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COLD THERMAL ENERGY STORAGE INTEGRATION IN A LARGE INDUSTRIAL REFRIGERATION SYSTEM

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ABSTRACT

Global warming is one of the greatest challenges our society faces today, and researchers strive to find solutions to reduce the emissions of greenhouse gases that accelerate the global warming effect. This paper describes a concept for a large cold thermal energy storage (CTES) system integrated in an industrial NH_3/CO_2 cascade refrigeration system for a poultry processing plant. The refrigeration system is fully centralized while oil-free CO_2 is pumped to the freezing and cooling equipment. The CTES consists of closed tanks that contain stacks of heat exchanger plates with circulating CO_2 on the inside and a phase change material (PCM) in the tank. During charging, the CO_2 evaporates inside the plates while the PCM changes phase from liquid to solid. The purpose of CTES is to reduce daytime peaks in the energy use, e.g. charging the storage during night and weekends and discharging during times of peak refrigeration demand. The performance of the system is investigated through simulations with Modelica/Dymola.

Keywords: Industrial refrigeration, Cold thermal energy storage, Ammonia, Carbon Dioxide, PCM

1. INTRODUCTION

Our world faces a tremendous challenge concerning the problem of global warming. Researchers strive to find solutions to reduce emissions of greenhouse gases from industry, households and transportation. During the last the last 30 years energy efficiency has played an important role in reducing the final energy use in industrialized countries. Due to lower gains than in earlier decades, the IEA emphasizes the importance of accelerating energy efficiency improvements in the near future (Taylor et. al, 2009). The Kigali amendment to the Montreal protocol ensures phase-down of high global warming potential (GWP) refrigerants as a measure to limit the contribution of climate change from the refrigeration sector and limit the increase in global temperature to below 2°C, as described by the Paris Agreement. A satisfactory replacement to the synthetic refrigerants affected by the Kigali amendment are the natural refrigerants CO_2, ammonia and hydrocarbons. These are the most suitable long-term alternatives in refrigeration and air-condition systems (Bolaji and Huan, 2012).

NH3/CO_2 cascade refrigeration systems have been studied intensively in the past. Both theoretical and experimental studies demonstrate similar performance to HFC-based cycles, in addition to avoiding the use of high GWP refrigerants. For low evaporating temperatures in the range -35 to -50°C, the NH_3/CO_2 cascade demonstrates comparable performance to a R404A two-stage cycle (Messineo, 2012). For freezing applications CO_2 is a good option for the bottom cycle in the cascade, and experiments using CO_2 in the low temperature stage show a COP improvement of maximum 19.5% over a two-stage NH_3 system when the evaporating temperature are in the range of -40 to -50°C (Dopazo and Fernañdez-Seara, 2010). Regarding the high temperature circuit of the cascade, NH_3 demonstrates higher COP with moderate superheat and subcooling compared to R404A using CO_2 as the low-temperature circuit in the cascade (Getu, 2007). Contrary to traditional direct expansion (DX) systems, designing a large refrigeration system for operation in a food processing plant to work with a secondary refrigerant circuit have multiple advantages, including reduction of primary refrigerant charge and avoiding harmful/toxic substances near the product in case of leakage. CO_2 indirect systems with R404A as the primary refrigerant has shown performance very close to traditional

R404A-DX systems in supermarket applications, due to favorable thermo-physical properties and low pumping power requirements (Sawalha and Palm, 2003).

This paper combines some of these features to describe a concept for a large-scale CTES system integrated into the refrigeration system for a large poultry processing plant that is under planning in Norway. Targets for the plant includes high energy efficiency, innovative solutions to refrigeration load shifting and reducing peak electricity use. One of the largest contributors to the electricity demand in such a plant is the refrigeration system, which is highly dependent on the throughput of goods and products in the production facility.

