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Field measurement analysis of integrated refrigeration system in a new supermarket

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ABSTRACT

The energy outlook of a supermarket in Stockholm, as well as its refrigeration cycle efficiency are investigated based on field measurements. The refrigeration unit of the system is a CO2 trans-critical booster system with heat recovery, air conditioning, and geothermal storage integration. Field data are analyzed from 1st of January 2019 until the end of the same year. Based on the field measurements, low, medium temperature level, air conditioning cooling and space heating demands, as well as COP's are calculated, for thirty-minute intervals, averaged to different ambient temperatures. The same method is used for calculating the thermal loads from the ground. The results show energy efficiency improvement comparing to previous studies, which originates from several factors such as: changes in the system design (e.g. three stage expansion), higher total efficiency of compressors, zero or low internal superheat at the three evaporation temperature levels resulting in higher evaporation temperatures. The COP for the medium temperature level reaches 8,5 and 7,5 for space heating.

Keywords: Refrigeration, Carbon Dioxide, COP, Energy Efficiency, Energy Outlook, Supermarket, Liquid ejector, Overfeed Evaporator.

INTRODUCTION

F-gas regulation (EU 517/2014, 2014) opens the doors for the use of natural refrigerant in the retail sector. Carbon dioxide is used as refrigerant in more than 14000 supermarkets worldwide (EIA, 2018), mainly due to its good safety characteristics. Also, refrigeration systems with carbon dioxide are more efficient comparing to conventional hydrofluorocarbon (HFC) systems in northern Europe where the ambient temperature is usually lower than 25 °C (Sawalha, 2008).

Carbon dioxide as refrigerant gives the opportunity to a multi-function refrigeration unit, which covers all the supermarket's thermal demands; refrigeration, heating, and air conditioning. Moreover, carbon dioxide gives the opportunity for an optimum heat recovery, since an integrated multi-controlling strategy is used. It has noted that independent operation control between HVAC and refrigeration unit drives to a decrease in the heat that could be reclaimed from the refrigeration system (Arias and Lundqvist, 2006).

Ground is used to carbon dioxide refrigeration units as an extra heat source when extra space heating is needed. The ground source is beneficial when the gas cooler is totally by-passed. However, the ground can provide subcooling in the system in the warm days, saving 4% of the total annual consumption in a stand-alone supermarket. (Karampour et al., 2018)

SYSTEM AND BOUNDARIES

The supermarket is located 40 km south of Stockholm, Sweden. Its operation started November of 2017. It is a stand-alone supermarket, which means that only the supermarket is serving the building. The building is heated by recovered heat from the refrigeration unit. Furthermore, eight boreholes with depth of 220 m each are connected to the refrigeration unit to ensure that the heat demand is totally covered by the refrigeration unit. These boreholes also provide free cooling in the building and subcooling in the refrigeration cycle. The products which need refrigeration are stored in two temperature levels, Medium Temperature (MT) level and Low Temperature (LT) level.

The refrigeration unit, presented in the schematic in Fig. 1, is a booster carbon dioxide unit with integration of a third evaporation stage for air conditioning and heat extraction from the ground. The MT cabinets operate under overfeed conditions thanks to liquid ejectors, which allow operation without internal superheat, increasing the evaporation temperature in this level. On the other hand, the LT cabinets don't operate under overfeed conditions, but low superheat is applied, providing safe conditions for the booster compressor. The third evaporation stage is connected to an extra heat exchanger, which is called Air Conditioning/Ground-Source (AC/GS) heat exchanger (see Fig.1), providing air conditioning in the warm days and extra heat from the ground in the cold period. Superheat is applied to this heat exchanger, ensuring that no liquid refrigerant will reach to the parallel compressor (Fig. 1)

Tap water is warmed up in the 1st de-superheater after the high-stage compressor (see Fig. 1). While the 2nd de-superheater after the high-stage compressor (Fig. 1) provides space heating to the building.

