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Design of a cold thermal energy storage unit for industrial applications using CO_2 as refrigerant

Håkon SELVNES[(a)], Armin HAFNER[(a)], Hanne KAUKO[(b)]

[(a)] Norwegian University of Science and Technology (NTNU), Department of Energy and Process Engineering
Trondheim, NO-7034, Norway, hakon.selvnes@ntnu.no
[(b)] SINTEF Energy Research
Trondheim, NO-7034, Norway, hanne.kauko@sintef.no

ABSTRACT

Natural refrigerants such as ammonia, hydrocarbons and CO_2 are becoming increasingly popular due to favorable thermo-physical properties, low environmental impact and low cost. Industrial refrigeration systems are often installed in applications where the difference in peak and average cooling load is substantial. Cold thermal energy storage (CTES) integrated into the system enables shifting of the load from peak hours to off-peak hours, which enables design of the system capacity closer to the average load rather than the peak load. This paper describes the design and development of a CTES unit and associated experimental test rig. The CTES unit consists of a stack of heat exchanger plates contained in a steel tank, initially filled with water as the phase change material (PCM). CO_2 circulates within the plates to freeze and melt the water during charge and discharge cycles, respectively.

Keywords: Refrigeration, Carbon Dioxide, Cold thermal energy storage, Energy Efficiency.

1. INTRODUCTION

CTES technology has over the years gained more attention as a measure to cope with high peaks in refrigeration demands in various applications, reducing the required installed capacity of equipment and offering a backup in case of system failure. Special attention is being paid to investigating latent CTES using phase change materials (PCMs) (Oró et al., 2012) (Li et al., 2013). Extensive literature reviews on CTES technology and PCMs applied in different sectors have been published, including domestic refrigeration (Joybari et al., 2015), integration in building applications (Cabeza et al, 2011) and domestic heat pump/air-conditioning systems (Moreno et al., 2014). These studies cover both short-term and long-term storages. Published research on large-scale cold thermal energy storages is scarcer, especially systems designed for short-term storage. Systems designed for seasonal storage are most commonly studied.

In many process industries, where large refrigeration systems are installed, there is a substantial difference in peak and average cooling load. In Norway, one of the largest sectors within industrial refrigeration is the food-processing industry. The peaks in refrigeration demand occur due to the throughput of product in the plant during processing, while the cold storage of products is the main contributor to off-peak demand. The change in refrigeration demand from off-peak to peak can be more than a multiplication of ten. Identifying this demand structure is one of the most important prerequisites to make a successful CTES implementation in a refrigeration system (Dincer and Rosen, 2002). The evaporation temperature level where the energy is required in these types of systems are in the range of -10°C to 0°C for chilling purposes and between -40°C and -50°C for freezing processes. To avoid using compressor power during peak hours for satisfying the thermal requirement, the thermal demand must be satisfied at these temperature levels. PCMs with fitting phase change temperature for this temperature range are salt-hydrates/water mixtures or organic paraffin PCMs.

Apart from identifying a suitable system where energy storage can offer beneficial features, reliable CTES units that are easily integrated directly into the refrigeration systems must be developed. Earlier studies have been focusing on units that are incorporated in the secondary circuits of the refrigeration systems, typically using ice water or glycol as brines. Typical examples in this category are tube-in-tank systems (Torregrosa-Jaime et al., 2013) and ice bank systems with brine circulation through pipes or vertical plates (Ismail et al., 1999). These systems have the additional heat transfer loss by heat exchanging heat between the refrigerant and secondary circuit before being able to store the energy in the CTES system. The challenge when moving to large-scale systems requiring low temperature is to extract the energy stored in the CTES system fast enough during the period that the peak occurs. This varies from system to system, but the peak usually lasts from one up to a few hours. Large-scale systems with freezing and cooling demands in the megawatt range require high heat transfer from the CTES system in order to cut the demand peaks. There are in essence two approaches to enhancing the heat transfer in a latent CTES system. The designer can either act on the PCM by enhancing the thermal properties or act on the storage system itself. Enhancement strategies for PCMs have been studied intensively over the past years and thorough reviews are available (Fan and Khodadadi, 2011) (Milian et al., 2017). The focus of this study is to design a CTES unit by acting on the system, ensuring adequate heat transfer area to get high refrigeration duty during discharging.

