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Two years of data monitoring of all-CO_2 retail stores within the MultiPACK project

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ABSTRACT

This paper presents the results of a 24-month field monitoring of CO_2 transcritical units designed to satisfy all the thermal needs of food retail stores, namely refrigeration, heating and cooling. The units, adopting state-of-the art technologies, such as two phase ejectors and parallel compression, are developed within the H2020 project MultiPACK. The monitored supermarkets are located in Italy, in two different climatic areas, featuring different heating and cooling demands for indoor comfort, as well as diverse building type and display cabinets mix. Long lasting measurements allow for evaluation of energy and efficiency related KPIs, together with operational indicators. These figures are relevant for benchmarking with traditional solutions.

Keywords: Carbon Dioxide, Commercial Refrigeration, Ejector, Heat Pump, Integrated Unit

1. INTRODUCTION

Due to the F-gas regulation and the Kigali amendment to the Montreal Protocol, commercial refrigeration has been forced to rapidly consolidate alternative eco-friendly solutions to traditional system. In the last twenty years, CO_2 has confirmed to be a reliable and sustainable alternative and an available solution for supermarkets after the 2020 and 2022 F-gas deadlines. The EU funded project SuperSmart (Minetto et al., 2018) has shown how non-technological barriers can hinder the diffusion of energy efficient solutions in the HVAC&R sector. After SuperSmart, the EU funded project MultiPACK's objective is to assure the market about the reliability and efficiency of CO_2 integrated system by installing, monitoring and analysing results collected on the field of integrated state-of-the art system in the South European Climate. The MultiPACK units include parallel compression, the use of two-phase ejector to recover expansion work and ensure liquid recirculation as described in Gullo et al. 2019, together with AC and heat pump functionalities. In this paper, the results of a 24-month field monitoring of two MultiPACK units installed in two supermarket are analysed. In particular, the performance, i.e. COP, of the system operating in heat pump configuration during winter conditions and providing cooling in summer conditions are presented as a function of the external environment temperature.

2. INSTALLATION SITES AND SYSTEMS LAYOUT

In this paper, two different integrated units installed in typical Italian neighbourhood supermarkets are considered. The two supermarkets are respectively located in the north-east area of Italy (Trento, Figure 1a), characterized by a relatively mild climate during summer and an harsh winter, and in the central area of Italy (Rome, Figure 1b) which is characterized by warmer winter and hot summer instead. This difference in the type of climates where the installations are located, gives the opportunity to analyse and compare the performance of the MultiPACK CO_2 integrated units at different external environment conditions. According to EN ISO 13926-6:2008, the Heating Degree Days of Rome and Trento are equal to 1415 and 3001 days respectively. As for the external ambient conditions (dry bulb temperature and relative humidity), they are taken from an official meteo station close to the supermarkets (http://storico.meteotrentino.it for Trento and http://meteoeplus.pd.cnr.it/stations/summary-rm01e.php for Rome).

(1a) **(1b)**

Figure 1 – Installation of the integrated unit in Trento (1a) and Rome (1b)

According to the MultiPACK design, the integrated unit must provide full thermal energy services to the sites while adopting state-of-the art technologies for CO_2 systems operating in warm climates. The system includes the use of parallel compression, two-phase multi-ejector system for expansion work recovery and superheat minimization at the evaporators. A more detailed description of the two MultiPACK installations considered in this paper, operation modes and performance analysis during a typical summer and winter day can be found in Tosato et al. 2020. The system lay-out installed in Trento is reported in Figure 2 while the system lay-out installed in Rome can be viewed in Figure 3.