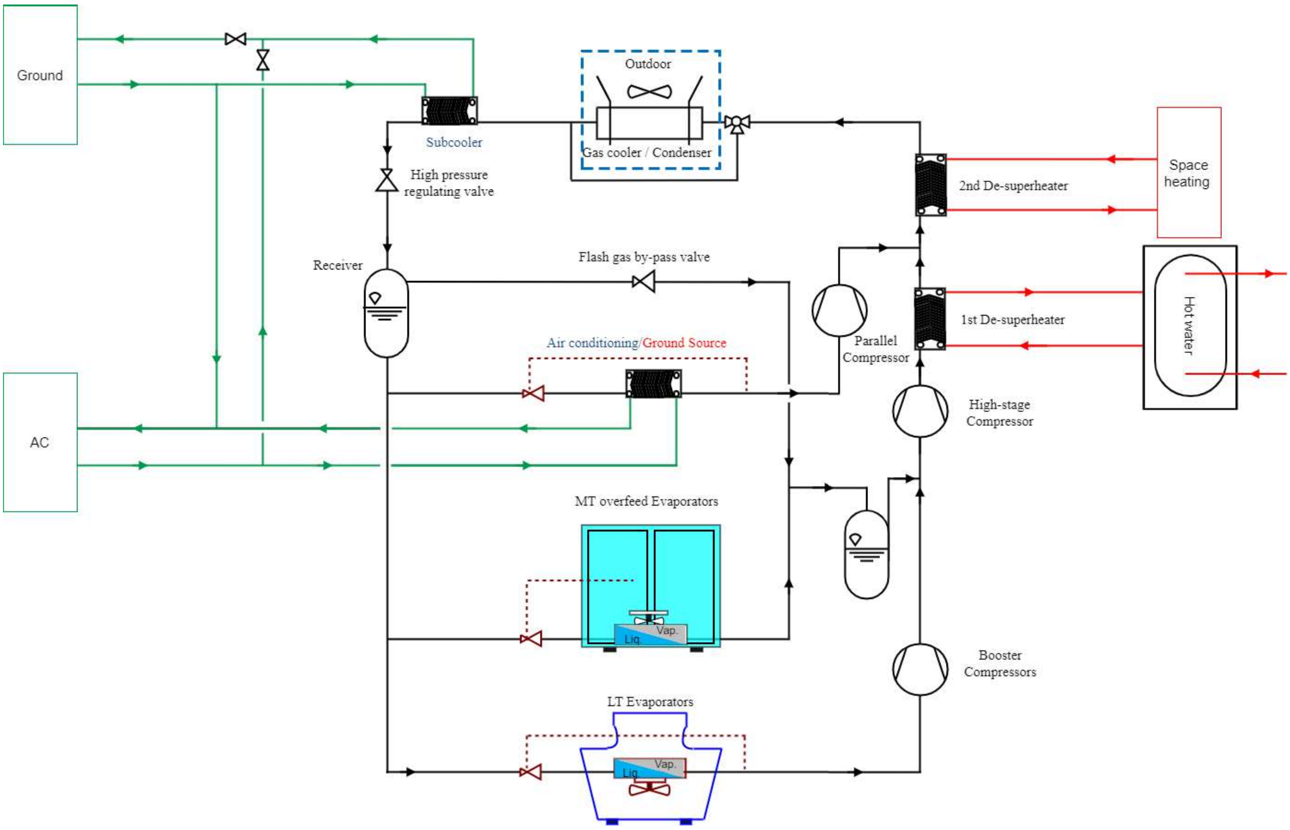

Figure 1: Schematic of refrigeration unit

Heat which is not used to warm up the building is rejected to ambient via the gas-coolers/condensers (Fig.1). The heat exchanger after the gas-coolers/condensers is called subcooler, this is connected to the ground loop and is used for injecting heat in the ground when the ground temperature is lower than the ambient and the ground is not used as a heat source.

The real time field measurements of the supermarket are available on Itop Huurre web-monitoring platform (Porkka, 2017). However, the ambient temperature is measured by the closest weather station of the traffic agency of Sweden, as the supermarket's sensors are not located properly. The data need synchronization, because of the two different data sources as it is already mentioned and because the measurements are updated when new conditions are detected by the sensors. A python-based tool is developed for this purpose, which also filters the data from wrong values, and missing measurements. Output of the python tool is the average value of each parameter every 30 minutes.