The proposed design of a CTES unit in this paper is based on a type of heat exchanger (HX) plates called pillow plates. Pillow plates have the ability to withstand the relatively high operating pressures in CO_2 refrigeration systems, thus the refrigerant can be evaporated/condensed directly in the CTES and exchange heat with the PCM without additional secondary fluid circuit in between.

The published work on heat transfer in pillow plates is limited. Geometric description of the wavy surface is difficult due to the complex shape created by the applied hydraulic pressure during inflation. Piper et al. (2015) made an important contribution to this topic. The study focused on establishing methods for determining the geometric design parameters for pillow plates using forming simulations. The simulations could accurately represent the wavy surface of the plates, and equations for heat transfer area, hydraulic diameter and cross-sectional area were established based on the results. These expressions are important for further developing correlations for heat transfer and pressure drop in pillow plates.

Most studies of pillow plates deal with single-phase flow, only a few cover condensation and evaporation. To the authors' knowledge, the published research on condensation and evaporation in pillow plates covers only applications in the process and chemical industry. Mitrovic and Peterson (2007) published one of the first papers dealing with experimental investigation of condensation on pillow plates, where the HX was applied as a top condenser in a distillation column. In this study, the condensation process of isopropanol was on the outside surface of the pillow plate with cooling water on the inside. Later work by Mitrovic and Maletic (2011) concerned a numerical investigation of the flow and heat transfer characteristics of cooling water inside of a pillow plate.

Over the last four years, the number of publications treating numerical and experimental studies of single-phase flow pillow plates has increased. Piper et al. (2016) carried out a numerical investigation of the heat transfer characteristics of a small periodic element of the pillow plate. The study showed that two distinct zones, the meandering core and the recirculation zone, characterize the flow inside the plate. In single-phase turbulent flow, the core flow dominates the heat transfer. The highest efficiency was observed for the lowest Reynolds numbers and the highest inflation height, and an efficiency increase by up to 37% was predicted for oval shaped welding spots compared to circular. This work was followed up by establishing heat transfer correlations for forced turbulent convection based on the CFD results (Piper et. al., 2017). A recent study has investigated the effect of geometric variations of the flow channel and spot welds on the heat transfer in thermoplates, a variation of the pillow-plate with a single row of spot welds in the flow direction (Khalil et al., 2018). This study considered incompressible laminar flow with water as the fluid. Results from the study show improvement in heat transfer for large cross-sectional flow area, larger spot-weld spacing and smaller spot-weld diameter. The results from the numerical study were validated with experimental data.

Ice bank systems based on pillow plates have recently become commercially available, serving as a thermal storage for cold water systems with temperature set point of 0.5°C to 2°C. These follow the same operational regime as the traditional ice banks with tubes. This involves immersing the pillow plate HX in a water tank, where the circulation of cold coolant/refrigerant on the inside of the plates freezes an ice layer on the plate surface during charging. During discharging, warm return water from ice water system pumped into the tank and circulated on the outside of the ice layer to melt it and cool the water. This can be referred to as an internal freeze/external melt system. In this paper, the proposed design is a pillow-plate CTES unit based on the internal freeze/internal melt principle. The details of the CTES unit, operation and associated test rig will be presented in the following sections, as well as the proposed method of integration in a refrigeration system.

2. DEVELOPMENT AND DESIGN OF A CTES UNIT

2.1. CTES unit

The prototype CTES unit is shown in Fig. 1 below. The unit consists of a welded case in stainless steel supported by a frame of steel square tube, as well as a lid with handles to cover the unit to prevent evaporation of the PCM. The frame is required for structural support once the unit is filled with PCM. The prototype has two windows of thick acrylic plexiglass on each side for visually observing the melting/freezing process when the experiments are running. LED lights can be installed at one side of the case, and a camera at the other side to clearly see the solid PCM layer between each pillow plate. The case should be insulated when experiments are running, and the windows fitted with removable pieces of insulation. In case of service or need to empty the tank, there is a tube for draining the PCM at the bottom of each sidewall.