2. SYSTEM DESCRIPTION AND MODEL

2.1 Motivation

The motivation for investigating the integration of CTES in an industrial refrigeration system is mainly divided into three aspects; peak load shifting, better utilization of refrigeration equipment and contributing to lower emissions of greenhouse gases. Distinct peaks characterize the refrigeration load in many industrial refrigeration systems, in particular food-processing plants, which is the focus of this paper. In these facilities the refrigeration load is mainly caused by the throughput of goods in the plant, resulting in high refrigeration demand during the daytime operation. During night-time, the load on the refrigeration system is mainly due to operation of the cold storage facilities, which typically requires much less capacity than the daytime operation. For a centralized plant, this demand pattern results in part-load operation of the refrigeration system for a significant fraction of the day.

The electricity price is typically highest during the day, as it is the time of highest load on the electricity grid. By integrating CTES into the refrigeration plant, a fraction of the total electricity use can be shifted to night hours when the cost is lower. In addition to lower electricity cost, lowering the maximum peak use of electricity can reduce the annual power tariff fee paid to the grid companies. This fee is typically based on the maximum power required from the grid during some period by the consumer, i.e. over a month or even a whole year. Thus, reducing the peak power requirement of the plant can result in significant savings for the plant owner. Two approaches to integrating a CTES system in a refrigeration plant is described below.

1) By reducing the peak cooling demand by load shifting, the installed compressor capacity can be reduced and thus induce savings on the compressor investment costs. This may however be outweighed by the investment cost for the CTES system.
2) Having the same installed compressor capacity as required without CTES integration, but having the flexibility to charge the CTES system as soon as the operation of the plant is off-peak and when low-cost electricity is available in the grid. Offers better flexibility for the plant operator, and a possibility to increase plant capacity in the future.

The system considered in this paper is mainly concerned with the approach described in point 2) in the list above. In addition to providing flexibility for charging, the CTES system offers a backup for refrigeration in the case of a power failure.

2.2 System Description

The system concept presented in this paper consists of two different parts integrated together; the industrial cascade refrigeration system and the CTES system. A simplified process and instrumentation diagram for the plant is shown in Figure 1 below. The low temperature (LT) part of the cascade system consists of a compressor circuit employing CO_2 as working fluid. An ammonia (NH_3) compressor circuit serves as the high temperature part of the cascade, delivering heat to the condensers in the circuit. The refrigeration demand in the poultry plant is due to deep freezing and chilling of products with air temperature demands of approximately -40°C and +2°C, respectively. To serve the cooling demand at each temperature level, oil-free CO_2 is pumped from the machine room, which is located on the outside of the main building, to the process equipment. Spiral freezers, chillers and storage rooms are the largest contributors to the refrigeration load, and the liquid CO_2 is distributed to the various refrigeration equipment in the plant by means of refrigerant pumps. The two oil-free CO_2 circuits are referred to as the LT circuit and a medium temperature (MT) circuit.