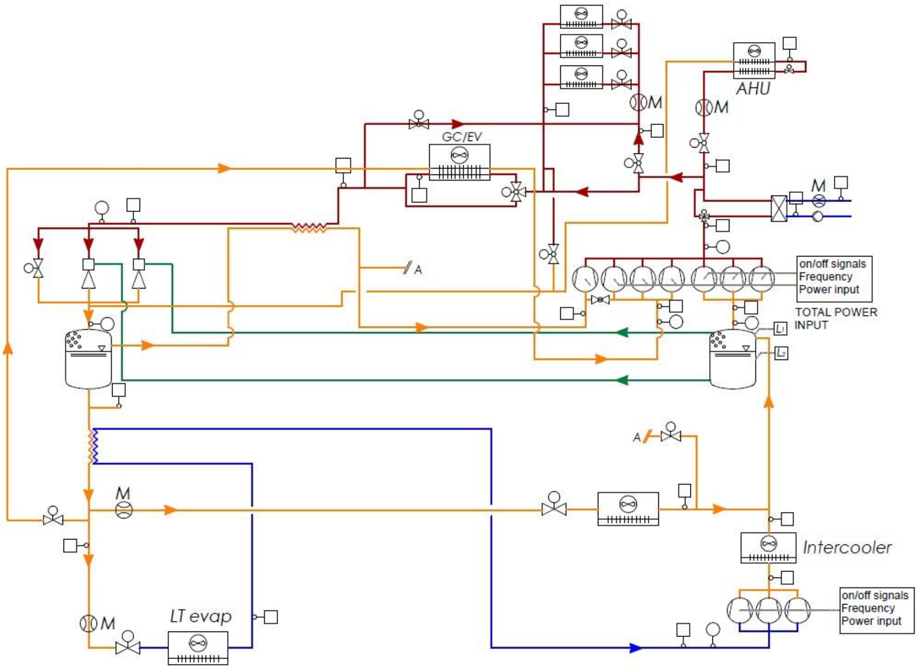


Figure 2: Trento site layout

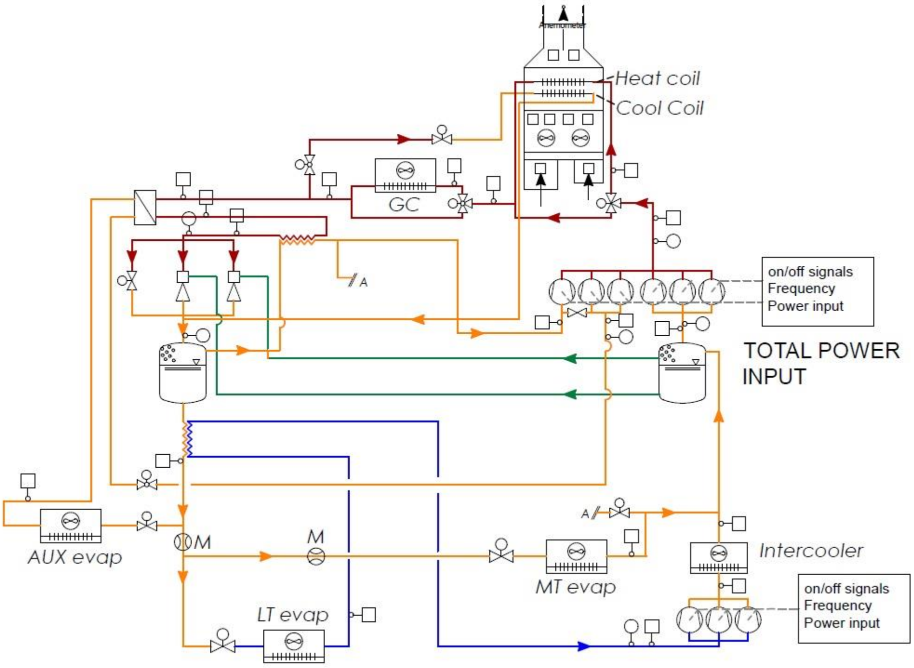


Figure 3: Rome site Layout

One of the main goals of the MultiPACK project is to monitor the operation of the units on the field: for this reason, both system are fully instrumented with temperature sensors (indicated as square elements), pressure sensors (indicated as circles) and mass flow rate meters (indicated as M). The liquid level (L) in the receivers and the electric power input at the compressors (P_{el}) are also measured. The detailed description of the measurement instrument accuracy can be found in Minetto et al., 2019. Temperature is measured with NTC 10 kΩ ±1% at 25 °C Beta 3435 sensors, whose declared precision is ±0.5 °C at 25 °C and ±1.0 °C in the range -40 °C to +90 °C. Pressure is measured with six commercial type piezoresistive pressure transmitters, with accuracy ranging from ± 1%FS to ±4 %FS (FS=60 10^5 Pa and 150 10^5 Pa on high pressure side) depending on temperature level pressure. The three-phase electric power meters, located before each compressors rack, measure the power input to Low Temperature ($P_{el,LT}$), Medium Temperature ($P_{el,MT}$), and Auxiliary ($P_{el,AUX}$) compressors, with ±0.5 % FS accuracy (FS is 24 kW for LT compressor rack and 120 kW for MT and AUX). The accuracy of the Coriolis mass flow meters is 0.1 % of the actual flow. A hot wire anemometer (accuracy ±0.2 m/s +3 % of measured value) is located on the main air duct. The accuracy of the RH probes is ±3 % and of the reading (temperature range 0 °C to -40 °C, RH up to 90 %) and ±0.5 °C for temperature from +10 °C to +30 °C.

While the lay-out of the two units is basically the same, the main difference between the two systems are the type of terminals selected for heating and cooling of indoors space. In Rome, HVAC are demanded to an Air Handle Unit while in Trento, shop ceiling indoor units are distributed in the shopping area according to Tosato et al.,2020. In order to provide a sizing of the two installations, Table 1 provides the design thermal loads and the supermarkets shopping and total area respectively.

Table 1 – Sizing of the two MultiPACK installations

	Rome	Trento
$Q_{MT,D}$	50 kW @ -4°C	90 kW @ -4°C
$Q_{LT,D}$	19 kW @ -30°C	22 kW @ -30°C
$Q_{H,D}$	75 kW @ 10°C external temp.	200 kW @ 10°C external temp.
