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Theoretical analysis of the power and annual energy demands of a supermarket with a CO2 refrigeration cycle

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1. ABSTRACT

This paper investigates the theoretical energy outlook of a supermarkets in Stockholm, as well as the energy efficiency of its refrigeration unit. The refrigeration unit is a CO2 trans-critical booster system with air conditioning and geothermal storage integration into the medium temperature level. This stage is operated under overfeed conditions (zero internal superheating) thanks to liquid ejectors. On the other hand, the freezers operate under direct expansion with an optimum superheat. The supermarket is heated up by reclaimed heat from the refrigeration unit. Two heat exchangers are integrated after the high-stage compressors where water is heated for tap water and space heating.

The simulation is done for a supermarket in the design stage as part of a study that will continue by collecting data from the supermarket when is in operation to evaluate its performance and compare to the results from the design phase. The cooling demand of the medium temperature level is estimated between 100-140 kW depended on the ambient conditions and around 40 kW for the freezers. The COP in the medium temperature level is expected to be up to 7.8 and 2.5 for the low temperature level. The space heating COP is expected to be up to 7.3.

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

2. INTRODUCTION

Refrigeration and air conditioning sector is the biggest CO2 emitting sector in Europe, counting to 81% of fluorinated gas emissions in 2017 (EEA, 2019). Supermarkets are part of this sector, because of their, refrigeration, air conditioning, and heating demands. Refrigeration units typically consume about 50% of the total power consumption in an average Swedish supermarket according to Arias (2005). Refrigeration units are also used for air conditioning and heat production in many of the modern supermarkets.

Carbon dioxide as a refrigerant is an environmentally friendly solution for supermarket applications because of its low GWP (Global Warming Potential) which is one of the reasons in combination with low emission regulations why more than 14000 stores worldwide use carbon dioxide refrigeration solutions (EIA, 2018). Heat recovery from carbon dioxide refrigeration systems is highly efficient this is one of the main reasons why these systems became standard in Northern Europe (Sawalha, 2013).

In this study, the refrigeration system is not just a refrigeration unit but it is all-in-one energy system where the main refrigeration unit provides also air conditioning, domestic hot water heating, and space heating with geothermal system integration to provide the highest potential for the lowest energy footprint.

This theoretical study is part of an extended research, where methods and tools, used to simulate the performance of thermal energy systems in supermarkets will be verified. The system of this study is compared to other systems. The results in this study will also be compared to operation data when the system is running.

The calculation tool CyberMart (Arias, 2005), Earth Energy Designer (EED) software (Blomberg et al.2017) and Engineering Equation Solver software (EES) (Klein, 2015) are used for the calculations in this study.

3. SYSTEM DESCRIPTION AND BOUNDARIES

The supermarket is located in Stockholm, Sweden, consisting of the main supermarket building and a small pharmacy store. The building is a heavy construction without many windows (20 m^2 per facade) in order for heat gains or losses to be avoided, since the most energy efficient solution is without windows (Kauko et al., 2016). The total area of this building is 6750 m^2 and the sale area is estimated to be 5000 m^2, which is considered as a hypermarket (EY, 2014). The designed cooling capacity of the Medium Temperature (MT) level is 160 kW, including 48 kW for the cooling rooms. The designed capacity of the Low Temperature (LT) level, which is the freezing level, is 50 kW, including 15 kW for the freezing rooms. There are six boreholes of 220 m length each connected to the refrigeration unit which are used as auxiliary heat source, since the supermarket is not connected to district heating network. Heaters are also integrated in the heating system as a backup solution in case of failure or maintenance.