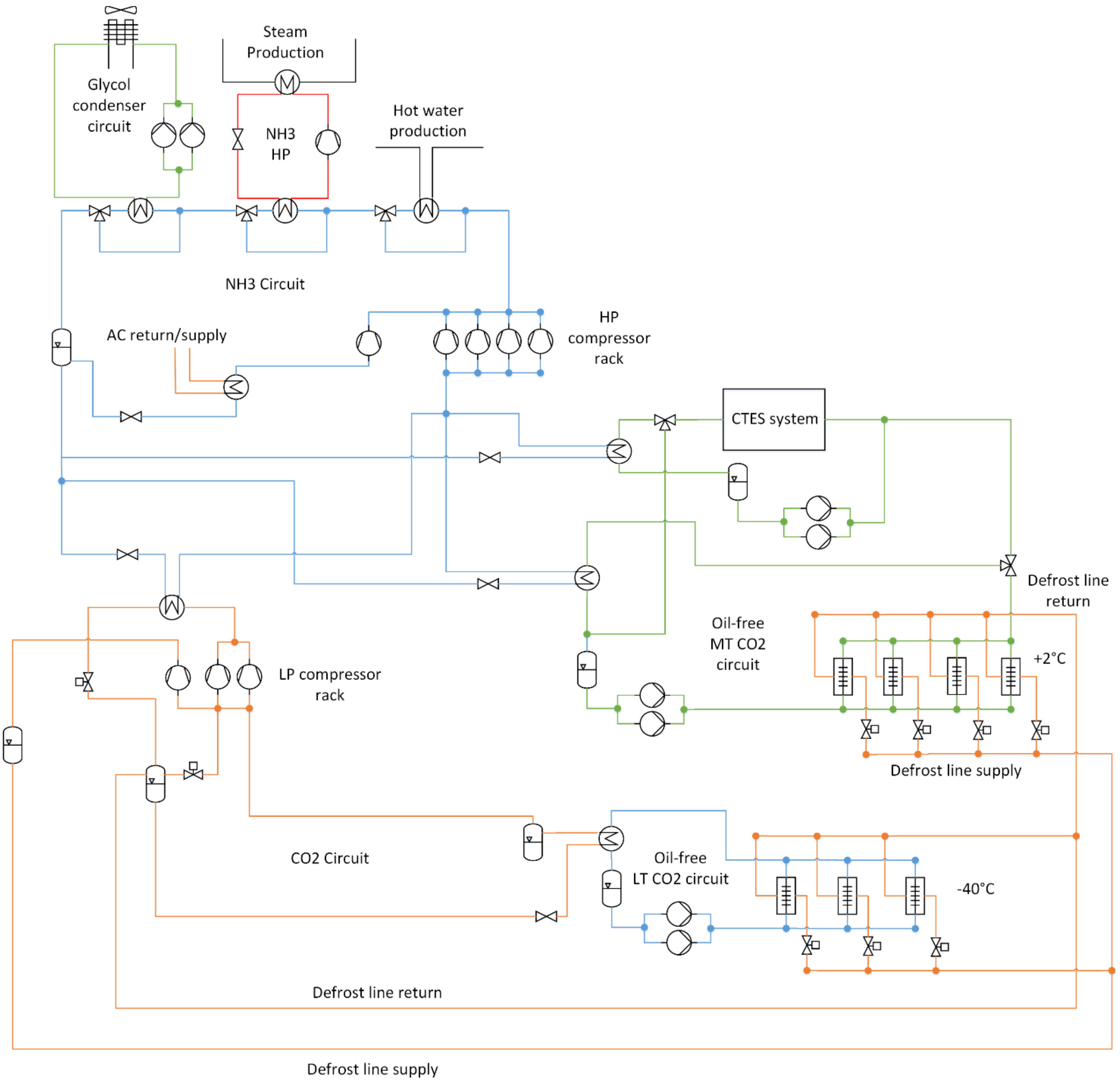

Figure 1: Simplified process and instrumentation diagram for the cascade refrigeration system in the plant.

The oil-free CO_2 is evaporated in the process equipment and then returned to the machine room and heat exchanged with CO_2 from the centralized compressor circuit, functioning as the low temperature part of the cascade. As the oil-free CO_2 is condensed, the liquid is drained to a receiver before being distributed in the plant by the pumps again. The heat load from the oil-free LT circuit is transferred to the CO_2 compressor circuit by means of a plate heat exchanger. The refrigerant in the compressor circuit is evaporated, and delivered to the suction line of the LP compressor rack. From the discharge of the LP compressor rack, the hot CO_2 gas is condensed in the cascade plate heat exchanger, and throttled to an intermediate pressure receiver. The flash gas is throttled to evaporation pressure in a flash-gas bypass valve, and controls the receiver pressure. A high-pressure control valve is used to set the high side pressure in the CO_2 circuit. The CO_2 compressor circuit handles defrosting of all the evaporators in both the MT and LT oil-free circuits by means of hot gas defrosting. Due to circulating refrigerant at sub-zero temperatures in the evaporators, moisture from the products and in the surrounding air freeze on the tube and fin surfaces. The ice layer grows over time and causes blockage of the air stream, and increases heat transfer resistance by acting as an insulator on the tubes. A compressor in the LP compressor rack maintains the pressure in a second receiver, which functions as a reservoir for the defrosting lines. As defrosting is required, valves opens to the evaporators, and hot refrigerant gas is condensed in the secondary set of pipes within the evaporator blocks while melting the ice. The condensed refrigerant is then returned to the intermediate pressure receiver.