$Q_{C,D}$	110 kW @ 30°C external temp.	280 kW @ 30°C external temp.
Shopping area	1450 m^2	1750 m^2
Total area	1900 m^2	2200 m^2

3. DATA COLLECTION AND PROCESSING

This paper presents the experimental data collected during a large test campaign, occurred between January 2019 and December 2020. In particular, the operation of the integrated system according to a heat pump configuration and a cooling configuration will be presented. The heat pump operating mode is activated during the harshest days of winter, when an additional heating power is required by the building. In this mode, in order to provide an additional heating power to the building's internal air, the additional external finned coil evaporator is utilized to get heat from the external ambient while the auxiliary compressors operate to ensure the flow of the refrigerant inside of the additional heat exchanger. On the other hand, during the summer months, the air inside of the building needs to be cooled down and dehumidified in order to satisfy the comfort requirements: in the cooling mode, the refrigerant derived from the high-pressure side of the system is expanded to the receiver's operating pressure and evaporated thus providing the required cooling effect. During the hottest days of the summer season, the auxiliary evaporator are activated as well, in order to remove the excess of vapour at the receiver and ensure a precise pressure control.
The cooling power at the MT and LT evaporators ($\dot{Q}_{MT}$, $\dot{Q}_{LT}$) is evaluated with a refrigerant heat balance as the value of temperature, pressure and refrigerant mass flowrate are all measured. However, the evaluation of the heating/cooling power provided to the building are calculated differently for the two installations. In the Trento installation, both DHW heating power ($\dot{Q}_{DHW}$) and heating/cooling power ($\dot{Q}_H$, $\dot{Q}_C$) are evaluated with a refrigerant heat balance measuring refrigerant temperature, pressure and mass flowrate flowing at the heat exchangers' inlet line. In the Rome installation, the heating/cooling power provided to satisfy the building's demand is evaluated with an air heat balance in the Air Handle Unit channel as the mean inlet and outlet temperature and relative humidity and air mean velocity are measured, knowing the conduit cross sectional area.