Figure 1: The designed prototype CTES unit (shown ten plates)

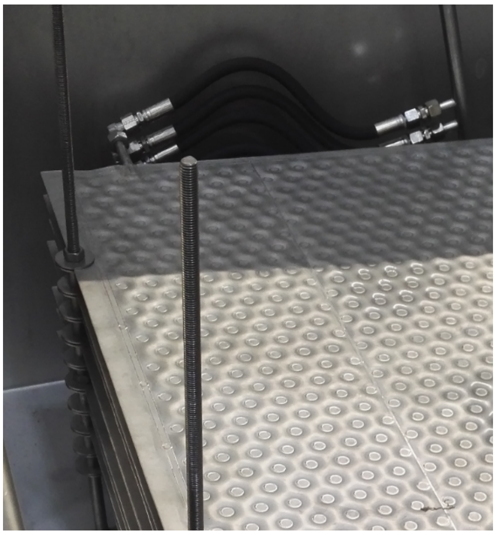

Figure 2: Detailed view of the plate stack in the unit

A stack of pillow-plates provides the heat exchange with the PCM in the unit. These plates consist of two thin metal sheets that are spot-welded together in a laser-welding machine. The diameter of the spot welds and the distance between them can be varied according to what type of refrigerant is used in the system. Higher operating pressures involves more spot welds per plate area. CO_2 requires relatively frequent spot welds due to the high pressure compared to other refrigerants. The spot welds are created in a certain repeating pattern. The pattern chosen in this unit has 50 mm longitudinal spot weld distance and 30 mm transversal spot weld distance. Other patterns are available. The plate pair is then seam welded along the edges to seal it completely, except for the inlet and outlet pipe. To create the flow channels for the refrigerant inside the plate, one of the pipes is blocked off and high pressure is applied on the inside of the plate with water. The plate is inflated and the channels are formed around the spot welds in between the two metal plates. This process gives the plates the characteristic wavy surface. The channel geometry promotes mixing of the flow and good distribution of refrigerant within the plate, which enhances heat transfer. In addition, longitudinal seam welds are made on each plate. This directs the refrigerant flow from the inlet pipe to the outlet via three passes over the plate. The longitudinal seam weld creating first refrigerant pass can be seen in Fig 2. Due to the width of the channel, the refrigerant velocities are relatively low, giving sufficient time for the refrigerant to evaporate/condense and exchange heat with the PCM on the outside.

The plate stack in the prototype is built to be flexible. Cylindrical spacers mounted in between the plates on the supporting rods set the distance between each plate. These can be changed with a set of different length to change the distance. The distance between the plates is an important parameter for the performance of the unit and the selection is depending on the thermal properties of the PCM, the time limit for charging/discharging and storage capacity requirements. As an example, lower thermal conductivity and high viscosity PCMs generally require shorter distance to activate all of the material in the tank. First tests are to be carried out with water as the PCM, and a distance of 50 mm between each plate is chosen. The first set of spacers are of unequal length, creating a tilt of the plate stack from the inlet to the outlet pipe. This design feature allows for efficient draining of the condensate during discharging of the system. The flow direction is reversed during charging so that the refrigerant evaporates and flows upwards to the outlet. The unit is intended to work with pump-circulated oil-free CO_2 refrigerant, but if lubrication oil is used, the tilting of the plate can help avoid an accumulation of oil in the unit. The pipes at each end of the stack are connected to a common manifold by a high-pressure flexible hose, which distributes the refrigerant to each plate in the stack from the common inlet pipe. The plates are free to move up and down the rods, to avoid mechanical stresses resulting from the expansion of the PCM during solidification. Main geometric parameters of the CTES prototype unit are summarized in Table 1 below.

Table 1: Geometric parameters of the prototype CTES unit

Parameter	Value	Unit
Longitudinal spot weld pitch	50	mm
Transversal spot weld pitch	30	mm
Pillow plate length	1500	mm
Pillow plate width	750	mm
Distance between each plate	50	mm
Number of plates in the stack	20	-
Total heat transfer area (assuming flat plate)	45	m^2