The high temperature part of the cascade comprises of a NH_3 compressor circuit, handling the refrigeration load from the low temperature part of the cascade, oil-free MT circuit, air conditioning and charging of the CTES system. From the discharge line of the HP compressor rack, the hot refrigerant gas is delivered to one or more of the condensers. The plant has a substantial need for both low-pressure steam and hot water, so heat recovery from the refrigeration system is advised here. Hot water is needed in large amounts during washing and sanitizing of the process equipment in the plant, and steam is used for numerous applications, e.g. in ovens for grilling the poultry after processing. Although not shown on the P&ID in Figure 1, preheating of hot water is also available from de-superheating the discharge CO_2 gas from the LP compressor rack. A high-temperature NH_3 heat pump is connected to the refrigeration system to upgrade the heat for steam production, delivering up to 90°C hot water at outlet. The share between hot water preheating and water to steam production is controlled by the demand for each utility. If there is any further excess heat available, a condenser connected to a secondary glycol circuit rejects the remaining heat to the ambient air by dry coolers. A secondary dry cooler circuit is used in order to limit the charge of NH_3 in the plant. The condensed refrigerant is then drained to a receiver to again be distributed to the various points in the system.

After cleaning and sanitizing the process equipment, the air and the facility needs to be properly dried to avoid bacterial growth on surfaces. This process is lengthy and involves heat exchanging the air from the facility with outside air in order to remove as much of the moisture content as possible. The final stages often requires cooling of the air in the air-handling unit by means of a glycol to reach acceptable moisture levels in the facility. This refrigeration demand is integrated as a utility in the centralized cascade system, where NH_3 is throttled and evaporated by exchanging heat with a glycol circuit. The glycol in this secondary circuit is pumped to the air-handling unit to cool the air from the plant, where the typical set point temperature for the supply of glycol is +7°C.

The oil-free MT CO_2 circuit operates by the same principle as the oil-free LT CO_2 circuit, working as a secondary fluid to the cascade system and transferring the heat from the products to the compressor circuit. In addition, the MT CO_2 circuit is integrated with the CTES system to enable shifting some of the compressor work from peak load hours in the plant to after working hours. In Figure 1 the CTES system is shown as one unit in order to reduce the level of details in the diagram. A more detailed schematic of the CTES system is shown in Figure 2. The CTES system consists of several modules connected in parallel with the MT oil-free CO_2 circuit. One module comprise of a steel tank with a stack of heat exchanger plates inside. The figure shows an example of 6 modules, with three and three modules grouped on the same main pipe that can be placed inside a standard 40ft shipping container if the CTES system is to be placed outdoors. The heat exchanger plates are two steel plates with channels on the inside where CO_2 is circulated to evaporate or condense, depending on the mode of operation. The plates in the stack has a certain distance between them, and the PCM solidifies on each side of the plate as CO_2 is evaporated on the inside. The plates are connected by a manifold on each end, joining all plates in the stack for a common exit pipe and entry pipe from the steel tank. The tank is filled with a PCM that has an appropriate phase-change temperature for the application. The concept of this CTES system is modular, i.e. the capacity of the storage can be scaled to fit the purpose both in terms of condensing duty in kW or as total storage capacity in kWh. This paper describes the integration of a CTES system in a poultry processing plant, but the same system can in principle be integrated into any refrigeration system with oil-free refrigerant circulation or another secondary liquid refrigerant. Applications can be extended by manipulating the phase-change temperature of the storage media by using salts, glycols or alcohols for freezing-point depression to the required level. For use in the poultry processing plant considered in this paper, a phase change temperature of approximately -10°C is required in order to condense the evaporated CO_2 refrigerant in the oil-free MT circuit.