The refrigeration unit is a two-stage booster carbon dioxide unit, shown in see Fig. 1, with direct expansion in the cabinets. The MT temperature cabinets operate under overfeed conditions, thanks to liquid ejectors. The advantage of overfeeding the evaporator; i.e. absence of internal superheat, is the possibility to run the system at higher evaporation temperature. Therefore, the evaporation temperature of the MT stage is assumed to be around -0.5 °C, this assumption is based on field measurement analysis of a relatively newly build supermarket. The heat exchanger that is connected in parallel to the MT cabinets, denoted as Air Conditioning/Ground-Source (AC/GS) (see Fig. 1), also operates under overfeed conditions. It provides air conditioning in the warm days, i.e. injecting heat in the ground, and it provides heat from the ground in the cold period. The LT cabinets operate with direct expansion with assumed internal superheat of 10 K. The overfeed solution, applied at MT, is not implemented at LT because of the relatively low refrigeration demand at LT; hence, the energy use savings due to overfeeding may not justify the installation cost. The evaporation temperature in this case is assumed to -30.5 °C, according to field measurement analysis. Heat is reclaimed by two heat exchangers connected in series after the high stage compressor as it is illustrated in Fig. 1. The first heat exchanger provides hot water and space heating to the building. This is connected to an accumulation tank, where water in the tank is heated up by a coil inside this tank. The second heat exchanger is connected to a second space heating loop. The return temperature of the water in the second heat exchanger is assumed to be 24 °C, based on new supermarket observations.

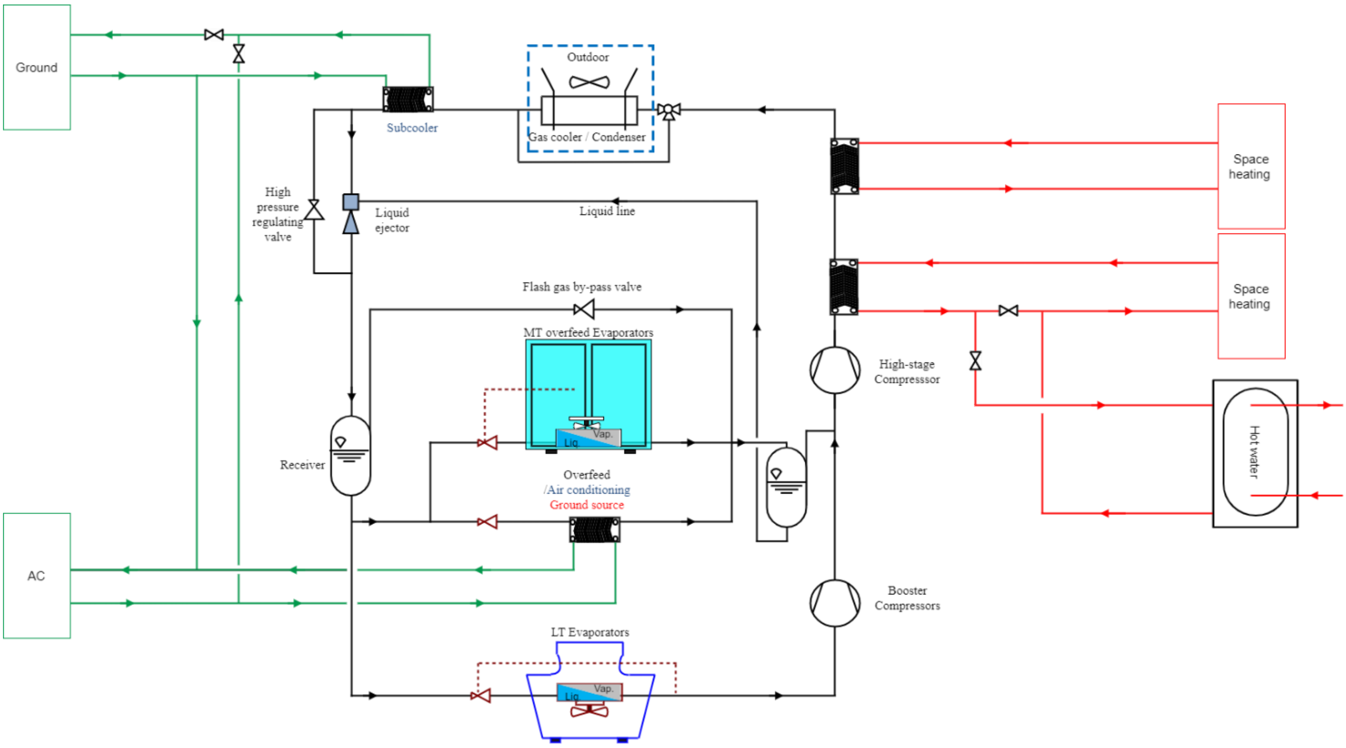

Figure 1 Refrigeration units schematic

Unutilized heat is rejected to the ambient via gas-coolers/condensers. Heat is also rejected to the ground via a heat exchanger connected to the ground source brine loop. This heat exchanger, which is called subcooler in

Fig. 1, is used when ground temperature is lower than the ambient and the ground is not used as a heat source. The heat rejection to the ground provides thermal balance to the ground in case the ground is needed as a heat source in the winter.

