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Cold thermal energy storage in solid-liquid transition of carbon dioxide: Investigating the possibility

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ABSTRACT

Industrial freezing is an energy-intensive process which is growing due to the increasing demand. This is exerting stress on electrical grids, especially at peak hours. To tackle this issue, thermal energy storage has received attention; however, there is a gap in terms of suitable materials for thermal energy storage with temperatures below -40 °C commonly needed in these applications. In this paper, the solid-liquid phase change of carbon dioxide has been conceptually considered for thermal energy storage in a special type of heat exchangers known as pillow plate heat exchangers. Characteristically, these heat exchangers can withstand very high pressures which is a technical requirement for carbon dioxide thermal energy storage. This paper discusses the potential system layout and challenges ahead of this technology, along with the proposal for further investigation to verify the concept.

Keywords: Industrial Refrigeration, Carbon Dioxide, Thermal Energy Storage, Phase Change Material, Pillow Plate Heat Exchanger.

1. INTRODUCTION

Global warming has triggered some aspects of our energy consumption to change, including energy consumption reduction, energy efficiency enhancement, incorporating renewable energy sources, etc. All these require fundamental changes in our consumption behaviour to match the new style. Meanwhile, refrigeration systems account for about 17% of the global electricity consumption which is expected to further increase due to global warming together with the continuous growth in refrigeration demand (Coulomb et al., 2015). This means that even a small electricity consumption reduction and/or energy efficiency enhancement would have a huge impact given the large share of refrigeration systems in global energy consumption. Food processing plants freezing meat, fish, fruits and vegetables are particularly large users of electricity since for an efficient freezing process they need low-temperature refrigeration, commonly below -40 °C (Mota-Babiloni et al., 2020). Moreover, our existing electrical grids face consumption variations throughout the day with some hours having peak energy demand. To make it even worse, most renewable energy sources such as wind and solar are inherently intermittent. This makes a temporal gap between the energy supply and demand. Thermal energy storage can be used to address such issues (Panchabikesan et al., 2021). To this end, energy can be stored during its availability to be used later when there is demand. Among thermal energy storage technologies, latent heat storage in phase change materials (PCMs) has received research momentum primarily due to the higher storage density and almost isothermal operation.

Several studies have been conducted on thermal energy storage in refrigeration systems; nevertheless, for low-temperature applications below -40 °C, fewer investigations are available. This topic received greater research attention recently for the storage temperature requirements between -60 and -80 °C for Pfizer COVID-19 mRNA vaccines (Sun et al., 2022). Almost all available commercial PCMs for low-temperature applications are eutectic mixtures (e.g., see Figure 1), which commonly suffer from subcooling. Other

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drawbacks of eutectic (salt hydrate/water) mixtures are incongruent melting, phase segregation and being corrosive to common metals used in heat exchangers (Selvnes et al., 2021b; Sevault et al., 2022b). Some other candidate materials are shown in Figure 2; however, they have lower latent heat capacity (compared to the options in Figure 1). Therefore, there is a lack of suitable PCMs for thermal energy storage for this temperature range. As such, it is important to address this issue and investigate alternative storage materials for low-temperature refrigeration to exploit the advantages of thermal energy storage.