Charging of the CTES system is done by isolating the CTES system from the rest of the oil-free MT CO_2 circuit, so that the evaporation pressure of the CO_2 can be lowered to below the phase-change temperature of the PCM in the tanks, without affecting the rest of the circuit. This is done by operating the two directional control valves in the circuit. The refrigerant pumps connected to the CTES system circuit is activated, and pumps liquid CO_2 to the CTES tanks where it is evaporated as it exchanges heat with the media in the tank. As the liquid CO_2 evaporates, the PCM solidifies on the surface of the plates, building an increasingly thicker layer of solid. The process continues until either of two situations occur; the layer has grown sufficiently thick so that two layers of solid from two neighbouring plates meet on the middle, or a peak load refrigeration load situation occurs, triggering a change from charging to discharging of the CTES system. During charging of the CTES system, the refrigeration load is satisfied by the cascade system only, isolating the CTES system. This means the CTES system is operated either in charge, discharge or standby mode.

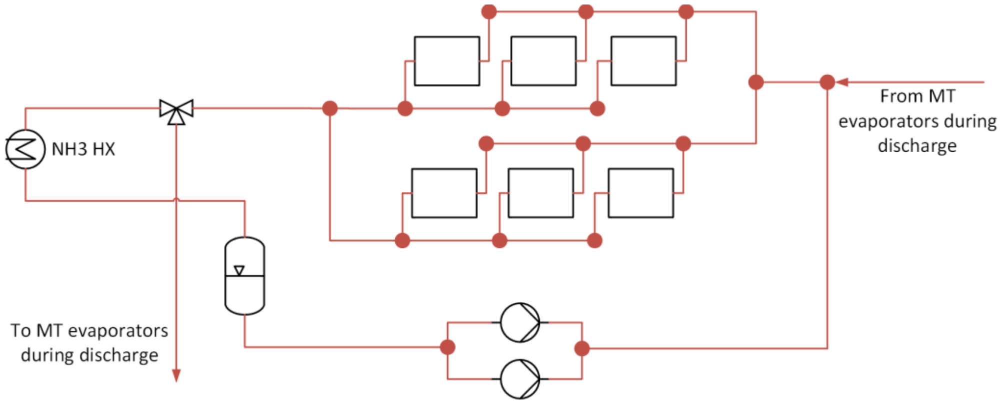

Figure 2: Schematic of the CTES system integrated into MT circuit.

When the CTES system is operated in discharge mode, some of the condensing duty from the MT oil-free CO_2 circuit is transferred from the plate heat exchanger connected to the NH_3 cascade circuit to the CTES system. This can be done by operating the two control valves in the circuit, letting some of the evaporated CO_2 to the CTES modules. The refrigerant pressure is now the same in the entire oil-free MT circuit, as required for the process equipment in the plant. As the evaporation temperature of the refrigerant now is higher than the freezing temperature of the PCM in the CTES tanks, the refrigerant condenses as it passes on the inside of the heat exchanger plates. The condensed CO_2 is drained to the receiver and distributed by the refrigerant pumps. The condensing duty in the MT circuit is now shared between the CTES system and the NH_3/Oil-free CO_2 plate heat exchanger, i.e. shared between actual compressor work and stored compressor work. During off-peak hours, when the CTES system is charging, the plant is using more electrical power than what is actually needed for serving the refrigeration demand. During peak hours the plant is using less compressor capacity than what is required according to the refrigeration demand. The fraction of condensing duty that is handled by the CTES system is dependent on its total available heat exchanger surface. The total amount of energy stored in the CTES system is dictated by the total mass and properties of the PCM that is available for freezing/melting in the tanks.