4. METHODOLOGY

CyberMart software is used for the hourly demand calculation through a year of the supermarket. This software is a tool which is developed at the Department of Energy Technology, KTH, (Arias, 2015). The tool calculates the cooling, heating and air conditioning demands according to the characteristics of the building, the occupancy, equipment and the climate.

The power consumption of the refrigeration cycle is estimated with the help of an EES code developed in this study. This tool simulates the operation of the refrigeration cycle in Fig. 1 under different ambient conditions. EED software is used in parallel to EES to estimate the subcooling effect in the refrigeration system when the conditions allow for subcooling. The temperature after the subcooler is determined after iterations between the two software. The subcooler is used when the refrigerant's temperature after the gas cooler is higher than 18 °C. The control strategy of the refrigeration cycle is based on commercial controllers (Danfoss, 2014) which agree with Karampour's suggestions (Karampour et al., 2019).

The annual energy demands as well as the cooling coefficients of performance (COP) per stage are calculated with the help of the EES code. The cooling COPs are calculated for floating condensing conditions, where the system is controlled so the condensing temperature is as low as possible, following the ambient temperature and not the heating demand.

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

$$COP_{MT} = \frac{Q_{MT}^{tot}}{E_{HS,fl}}, \qquad \text{Eq. (1)}$$

where $E_{HS,fl}$ is the power consumption of the high-stage compressor under floated conditions in the condensing side. Q_{MT}^{tot} is the total capacity in the MT level included the heat loads from the LT stage and the air conditioning, as shown in Eq. (2).

$$Q_{MT}^{tot} = Q_{MT} + Q_{AC} + Q_{LT} + Q_{LT,xSH} + 0.93 * E_B, \qquad \text{Eq. (2)}$$

where Q_{MT} is the cooling capacity of the MT level, Q_{AC} is the cooling capacity of the air conditioning, Q_{LT} is the cooling capacity of the LT level, $Q_{LT,xSH}$ is the heat gain in the LT suction line because of external superheating and E_B is the power consumption of the booster compressor. In this evaluation, 7% of heat losses are assumed in the booster compressor (Berglöf, 2005).

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

$$COP_{LT} = \frac{Q_{LT}}{E_{booster} + \frac{Q_{LT} + Q_{LT,xSH} + 0.93 * E_B}{COP_{MT}}}, \qquad \text{Eq. (3)}$$

The air conditioning level COP_{AC} for the booster system is the same as COP_{MT} because air conditioning is provided under the same conditions as MT capacity.

The space heating COP (COP_{SH}) for the booster system is calculated as:

$$COP_{SH} = \frac{Q_{SH}}{E_{HS,HR} - E_{HS,fl}}, \text{Eq. (4)}$$

where Q_{SH} is the space heating capacity and $E_{HS,HR}$is the power consumption of all the high-stage compressor under the heat recovery mode.

5. RESULTS

The calculated MT stage cooling demand, using CyberMart software, is around 100 kW in the winter period, as shown in Fig. 2. According to same figure this demand is expected to be increased by up to 40% in the summer period, reaching 135 kW. The LT stage cooling demand is calculated to be around 40 kW in the winter period, whilst this demand is be increased up to 20% in the summer period (Fig. 2).

The air conditioning is needed when the ambient temperature is higher than 19 °C, which is a result after iterations as steady indoor conditions to be kept in the retail area. Otherwise, heating and air conditioning would be provided to the building when the ambient temperature is between 15 °C and 19 °C. The air conditioning demand can be up to 60 kW in a warm day.

The supermarket building needs space heating when the ambient temperature is lower than 14 °C (see Fig. 2). The space heating demand has a linear profile to the ambient temperature, but the maximum heating demand is 90 kW. The building is designed in a more efficient way, decreasing the heat losses in the winter period. The hot water demand is assumed constant of 2 kW when the supermarket is in operation.