3.1. Definition of steady state operation

With the aim of characterizing the typical performance of the integrated units under a large range of operating conditions, heat loads and external ambient temperature, the experimental data collected during the arc of the two years were logged with a frequency of 60 seconds, providing a large database. As the operation of the system is mainly characterized by transient conditions due to the high variability of the thermal loads, the performance of the system was considered only in specific intervals where the units was considered to operate in steady-state condition. In order to define the typical steady-state interval, a total of 10 variables are considered: the heat flow rates of the system $\dot{Q}_{MT}$, $\dot{Q}_{LT}$, $\dot{Q}_{DHW}$ for the Trento unit, $\dot{Q}_H$ or $\dot{Q}_C$ depending on the operating configuration, the electric power input at the compressors P_{el}^{MT}, P_{el}^{LT}, P_{el}^{AUX} and the inverter signal at the inverter-driven compressor in each compressor rack inv_{MT}, inv_{AUX}, inv_{LT}. Considering a moving average of 15 minutes, in the typical steady-state interval the value of all the mentioned variable must not vary more than 10% between the previous minute j and the next one j+1, as reported in Eq.1:

$$X = [\dot{Q}_{MT}\ \dot{Q}_{LT}\ \dot{Q}_{DHW}\ \dot{Q}_{H/C}\ \ P_{el}^{MT}\ P_{el}^{LT}\ \ P_{el}^{AUX}\ \ inv_{MT}\ \ inv_{AUX}\ \ inv_{LT}]$$

$$\Delta\delta_{\%} = \left|\frac{X_j - X_{j+1}}{X_j}\right| \cdot 100 \le 10\%, \qquad \text{Eq.1}$$

Furthermore, to neglect the transient conditions introduced by the ON/OFF of the compressors, an additive constrain requires the ON or OFF state of all the compressor to be constant in the considered intervals. Once the steady-state intervals are defined, they are associated to the mean values of external ambient temperature, operating pressures, heat flowrates and COP calculated according to Eq.2 and Eq.3 for the Trento and Rome installation respectively.

$$COP = \frac{\dot{Q}_{MT}+\dot{Q}_{LT}+\dot{Q}_{DHW}+\dot{Q}_H+\dot{Q}_C}{P_{el}^{MT}+P_{el}^{LT}+P_{el}^{AUX}} \qquad \text{Eq.2}$$

$$COP = \frac{\dot{Q}_{MT}+\dot{Q}_{LT}+\dot{Q}_H+\dot{Q}_C}{P_{el}^{MT}+P_{el}^{LT}+P_{el}^{AUX}} \qquad \text{Eq.3}$$

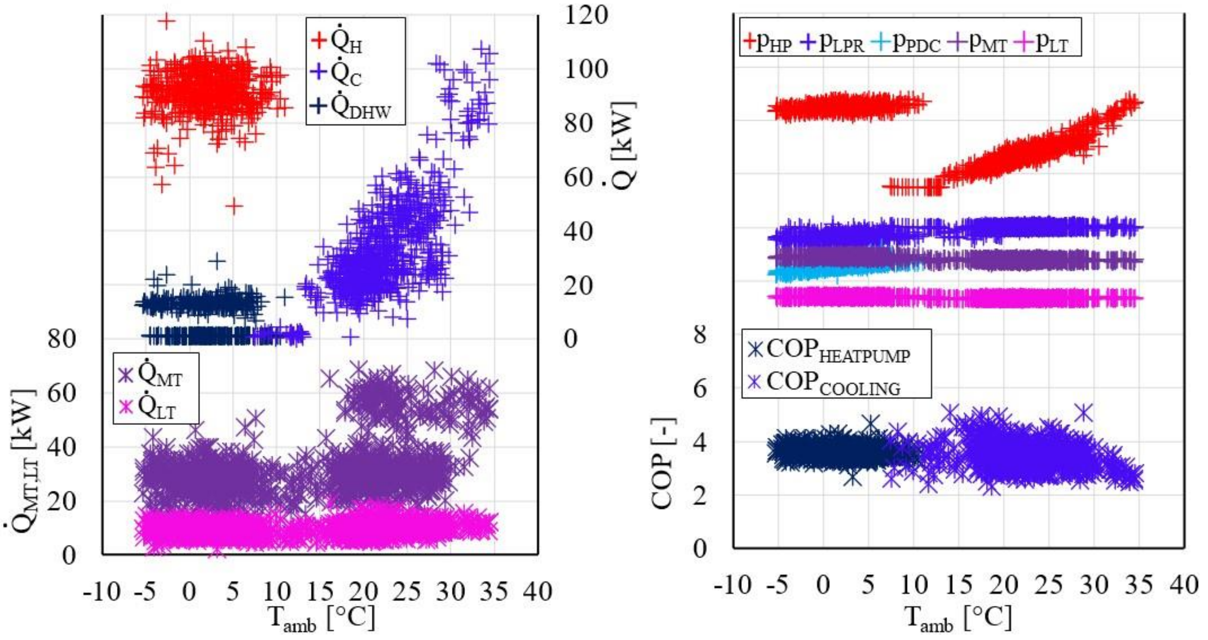
In this definition of COP, all the heating and cooling effect provided by the system are considered, while the electric power of the fans of the gas-cooler and Air Handle Unit are neglected.