2.2. CTES test rig

To test the performance of the newly developed prototype CTES unit, a test rig needs to be developed and constructed. Special focus is to make the rig as flexible as possible, with the ability to test the CTES unit with numerous PCMs of different composition, properties and phase change temperatures. A simplified process and instrumentation diagram (PID) of the test rig is shown in Fig 3. The two main functions of the rig are to add and remove heat from the refrigerant circuit during the discharging and charging process, respectively. Heat to the circuit is provided by a closed-loop glycol system, with 30% glycol concentration as heat transfer fluid. The heating circuit consists of 2 x 9 kW electric immersion heaters with thermostatic control (0°C to 50°C), a circulation pump and an expansion vessel with microbubble air separator and safety valve. The heat transfer to the CO_2 circuit is done in a CO_2/glycol plate HX from Alfa Laval, functioning as an evaporator. A differential pressure sensor measures the pressure drop over the evaporator on the refrigerant side. Flow data is collected by a Coriolis mass flow meter, while resistance temperature detectors (RTD) pt100 sensors measure the inlet and outlet glycol temperature to the evaporator. The probes of the temperature sensors are installed directly in the glycol flow. The heating circuit is completed with 28 mm copper tube with press fittings.

Heat is removed from the CO_2 circuit by connecting the test rig to the centralized CO_2 unit in the refrigeration laboratory. The centralized unit has three evaporation levels, -53°C, -25°C and -10°C, which can be chosen by operating a valve station. This gives the possibility to remove heat at a large temperature range, meaning PCMs with phase change temperatures from approximately 0°C to -45°C can be tested in the unit. The heat from the test rig CO_2 circuit is transferred to the centralized CO_2 unit by a plate HX from Alfa Laval. The HX serves as a condenser on the test rig side and as an evaporator for the centralized unit. A differential pressure sensor measures the pressure drop on the test rig side of the condenser. A Danfoss CCMT-2 electronic expansion valve controls the refrigerant flow and superheat of the suction gas to the centralized CO_2 unit. When the facility is not running, the pressure and temperature of the liquid CO_2 in the receiver are kept low by a subcooler HX (see Fig. 3). The HX consists of a 6 mm copper tube that is coiled around the liquid receiver, with a total length of 15 meters. This prevents the temperature of the liquid CO_2 in the system reaching room temperature and excessive pressures during standstill. A Danfoss AKVH electronic expansion valve controls the refrigerant flow and superheat of the subcooler.

A high-pressure hermetic refrigerant pump from HERMETIC-Pumpen GmbH equipped with a frequency converter provides circulation of CO_2 in the refrigerant circuit of the test rig. Liquid CO_2 is supplied to the pump from the refrigerant receiver. To avoid cavitation problems and provide the required suction head for the pump, it is placed in the basement while the rest of the rig is located at the ground floor. In addition, the suction pipe has an increased pipe diameter compared to the rest of the rig to obtain sufficiently low refrigerant velocities at the pump inlet. The test rig refrigerant circuit is constructed with K65 high-pressure copper tube and fittings that are brazed together. The tubes are of 3/4" size, except for the suction tube of the pump, which is of 1.5/8” size. A recirculation line back to the receiver with a minimum flow orifice is fitted to the system to ensure the minimum flow requirement of the pump is maintained at all times.