The analysis period is from 1st of January 2019 until the last day of the same year, which provides a complete picture of the supermarket's operation and demand. This annual study shows how the refrigeration system's efficiency changes into different ambient conditions, as well as the reaction of the building to the ambient.

Another python-Coolprop tool is used for the calculation of key parameters such as: COP, cooling and the heating demands based on indirect mass flow rate assessment, as a mass flow meter installation is rare in the supermarkets' refrigeration units because of its price. The compressors are used to estimate the refrigerant's mass flow in the system, using their volumetric efficiency and electricity frequency (Sawalha et al., 2017).

Thermal loads exchanged with the ground are calculated using the volume flow rate of the brine and the temperature differences in key points. For this calculation fluid properties of the commercial brine Ethylene Alcohol 18%+Propyl Alcohol 1.6%+n-Butyl Alcohol 0.4% are used. (Ignatowicz et al., 2017)

Having calculated the cooling and heating demands, and verified the calculated power consumption with the measured consumption of the compressors for different operation conditions, different Coefficients of Performance (COPs) are calculated. Different COPs are needed because of the multi-functionality of the system.

The high-stage compressors are used to compress the refrigerant from MT cabinets, the refrigerant after the booster compressors, and refrigerant from the flash-gas by-pass (see Fig.1). Running energy balance in the system, the power consumption of the refrigeration system will be divided in three different parts: the power consumption needed for the LT cooling demand (E_{LT}), the power consumption needed for the MT cooling demand (E_{MT}), and the power consumption needed for the air conditioning demand (E_{AC}).

E_{LT} includes the booster compressors' power consumption and part of the high-stage compressors' power consumption. E_{MT} is part of the high-stage compressors' power consumption. E_{AC} includes the parallel compressors' power consumption and part of the high-stage compressors' power consumption.

When heat is needed the system operates at higher discharge pressure resulting in increased power consumption. This additional power consumption affects the COPs negatively, hence the COPs are calculated under floating condenser operation. Floating condenser operation is the operation where the pressure in the condenser/Gas cooler (Fig. 1) is controlled following the ambient temperature, covering only the cooling demand.

The medium temperature level COP (COP_{MT}) for this system is calculated as:

$$COP_{MT} = \frac{Q_{MT}}{E_{MT,fl}}, \quad \text{Eq. (1)}$$

where Q_{MT} is the cooling demand of the MT level and $E_{MT,fl}$ is the E_{MT} under floating conditions.

The low temperature level COP (COP_{LT}) for this system is calculated as:

$$COP_{LT} = \frac{Q_{LT}}{E_{LT,fl}}, \quad \text{Eq. (2)}$$

where Q_{LT} is the cooling demand of the LT level and $E_{LT,fl}$ is the E_{LT} under floating conditions.

The air conditioning COP (COP_{AC}) for this system is calculated as:

$$COP_{AC} = \frac{Q_{AC}}{E_{AC,fl}}, \quad \text{Eq. (3)}$$

where Q_{AC} is the air conditioning demand and $E_{AC,fl}$ is the E_{AC} under floating conditions.

Space heating COP ($COP_{Space\ heating}$) is defined as:

$$COP_{Space\ heating} = \frac{Q_{space\ heating}}{E_{tot}-E_{tot,fl}}, \quad \text{Eq. (4)}$$

where $COP_{Space\ heating}$ is the space heating demand, E_{tot} is the total measured power consumption of the system and $E_{tot,fl}$ is the calculated total power consumption of the system under floating conditions.

No COP is defined for domestic hot water since this demand is low comparing to the space heating demand. Therefore, it may affect the $COP_{Space\ heating}$, since extra power which is needed for hot water production is considered that it is used for covering the space heating demand.

RESULTS

The evaporation temperature for the MT level is around 0 °C as can be seen in Fig. 2, instead of the typical temperatures of around -8 °C which was noted in previous studies (Sawalha et al., 2017). The evaporation temperature in the AC/GS is close to the evaporation temperature of the MT level, when it is used for air conditioning purposes. However, this stage operates under superheat conditions. Overfeeding this evaporator could also provide a better efficiency because the supply temperature in the air conditioning is 7 °C, according to measurements. The evaporation temperature of the LT stage is almost constant around -30°C (see Fig. 2), having 10K superheating the whole year regardless the ambient temperature.