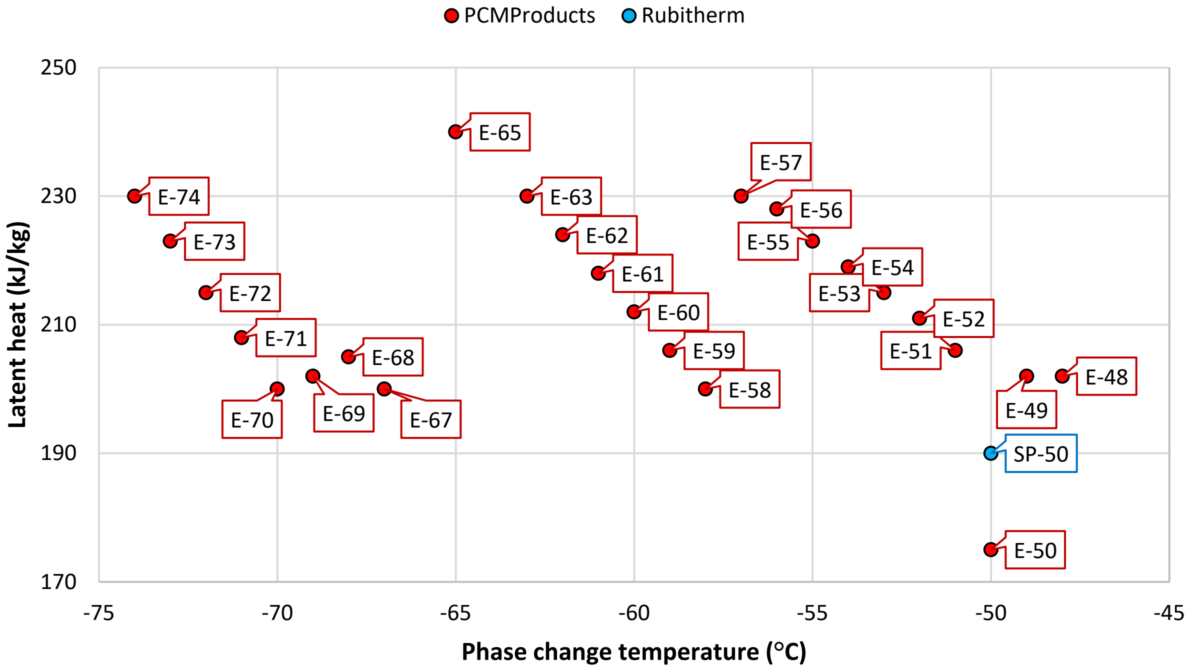

Figure 1: Commercial PCMs for ULT applications (PCMProducts, 2022; Rubitherm, 2022)

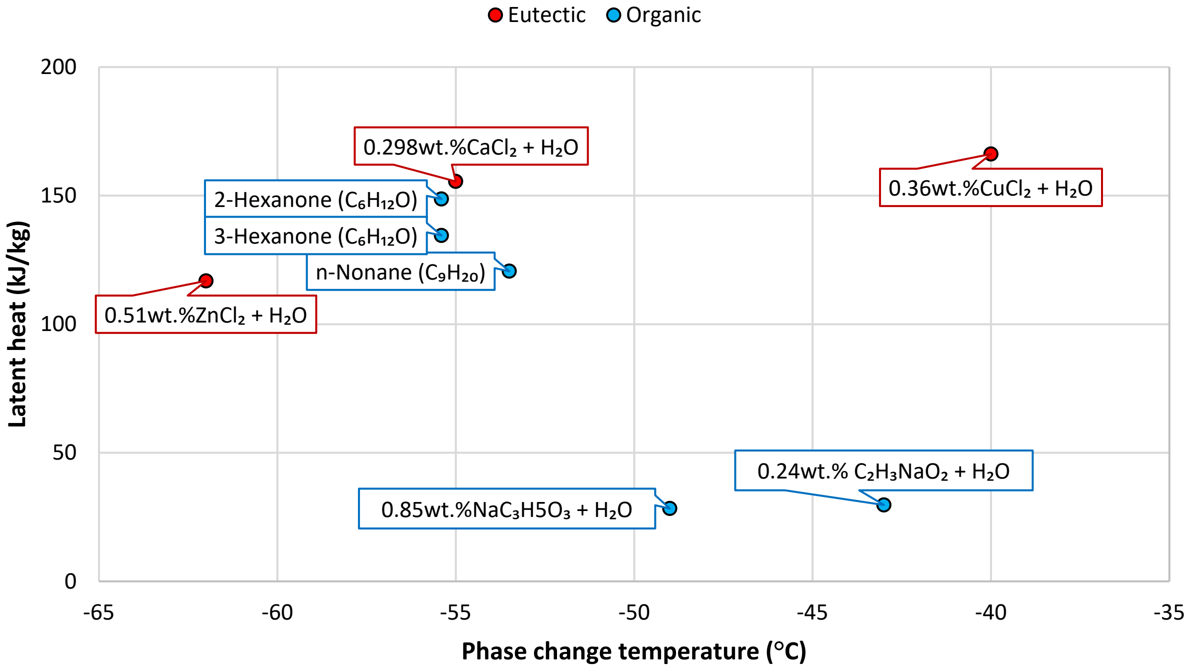

Figure 2. Thermophysical properties of some options for ULT thermal storage applications (Li et al., 2013)