The total annual MT cooling demand is calculated to 920 MWh/year, whilst for the LT stage is 338 MWh/year. The air conditioning demand is not that significant, it is only 13 MWh/year. This low air conditioning demand led to this solution (Fig. 1) where the AC evaporator is in the same temperatre level as the MT cabinets. The heating demand is 213 MWh/year, counting space heating and domestic hot water.

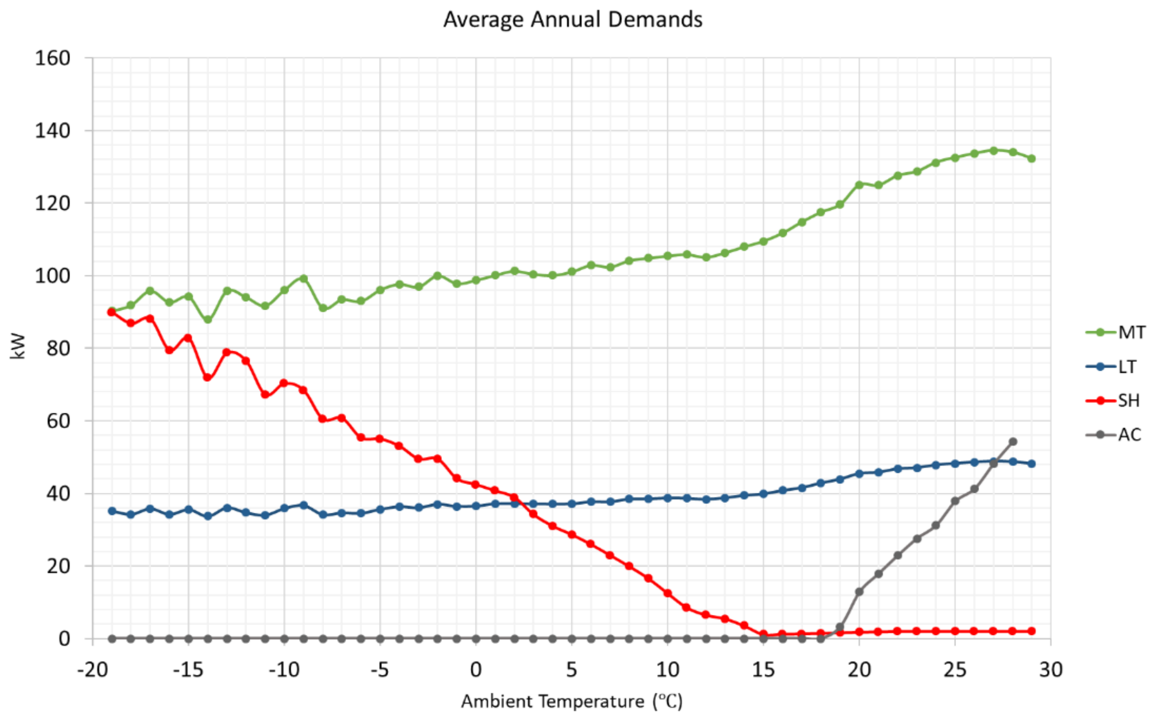

Figure 2: Profile of annual demands

COP_{MT} can be observed in Fig. 3 to be constant at 8.5 in the winter period because of the fixed conditions before the expansion device. COP_{MT} decreases when the ambient temperature increases higher than 6 °C, reaching 3.6 when the ambient temperature is 29 °C. COP_{MT} is higher than 7.5 of the previous study (Karampour and Sawalha, 2018) because of higher evaporation temperature. Indeed, the evaporation temperature was -8 °C and not -0.5 °C as in this study. The ground source subcooler also contributes to this higher COP in the summer period, as 37 MWh/year of heat is rejected to the ground.

COP_{LT} can be seen in Fig. 3 to be constant at 2.3 during the winter period for the same reason as for COP_{MT}. This becomes lower when the ambient temperature is higher than 6 °C, reaching 1.9 when the ambient temperature is 29 °C. This follows the trend of the previous study for the winter period (Karampour and

Sawalha, 2018). However, COP_{LT} that is calculated in this study is slightly higher in the summer period comparing to the older study because of the ground source subcooler.