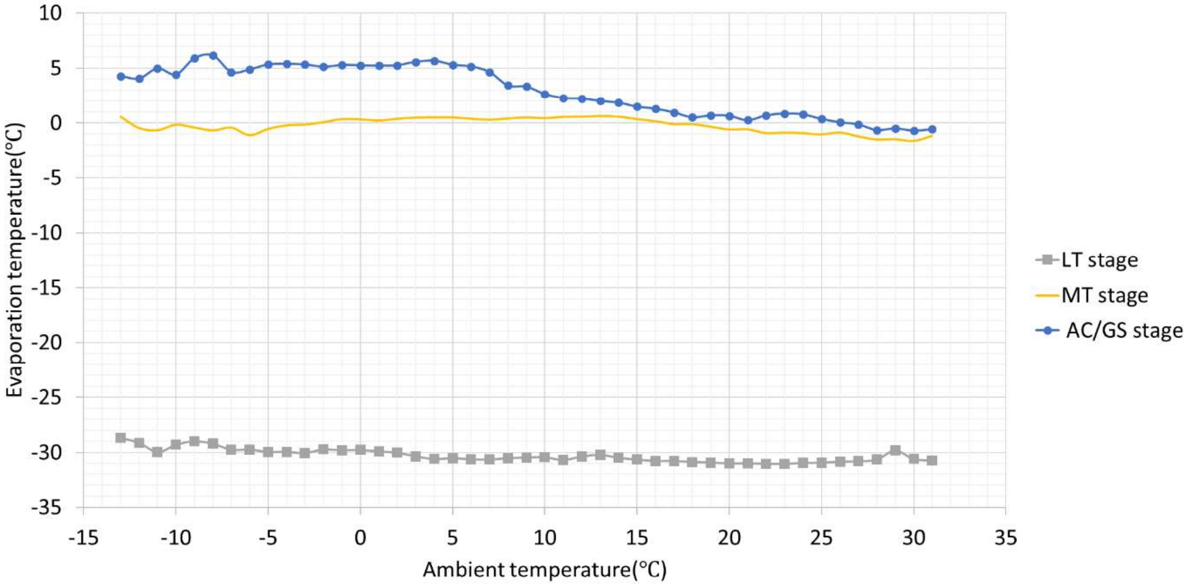

Figure 2: Evaporation temperatures in the refrigeration unit vs ambient temperature

The COPs as are presented in Fig. 3. The COP_{MT} reaches 8.5 which is higher than 7.5 of previous theoretical study presented by Karampour & Sawalha (2018). However, it is not as high as it is expected because COP_{MT} is calculated counting the superheating effect because of the discharge line of the booster compressor, in contrast to the previous study. Indeed, the COP_{MT} becomes lower when the ambient temperature is lower because the MT cooling demand is decreased while the LT cooling demand doesn't change (see fig. 4), enforcing this superheating effect. The superheating effect also explains why the COP_{AC} is higher than the COP_{MT} even if the evaporation temperature is almost the same in these two stages. The $COP_{Space\ heating}$ is decreased when the ambient temperature is low because the discharge pressure is increased to be provided more heating to the building. The $COP_{Space\ heating}$ reaches a peak of 7.5 instead of a peak of 4.8 as expected from a previous study (Karampour & Sawalha, 2018) because the return temperature of the space heating is between 24 °C and 26 °C. This return temperature helps the system to recover more heat in 2nd de-superheater (see Fig. 1) where the refrigerant's exit temperature fluctuates around 27 °C, in previous study this was set to 35 °C (Karampour & Sawalha, 2018).