4. RESULTS

In this section, the operation of the two integrated units in the identified steady state intervals is discussed. In this discussion, however, only the operation in heat pump configuration using the auxiliary external evaporator and cooling configuration providing cooling and dehumidification to the building is considered.

4.1. Trento installation

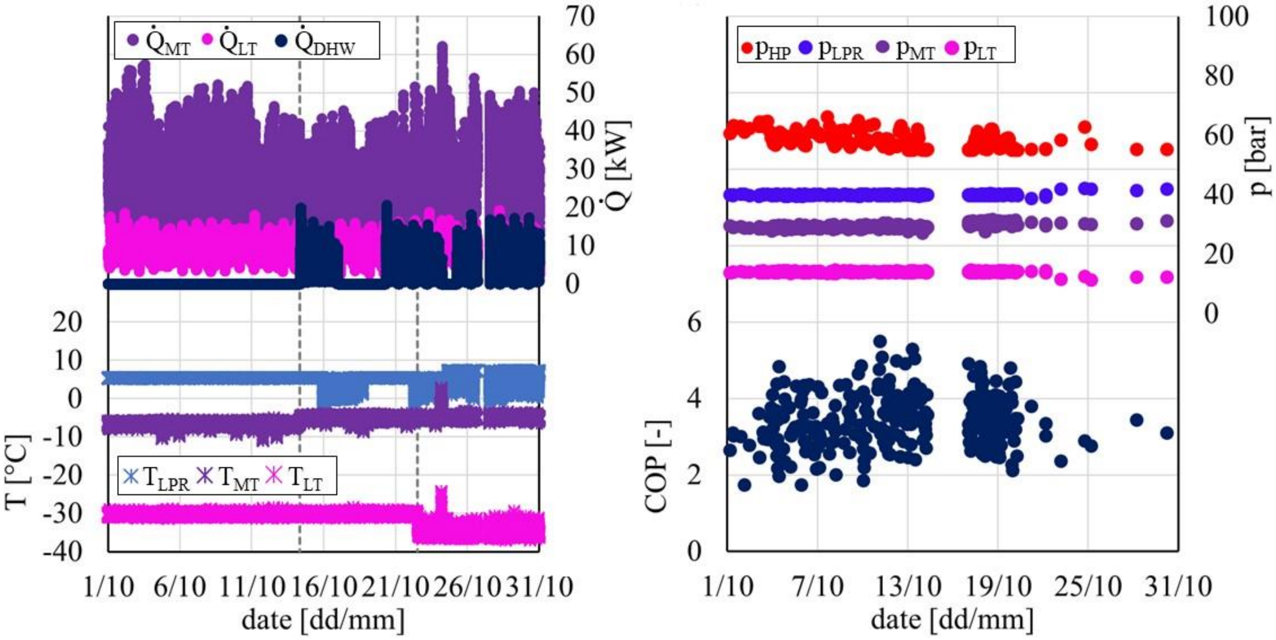
Using the definition of steady state operation given in Eq.1, a total of 1112 interval were identified when the system is operating in heat pump configuration and cooling configuration respectively. For this installation, the identified steady-state intervals have a mean length of 10 minutes while the associated mean ambient temperature is comprehended between -5.3 °C and 34.5 °C. Figure 4a provides the trend of the system heat flowrates while Figure 4b provides the values of operating pressures and coefficient of performance defined according to Eq.2 and Eq.3, all against the external environment temperature. When operating in heat pump configuration, the high pressure p_{HP} is kept constant with a set-point value of 85 bar in due to the heat recovery and the domestic hot water production. The refrigerant flowing in the additional external finned coil heat exchanger evaporates at the pressure p_{PDC}, which is then bound to the external environment temperature and thus decreases as the ambient temperature decreases. The heating power provided to the building in winter seasons has a mean value of 91.6 kW and has a constant trend. Consequently, the $COP_{HEAT\ PUMP}$ has the same constant trend with a mean value of 3.5. However, due to the high variability of operating conditions, the values of $\dot{Q}_H$ and $COP_{HEAT\ PUMP}$ result scattered around the mean value. When the system is operating in cooling configuration during the summer months, the high pressure p_{HP} increases as the external ambient temperature increases: the same trend can be observed for the cooling power, reaching a maximum value of 107.6 kW. The cooling power required by the MT evaporators obviously increases with increasing ambient temperature. Finally, $COP_{COOLING}$ presents a different trend from the previous configuration, and is slightly decreasing as the external ambient temperature increases. The value of COP in this case are far more scattered respect to the heat pump configuration which makes difficult to identify a decisive trend.