2.3 Simulation Model and case description

Simplified simulation models were developed in Dymola[1] for investigating the performance of the refrigeration system integrated with CTES integration. The software add-on TIL Suite[2] to Dymola was used for retrieving thermodynamic properties for refrigerants and as the source for standardized process components, i.e. valves, compressors, heat exchangers and more. Since the focus of this paper is on the effect of integrating CTES, the low temperature CO_2 part of the cascade was not modelled in detail, but represented by refrigeration load on the cascade heat exchanger. Except for the high pressure (HP) compressors, the high-pressure side of the NH_3 circuit was not included in the model. Further assumptions for simulations:

- Constant compressor isentropic efficiency of 70%
- All unintentional pressure drops are neglected
- Heat transfer coefficients are assumed constant throughout heat exchangers and equal to 2000 $W\ m^{-2}\ K^{-1}$ for evaporation/condensing of refrigerant
- Defrosting of evaporators are not taken into consideration
- Electric power to LP compressor rack is not taken into consideration

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[1] Dymola version 2018. Developed by Dassault Systèmes.
Web: https://www.3ds.com/products-services/catia/products/dymola

[2] TIL Suite version 3.5. Developed by TLK-Thermo GmbH. Web: https://www.tlk-thermo.com/index.php/en/software-products/til-suite

A plausible refrigeration load profile for a food processing plant was constructed to investigate how the integration of a CTES system enables shifting of compressor power and refrigeration load to off-peak hours. The load profile is shown in Figure 3 below, where MT load accounts for 60% percent of the total duty, and the rest originates from the LT level through the cascade heat exchanger. The refrigeration loads were scaled down compared to the expected numbers for the planned plant for simulation purposes. However, the demonstration of the load shifting principle still applies.

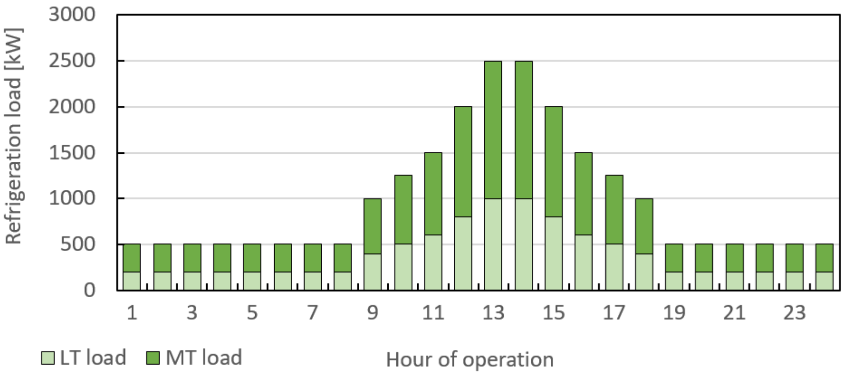

Figure 3: Refrigeration load over a working day

For comparison and evaluation of the CTES integration, two models representing the refrigeration system were developed in Dymola, one model with CTES integration and the other without. Except from including the CTES system, there is no difference between the two models. For the example case study presented in this paper, a total of six CTES modules were included. Specifications of the CTES system is presented in Table 1.

Table 1: Specifications of one CTES module used in simulations.

Data	Value	Unit
Phase-change medium	AdBlue	-
Enthalpy of fusion, PCM	270	kJ kg^{-1}
Freezing point	-11	°C
Total mass PCM in one module	4190	kg
Outer heat transfer area	852	m^2
Inner heat transfer area	825	m^2
Number of modules	6	-

The thermal storage model used to represent the planned CTES module is a recent tube-based storage model developed by TLK-Thermo included in an add-on thermal storage library to TIL Suite. The library features selection of PCM for use with the storage models. The parameter selection for the model was made in order to have comparable heat transfer area to that of a plate-based storage module, which is planned for the poultry plant. This choice was considered acceptable as a first investigation of CTES integration in a refrigeration system.

2.4 Results and Discussion

For this first investigation of the behaviour of the system, one working day was simulated. Based on the refrigeration duty in the plant given in Figure 3, the resulting compressor power for the case with and without CTES integration are presented in the upper half of Figure 4 below. The simulation is initiated at midnight when all PCM is liquid. The charging process is set in operation as the refrigeration demand is low and excess compressor capacity is available. For all CTES media to go from pure liquid to solid takes about five and a half hour, as can be seen in the lower half of Figure 4. The total compressor power increases by about 200 kW during this period compared to no CTES integration to handle the additional heat load from the CTES charging process.