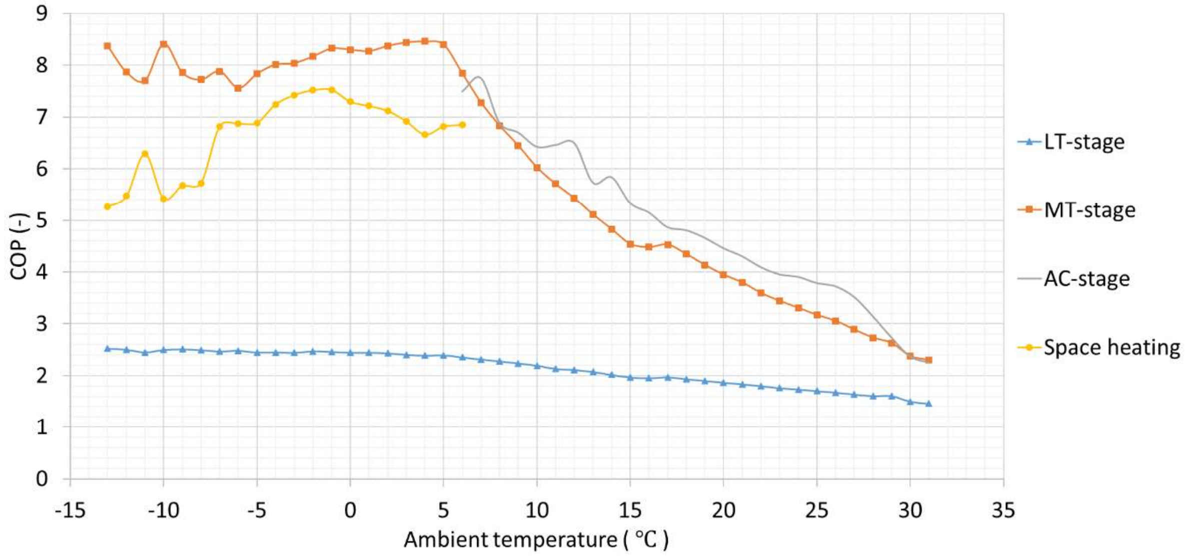

Figure 3: Coefficients of performance vs ambient temperature

The MT demand is increased from 60 kW to 100 kW between summer and winter, whilst the LT demand is almost constant to 30 kW, as can be observed in Figure 4. The ratio between the two cooling demands (MT/LT) is 2.3 which lower than 3 that is expected from previous studies (Karampour & Sawalha, 2018) (Sawalha et al., 2017). Explanation is the fact that the supermarket has more vertical cabinets in the LT stage than usual, and all the MT cabinets have glass doors.

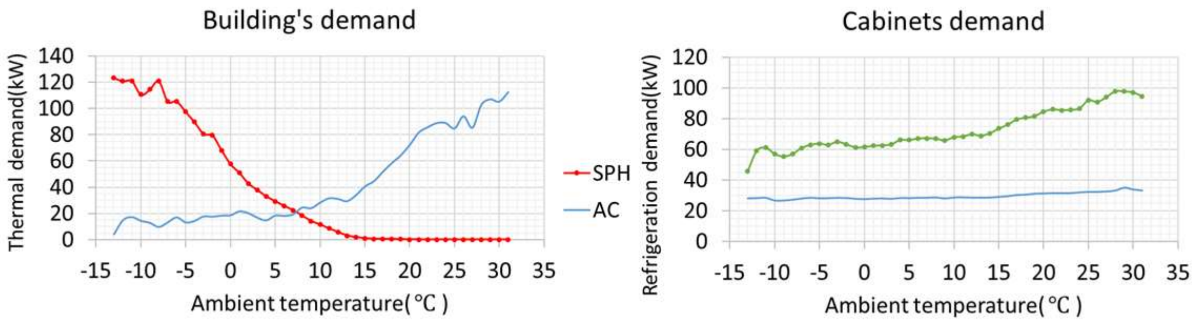

Figure 4: Supermarkets's thermal demands vs ambient temperature: space heating and AC (left), refrigeration (right)

The heat demand starts when the ambient temperature is lower than 14 °C (see gray line in Fig. 4 right), whilst the average demand for hot water is 9 kW constantly regardless the ambient temperature. Air-conditioning is provided the whole year by two air conditioning sources, free cooling and load from the refrigeration cycle. The refrigeration unit starts providing air conditioning when the ambient temperature is higher than 6 °C. So, free cooling is provided for lower ambient temperature in Fig. 4, which is result of bad controlling, and that increases the heat demand in the system.