(4a) **(4)**

Figure 4 - Trend of : (4a) main heat loads of the Trento unit as a function of ambient temperature (4b) COP and operating pressure as a function of ambient temperature

Figure 5 provides an analysis of the performance of the Trento refrigerated unit during the month of October 2020: the trend of cooling power at the MT, LT evaporators, DHW heating power, low pressure receiver operating temperature and mean MT and LT evaporation temperature are reported in Figure 5a, considering a moving average of 15 minutes. As it can be observed, an increase of the MT evaporation set-point temperature was given during 14 October increasing the mean value of the evaporation temperature from -6.6 °C to -5.0 °C.



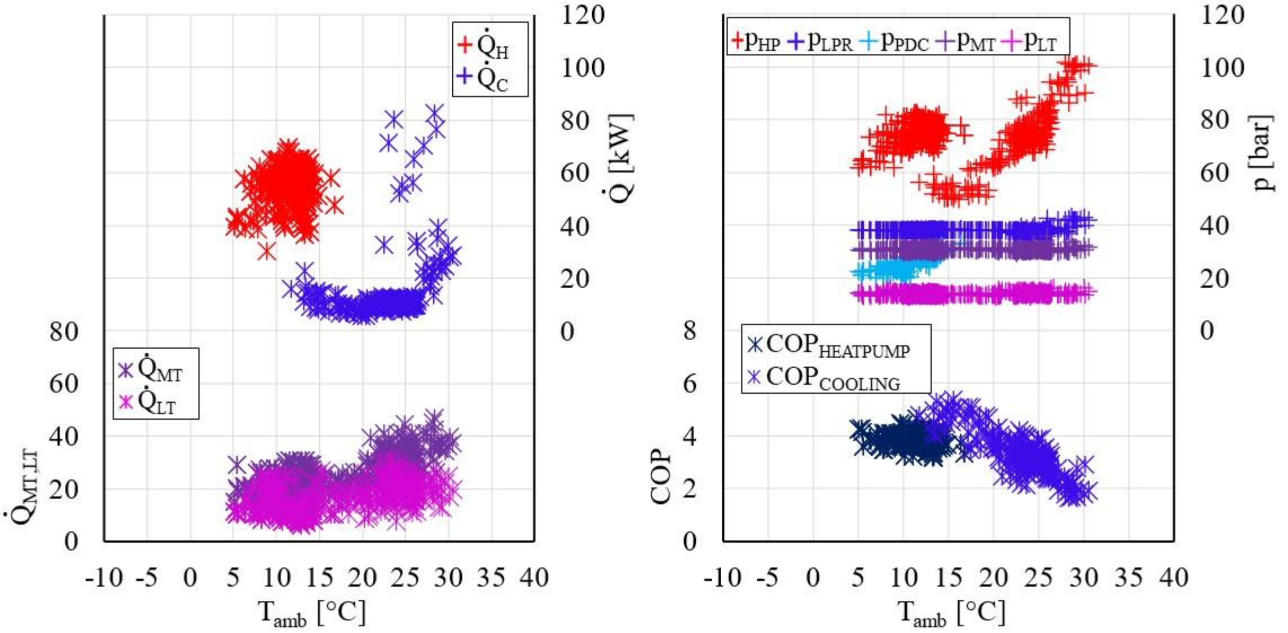
(5a) **(5b)**

Figure 5 - Trend of : (5a) main heat loads and operating temperature (5b) operating pressures and COP in the steady state intervals, during October 2020 for the Trento installation

On the other hand, a sudden decrease of the LT evaporation temperature can be observed during the 22nd of October: the mean LT evaporation temperature changes from -30.2 °C to -34.6 °C. Figure 5b reports the trend of the operating pressures and COP in the steady state intervals identified during the considered month. However, no major changes can be observed in the average COP in the selected period.

4.2. Rome installation

In this installation, using the definition of steady state operation given in Eq.1, a total of 681 interval were identified when the system was operating in heat pump and cooling configuration respectively. Differently from the Trento unit, where the system's high pressure is kept to a set-point value of 85 bar due to the necessity of heat recovery for the production of domestic hot water, the high pressure in the Rome installation varies depending on the external ambient temperature. Due to the low value of ambient temperature, which in winter season lays between 5.1 °C and 16.7 °C, the mean operating high pressure is equal to 74.8 bar. Consequently, as the operating pressure of the low-pressure receiver and