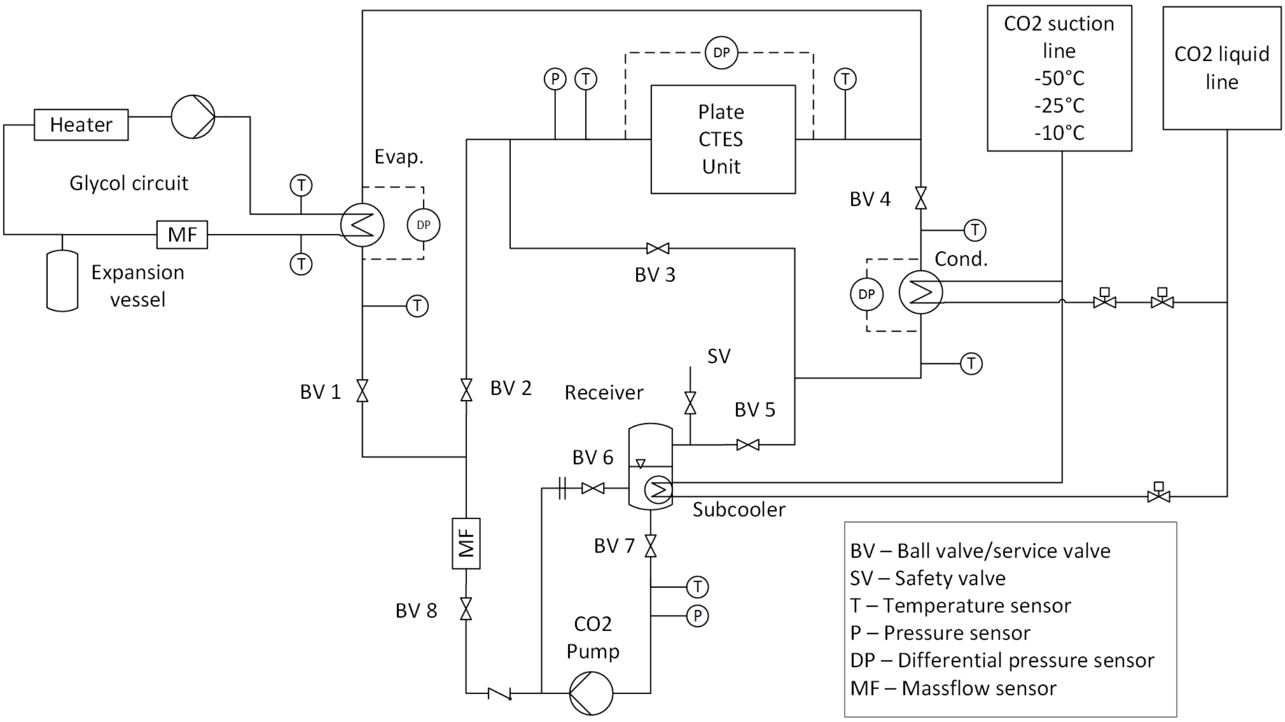

Figure 3: Simplified process and instrumentation diagram of the CTES test rig

The test rig can operate in two modes, charging or discharging of the CTES unit. When the system is running in charging mode, ball valve 1 and 3 are closed. The remaining valves are open. The refrigerant is pumped from the liquid receiver, through a Coriolis mass flow meter before entering the CTES unit. The liquid refrigerant evaporates in the unit as it exchanges heat with the PCM in the pillow plates, solidifying the PCM. The gas is then condensed in the CO_2/CO_2 condenser before it is drained to the receiver. The evaporated CO_2 from the centralized unit is transported back to the rack by operating the appropriate compressor suction level. During discharging of the CTES unit, ball valve 2 and 4 are closed. The rest of the valves are in the open position. Liquid CO_2 is pumped from the receiver through the Coriolis mass flow meter, and then to the evaporator. The heaters and the pump in the glycol circuit are activated, and warm glycol is circulated through the plate HX to evaporate the CO_2. The refrigerant gas then flows through the CTES unit and condenses as it exchanges heat and melts the PCM. The liquid CO_2 is drained back to the receiver by gravity.

The plates in the CTES unit are stacked horizontally. This choice was made to take advantage of the buoyancy effect on the solid PCM during the discharging/melting process. Since CO_2 is condensing in the plates, the PCM will melt close to the plate surface first. When the PCM between a pair of plates is melted from the top and bottom, it is free to move in the liquid PCM. Due to density differences between the solid and liquid PCM, the solid bulk will rise and make contact with the upper plate. This will create a situation called close-contact melting (CCM), providing high heat transfer between the solid PCM and the condensing refrigerant on the other side of the plate wall.

The test rig is installed with a differential pressure sensor over the CTES unit, evaporator and condenser. In addition, there are absolute pressure sensors fitted at the receiver outlet and in front of the CTES unit. 3 mm diameter closed-end tubes are fitted into the refrigerant flow in order to mount RTD pt100 temperature sensors. They are installed at the receiver outlet, before the evaporator, after the condenser and before/after the CTES unit. Up to 32 thermocouples can be fitted on the pillow plate surface in the CTES unit to observe the temperature distribution. Three plates in the stack (upper, middle and lower part of the stack) are fitted with thermocouples. All data from the test rig is transmitted by a central data acquisition system from National Instruments and logged by a program in the computer software LabVIEW. An overview of the measurement equipment and the indication of the accuracy are shown in Table 2.

With the latent heat of water as PCM (333.55 kJ kg^{-1}), the described geometry and by considering only the volume of PCM between the plates as the active PCM, the expected storage capacity of the prototype CTES unit is about 104.1 kWh. The peak condensing duty for the unit with saturated CO_2 gas entering at 5°C (39.67 bar) is about 26 kW, slowly decreasing as the melting process continues.