The building is heated up with free energy when the ambient temperature is between 14 °C and 6 °C. The available heat in the de-superheaters in floating condensing mode is sufficient to cover the heating demand; i.e. no need to increase the discharge pressure for heat recovery. Which results in infinite COP_{SH} for ambient temperatures higher than 6 °C, it can be observed that no values for COP_{SH} are plotted for ambient temperatures higher than 6 °C in Fig. 3. The temperature return of the space heating system is set to 24 °C as it has already been mentioned, which allows COP_{SH} to reach 7.3 instead of 4.8 in previous earlier study (Karampour and Sawalha, 2018), where the water return temperature was assumed 30 °C. According to calculations no extra heat from ground is needed, since the heat which comes from the cabinets is enough.

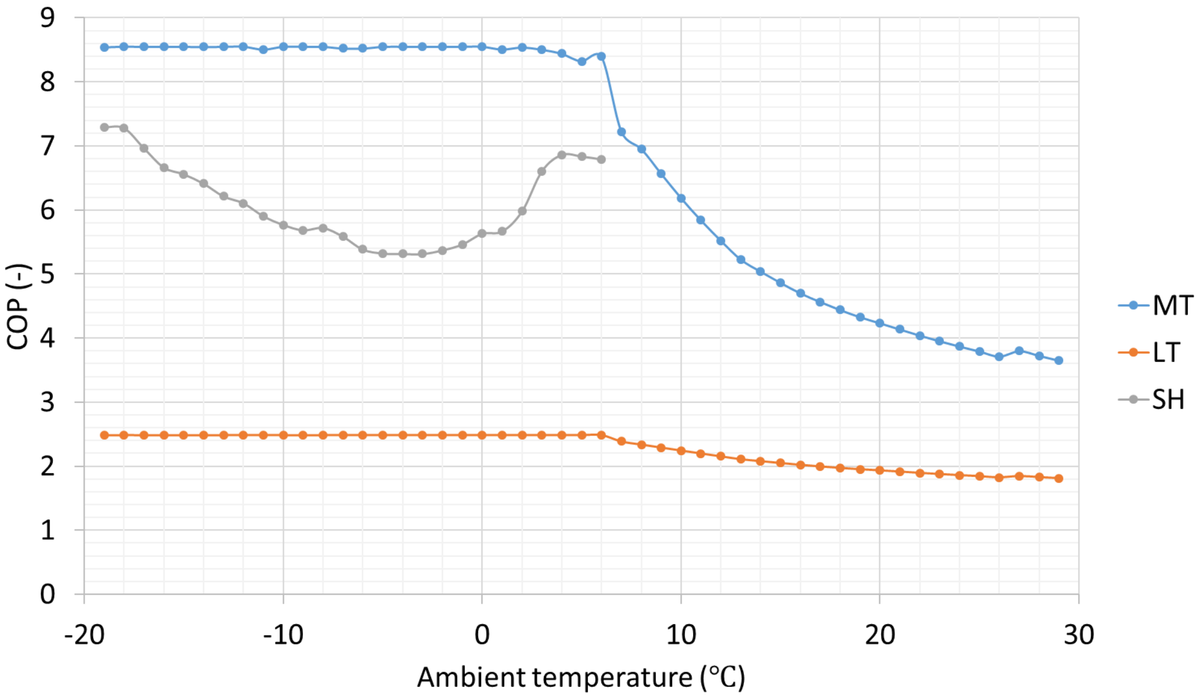

Figure 3: Coefficients of performance

The annual energy consumption of the system for refrigeration, air conditioning and heating is estimated to 346 MWh/year. The high-stage compressor consumes 248 MWh/year while the remaining 98 MWh/year is consumed from the booster compressor.

6. CONCLUSION

The theoretical energy outlook of a future supermarket has been investigated. A combination of three software is used for the design and the evaluation of the system.

Evaporation temperature of 0 °C in the MT level provides up to 8.5 COP_{MT}, which is 15% higher comparing to evaporation temperature of -4.3 °C.

The 24 °C water return temperature from space heating system provides $COP_{Space\ heating}$ up to 7.3, which is 50% higher than in case of 30 °C water return temperature.

The ground source can provide more efficient operation in the summer period, providing subcooling in the system. However, it is not used as heat source because of low space heating demand.

The MT cooling demand increases 40% in the summer period, while the LT cooling demand increases 20% in the summer.

7. ACKNOWLEDGEMENTS

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