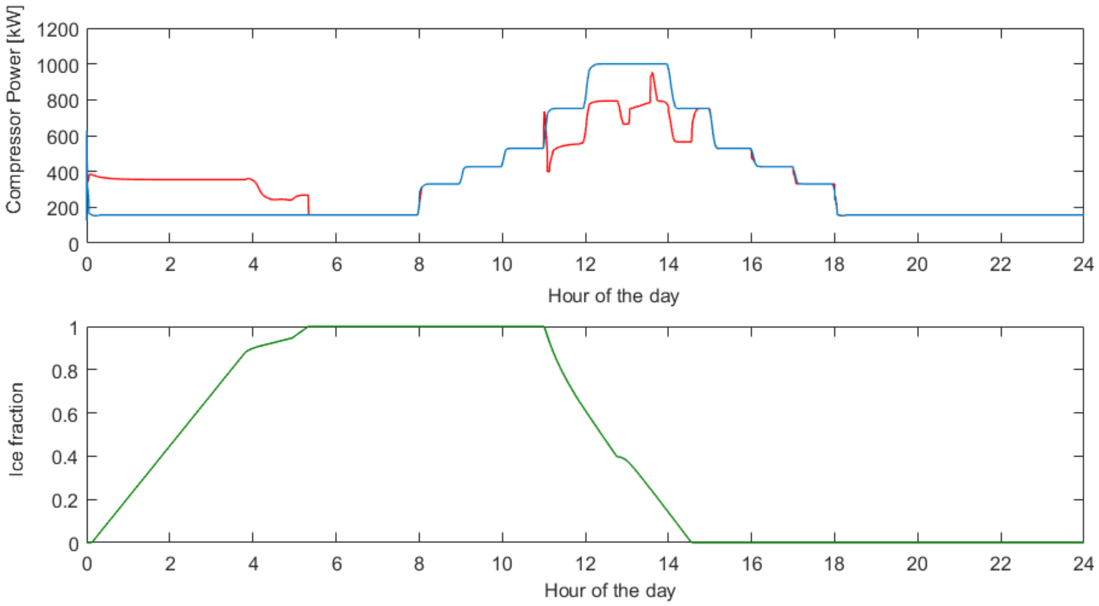

Figure 4: Upper half; Total compressor power, red and blue lines for operation with and without CTES integration. Lower half; Fraction of total CTES medium which is frozen at a given time during the day.

The discharge process is initiated as the total refrigeration load surpasses 1.5 MW at hour 11. Some of the evaporated CO_2 in the oil-free MT circuit is then sent to condense in the storage modules in the CTES system. As a result, some of the refrigeration duty is shifted from the MT plate CO_2/NH_3 heat exchanger to the CTES modules. This is showed in Figure 5 below. During the first hour the CTES system is set to discharge mode, the share of total duty condensed in the CTES modules accounts to 30-35%, then stabilizes at approximately 20% until all the PCM is melted. The discharge time takes about 3.75 hours, which is shorter than the charging time due to the larger duty at the beginning of the discharge process.

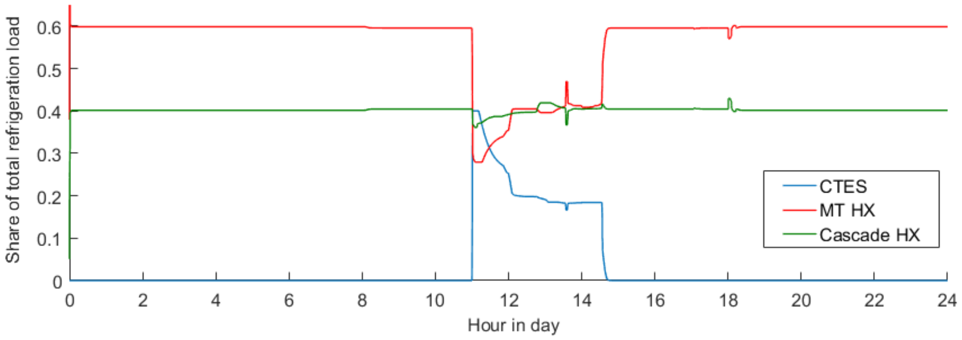

Figure 5: Share of total refrigeration duty handled in different parts of the system integrated with CTES.