The geothermal loop (see green line in Fig.1) provides free cooling and sub-cooling in the summer time; however, it is used as heat source when the heating demand is higher than what the refrigeration system can provide, in the winter time. Thermal loads in and out of the ground in kW are presented in Fig. 5. The ground is used as additional heat source when the ambient temperature is lower than -5 °C only in some peak demands, which explains why the average extracted load is usually less than 20 kW.

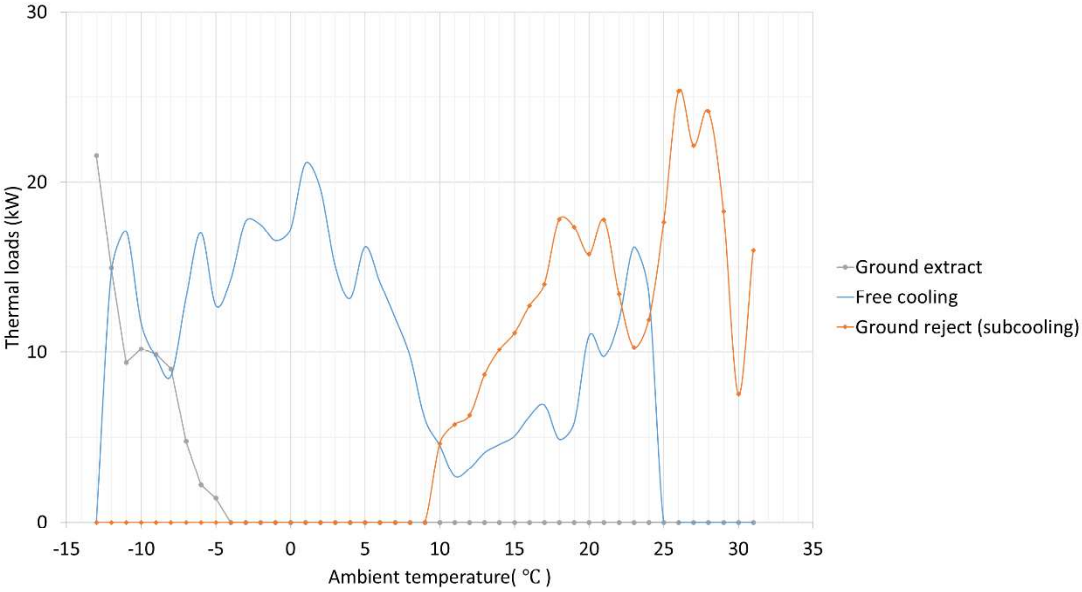

Figure 5: Ground usage

The ground is used for subcooling purposes when the ambient temperature is higher than 10 °C, and for free cooling when the ground's temperature is cold enough. Indeed, no free cooling is used when the ambient temperature is higher than 24 °C because the ground's temperature is too high to cool down the building due to the subcooling. However, free cooling could be used as an additional load even if the refrigeration unit provides the main air conditioning load, after a comparison between Fig. 4 right and Fig. 5.

CONCLUSION

Field measurements of a supermarket in Sweden for one year are analyzed. The frequency of the compressors is used to estimate the mass flow rate of the refrigerant in each stage, since no mass flow meter is integrated. Performance data sheets from compressor manufacturers were used to generate the total efficiency curve at different pressure ratios.

The supermarket operates under very efficient conditions. The MT level evaporation temperature of around 0 °C provides COP_{MT} up to 8.5. The 24 °C to 26 °C water return temperature from space heating system provides $COP_{Space\ heating}$ up to 7.5.

The MT demand varies from 60 kW to 100 kW, while the LT demand is around 30 kW. The MT stage becomes more efficient, resulting to 2.3 cooling demands ratio.

False heating demand is created to the building because of free cooling in the cold days. The space heating demand would be lower if this extra cooling load is avoided. This shows the importance of following up the system operation to make sure it runs properly.

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