Table 2: Measurement equipment

Component	Type/Producer	Indicated accuracy
Pressure sensor	Cerabar S PMP71 / Endress+Hauser	± 0.075 % of set span
Differential pressure sensor	Deltabar S PMD75 / Endress+Hauser	± 0.05 % of set span
Temperature sensor flow	Class B RTD Pt100 / RS PRO	± 0.12 % of resistance
Temperature sensor PCM	K-type thermocouples / RS PRO	± 0.75 % of range
Mass flow meter glycol	RHM 15 Coriolis meter/ Rheonik	± 0.2 % of rate
Mass flow meter CO_2	RHM 06 Coriolis meter / Rheonik	± 0.2 % of rate

2.3. Integration in a refrigeration system

The unit is designed to be integrated and operated as a CTES system in a pumped CO_2 secondary refrigeration circuit. A case example showing how to integrate and operate the CTES unit in an NH_3/CO_2 cascade refrigeration system for a food processing plant now follows. The design of the cascade system is taken from a poultry processing plant under construction in central Norway. NH_3/CO_2 cascade systems are gaining popularity for large refrigeration systems, and they show advantages over pure NH_3 systems for evaporation temperatures at -40°C and lower (Bingming et al., 2009) (Dopazo et al., 2011). Using CO_2 in the lower stage as a pump-circulated secondary refrigerant offers operating benefits compared to traditional brines, especially for long piping distances. Reduced pipe diameter, low pumping costs, no toxicity or flammability concerns, as well as high heat transfer in process equipment by direct evaporation are some of the favorable features of using CO_2 as a secondary fluid. CTES implemented in these types of systems can offer compressor power peak load shifting when they are installed in the low-temperature stages (Selvnes et al., 2018). The CTES unit proposed in this paper is intended to work as an alternative to the traditional sensible thermal storages, such as ice water tanks often used as peak shaving devices in the food industry. A simplified flowsheet of the bottom cycle of the cascade refrigeration system with integration of the CTES unit is shown in Fig. 4 below.