As a consequence of shifting some of the load from the MT heat exchanger to the CTES modules, the required compressor power is reduced by an average 19% during the discharge operation as compared to the case without no CTES integration. Over the 24-hour simulation the average COP without CTES is 2.82, while the average COP is 2.76 with CTES integration. This small difference can be explained by the charging process of the CTES. For freezing the storage medium, the evaporation temperature of the CTES part of the oil-free CO_2 circuit is lowered to about -16°C. If the load was handled directly by the HP compressor rack, the evaporation temperature in the CO_2 MT circuit is about -3.5°C. This is the cost to pay for enabling shifting of some compressor electricity use to nighttime. In other words, integrating CTES to the system enables a considerable reduction in peak electricity use with only small reduction in overall performance of the refrigeration system.

In this study only the refrigeration load at MT level can be load shifted by the CTES system. For further studies the possibility of shifting the refrigeration load at LT level should also be investigated, either by condensing discharge gas from LP compressor rack in the CTES system, or by integrating a separate CTES storage at LT level for even higher reduction in peak electricity use. The latter option requires investigation of a suitable PCM with temperatures down to -50°C. Optimization of number of modules, heat exchange area in modules, total storage capacity and duty enables a more in-depth evaluation of the concept, including an economical consideration. Comparison with measured data for load characteristics and electrical power demand in a real plant will help validate the results from this study.

3. CONCLUSIONS

This paper presents a concept for an industrial refrigeration system in a poultry processing plant integrated with a cold thermal energy storage system. The system consists of a CO_2/NH_3 cascade refrigeration system where the heat load from the refrigeration equipment in the plant is transferred to the cascade by means of pumped oil-free CO_2 circuits at both MT and LT level. The CTES system is integrated into the MT level oil-free CO_2 circuit, with the purpose of reducing the peaks in electricity use during daytime operation. Simplified simulation models were developed as a first investigation for the performance of the combined CTES and refrigeration system. The results show that six CTES modules offer a reduction in required compressor power of 19% during discharge, shifting some condensing duty at MT level to the CTES modules. The study show only a small change in COP by integrating a CTES system, reducing from 2.82 to 2.76.

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ABBREVIATIONS

COP	*Coefficient of Performance*	*LP*	*Low Pressure*
CTES	*Cold Thermal Energy Storage*	*LT*	*Low temperature*
GWP	*Global Warming Potential*	*MT*	*Medium temperature*
HP	*High Pressure*		

REFERENCES

Bolaji, B.O., Huan, Z., 2013. Ozone depletion and global warming: Case for the use of natural refrigerant – a review. In: Renewable and Sustainable Energy Reviews, Volume 18, 2013, Pages 49-54.

Dopazo, J.A., Fernández-Seara, J., 2011. Experimental evaluation of a cascade refrigeration system prototype with CO2 and NH3 for freezing process applications. In: International Journal of Refrigeration, Volume 34, Issue 1, 2011, Pages 257-267.

Getu, H.M., Bansal, P.K., 2008. Thermodynamic analysis of an R744–R717 cascade refrigeration system, In: International Journal of Refrigeration, Volume 31, Issue 1, 2008, Pages 45-54.

Messineo, A., 2012. R744-R717 Cascade Refrigeration System: Performance Evaluation compared with a HFC Two-Stage System. In: Energy Procedia, Volume 14, 2012, Pages 56-65.

Sawalha S., Palm B., 2003. Energy consumption evaluation of indirect systems with CO2 as secondary refrigerant in supermarket refrigeration. In: Proceedings of the 21st IIR International Congress of Refrigeration, Washington DC, United States.

Taylor, P.G., Lavagne d'Ortigue, O., Francoeur, N.T., 2010. Final energy use in IEA countries: The role of energy efficiency. In: Energy Policy, Volume 38, Issue 11, 2010, Pages 6463-6474.