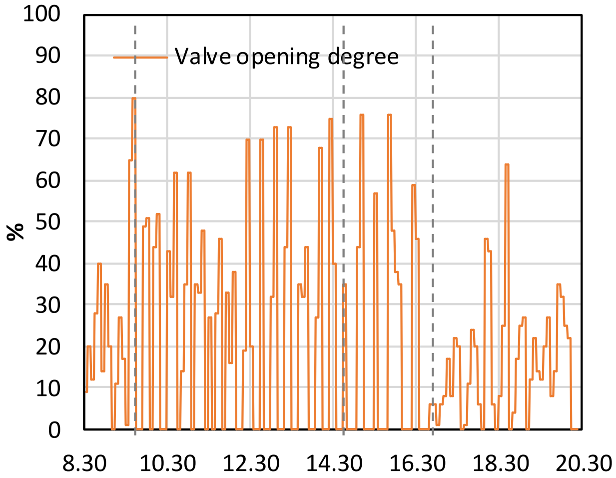

Figure 5c: Valve opening degree

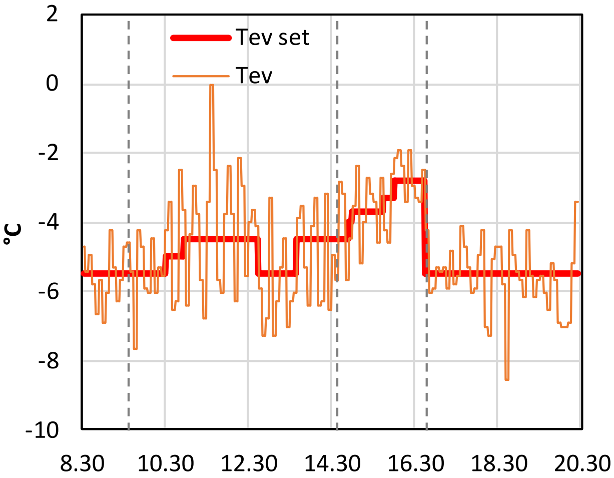

Figure 5d: Set and measured evaporation temperature

6 SUMMARY

The activity performed within the project MultiPACK is progressively demonstrating that CO_2 integrated systems, providing all thermal services for a supermarket and including state-of-the-art technology parallel compression, ejectors and evaporator overfeeding, are feasible and reliable and are an available alternative to traditional, non-integrated, solutions.

The project is filling the gap represented by the under availability of data from the field, by providing measured data of the overall performance, as well as documenting the unit behavior at different operating conditions and demands.

While maintaining the standardization and modularity of the design, the MultiPACK unit can meet different needs, such as specific needs for retrofitting of existing sites. In this paper, a specific arrangement, based on localized AC and heating cassettes inside the shopping area, is illustrated and preliminary performance data are evaluated in terms of cooling and heating loads, first and second law efficiency.

The advantage given by superheat minimization is fully documented in the field. The next steps will include superheat minimization for all MT cabinets, with winter and summer performance monitoring, to fully satisfy the MultiPACK project goals.

ACKNOWLEDGEMENTS

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NOMENCLATURE

p	Pressure (kPa)
T	Temperature (°C)
P	Electrical Power (kW)
Q	Thermal Power (kW)
SH	SuperHeat (K)

Suffixes and acronyms

AC	Air Conditioning
AHU	Air Handling Unit
air	Cabinet internal air
Aux	Auxiliary
DHW	Domestic Hot Water
EEV	Electronic Expansion Valve
ev	Evaporation
GC	Gas cooler
H	Heating
HP	Heat Pump
in	Measured at the inlet of
IU	Internal Unit
LT	Low temperature application
MT	Medium temperature application
out	Measured at the exit of
PWM	Pulse-Width Modulation
Rec	Receiver
sat	Saturation
set	Set value

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