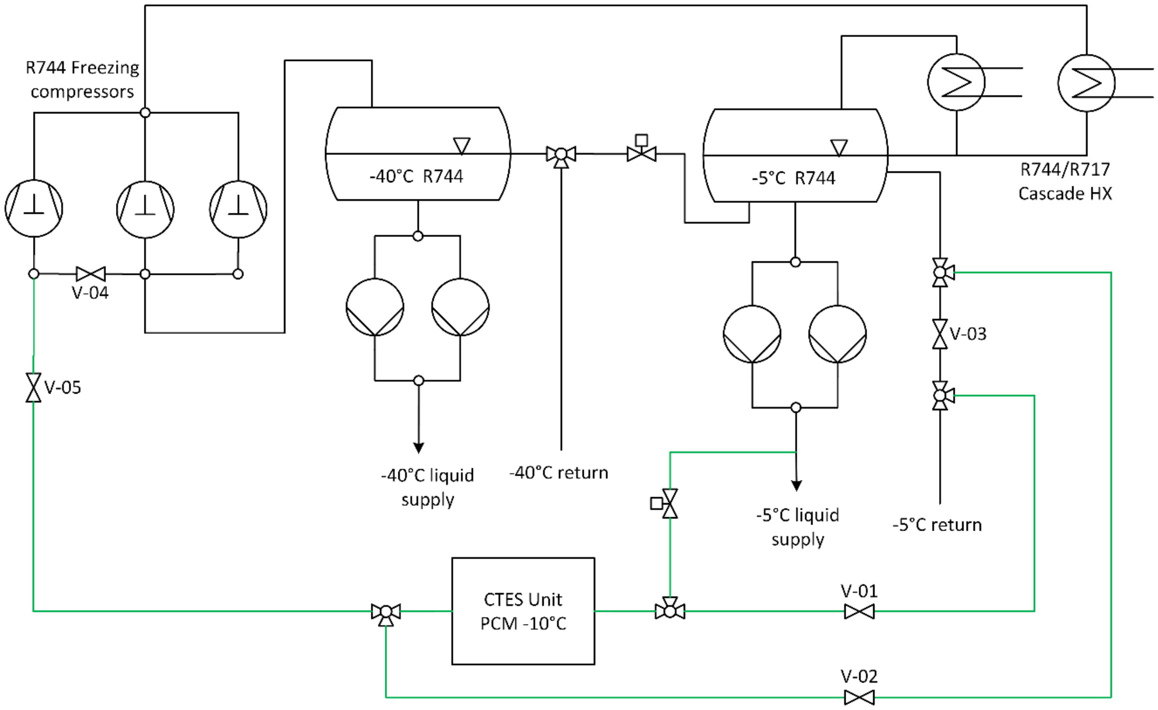

Figure 4: Example on how to integrate the CTES unit in a secondary refrigeration circuit

The bottom cycle consists of a -5°C and -40°C temperature level for cooling and freezing applications, respectively. The refrigerant is pump-circulated and distributed from the two liquid receivers with a typical circulating rate of 3, referring to the ratio of evaporated refrigerant to the total amount of refrigerant pumped to the evaporators. The evaporated refrigerant at -40°C returning from the process equipment in the plant is compressed to -5°C saturation pressure (30.47 bar) and then condensed in the cascade HX. The return line from the -5°C distribution pipe is directed back to the liquid separator, and the gas is condensed in the cascade HX by natural circulation. The additional piping required for integration of the CTES system is displayed with green color in Fig. 4. In the example shown here, the CTES system works as a peak shaving device at the -5°C temperature level in the plant. The focus of the integration is to use the equipment already required for conventional operation to charge and discharge the CTES system. During the hours without production, (night) the load on the refrigeration system is only to maintain the set-point temperature in the cold storages. Consequently, there is compressor capacity available to charge the CTES system. During charging valve V-01, V-02 and V-04 are closed, while V-03 and V-05 are open. CO_2 liquid from the -5°C liquid separator is throttled to -20°C saturation temperature (19.72 bar), and evaporated in the CTES unit while exchanging heat with the PCM. An appropriate phase change temperature for the PCM for this temperature level is -10°C, giving a 5 K temperature difference between the refrigerant and the solid PCM. Possible candidates to use as PCM are based on paraffin or salt-hydrate/water mixture. The evaporated CO_2 is compressed and delivered to the cascade HX by one of the machines in the compressor rack.

During peak hours of production, the system can be discharged to unload the R717 compressors in the upper part of the cascade. Valve V-01, V-02 and V-04 are now open, while V-03 and V-05 are closed. The two-phase mixture in the -5°C return line from the plant is directed to the CTES unit where the gas is condensed before returned to the liquid separator. If the storage does not have the capacity to condense the returning refrigerant completely, the remaining gas is condensed in the cascade HX. The CTES system can be extended to the required storage capacity and condensing duty by connecting more units in parallel.

3. CONCLUSIONS

This paper presents the design of a novel CTES unit that is suitable for installing in industrial refrigeration systems using CO_2 as refrigerant. An example of how to integrate and operate the CTES unit in an NH_3/CO_2 cascade refrigeration system is shown in section 2.3. The design of the unit is based on a type of HX plates called pillow plates. The flexible design of the prototype allows for variation of important geometric parameters during the experimental campaign, such as the plate welding pattern, the distance between plates in the stack and the total number of plates. The arrangement enables optimizing the unit geometry to fit PCMs with different thermal properties.

An associated test rig using oil-free CO_2 as refrigerant was developed to investigate the performance of the prototype CTES unit. It is designed to handle experimental studies involving PCMs with phase change temperature in the range from 0°C to -45°C, which is adapted to the required temperature levels in the food processing industry. The working fluid in the test facility is pump-circulated. The test facility is able to operate both in charging and in discharging mode. During discharging, an electrically heated closed-loop glycol circuit provides heat input to the oil-free CO_2. The CO_2 condenses in the CTES unit while melting the PCM. In charging mode, liquid refrigerant is pumped through the CTES unit. The refrigerant evaporates while it solidifies the PCM. The refrigerant gas is condensed in an HX connected to a centralized CO_2 refrigeration unit in the laboratory. The centralized unit can provide refrigeration from -5°C down to -53°C. This enables tests of low-temperature PCMs, too. These investigations will be performed after the tests with water as PCM.

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