mean evaporation pressure of the MT and LT evaporators are similar to the ones in the Trento installations, the corresponding COP results to have a higher value, with a mean value of 3.9, as the system operates in heat pump configuration. As it can be observed in Figure 6b, during the summer month, as the system is satisfying the cooling demand of the building, the COP of the system decreases linearly with the external environment temperature. However, observing the heat loads of the system in Figure 6b, for the majority of identified steady state intervals a low value of cooling power below 20 kW is usually required, while the cooling power required by the MT and LT evaporators increase as the external environment temperature raises.



(6a) **(6b)**

Figure 6 - Trend of : (6a) main flowrates of the Roma unit as a function of ambient temperature (6b) COP and operating pressure as a function of ambient temperature

5. CONCLUSIONS

This paper presents the results of a long lasting measuring campaign performed on two supermarket sites installed within the EU project MultiPACK. Due to the huge amount of data, a proper data filtering process needs to be performed to identify stable periods where CO can be calculated. The paper shows energy and efficiency parameters for both sites; in particular, the mapping of COP as a function of outdoors temperature opens the way to comparison with other sites. For a reliable comparison, however, the loads, and in particular the load ratios, need to be carefully considered. Further development of this work will include the analysis of the impact of load ratios on COP, together with the other influencing parameters, like the outdoor temperature.

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NOMENCLATURE

$\dot{Q}$	Heat flow rate (kW)	COP	Coefficient of performance (-)
P_{el}	Electric power input (K)	inv	Inverter signal (%)
p	Pressure (bar)	T	Temperature (°C)

subscript

LT	Low temperature	MT	Medium temperature
DHW	Domestic hot water	H	Heating
C	Cooling	AUX	Auxiliary compression rack

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