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Carbon dioxide (CO_2) is a naturally and abundantly available material. It is very commonly used as the refrigerant (R744) for low-temperature refrigeration; e.g., as the refrigerant in the lower stage cycle of cascade refrigeration systems with ammonia (R717) in the high-temperature circuit (Dopazo and Fernández-Seara, 2011). As such, it can be a prime option for thermal energy storage as well. Aside from relatively high latent heat capacity, it has several advantages including low cost, molecular stability, noninflammability, low toxicity, noncorrosiveness (for most materials), zero ozone depletion potential (ODP) and low global warming potential (GWP), making it a desirable storage medium for low-temperature applications. In addition, if used as the storage medium, CO_2 not only saves greenhouse gas (GHG) emissions during electricity generation, but also in itself would be a carbon storage, further lowering GHG emissions.

The use of the solid-vapour transition (sublimation) of CO_2 in two-phase flow is a method of achieving ultra-low temperature (ULT) refrigeration below the triple point of CO_2 (-56.6 °C). The use of this technology in a cascade refrigeration system was experimentally investigated by Yamaguchi et al. (2011). Liquid CO_2 was throttled to a pressure in the range of 1.63-1.86 bar at the inlet of a test tube. By carrying out visualisation tests while heating the test section, it was found that below a certain threshold of CO_2 mass flow rate, accumulation of dry ice particles occurred at the bottom of the tube which increased the risk of blocking the flow. Tests were then carried out for the cascade refrigeration system with evaporation pressure of 3.6 bar, proving that the system could achieve stable two-phase dry ice/vapour flow and continuously provide -62 °C inside the expansion tube. However, under certain conditions it was found that blocking of the evaporator occurred. As a measure to reduce the risk of dry ice blocking in the evaporator tubes, the use of a swirl promoter at the inlet of the tube has been proposed (Yamasaki et al., 2017). It was shown by visualisation tests that using the swirl promoter would result in a more uniform dispersion of dry ice particles, improve the heat transfer, and reduce the risk of downstream blocking of the flow. The concept was further developed by proposing the use of a cyclone for collecting the dry ice particles on a bottom plate instead of the standard evaporator tube (Yamasaki et al., 2020). The experimental investigation showed that the conical design had the best collection efficiency compared to cylindric and non-swirling cyclones and could continuously maintain -76 °C at the bottom plate.

The use of CO_2 as a solid-liquid storage medium for cold thermal energy storage purpose in an industrial R744/R717 cascade refrigeration plant was proposed by Hafner et al. (2011). The theoretical concept was outlined using a shell and tube heat exchanger integrated into the R744 circuit of the cascade system, with the CO_2 undergoing solid-liquid transition on the shell side of the heat exchanger. The calculations showed up to 30% reduction in electricity use was possible by avoiding inefficient part-load operation of the refrigeration plant; however, more research on the solid-liquid CO_2 transition was needed to verify the concept. Following the previous work, the same concept was applied to a CO_2 refrigeration plant utilising plate freezers onboard a fishing vessel (Verpe et al., 2019). The numerical model predicted about 3.2% decrease in the freezing time using the cold thermal energy storage, enabling increasing the production capacity of the refrigeration system.

Several options are available for heat exchangers for instance shell and tube heat exchangers (as described above), plate heat exchangers, etc. Nevertheless, plate heat exchangers can be regarded as more suitable for thermal storage since, among others, they benefit from compact design and can withstand high pressures. These are desirable properties for thermal energy storage in the solid-liquid transition of CO_2, which deals with high pressure values (further details in Section 2.1). Among plate heat exchangers, pillow plate heat exchangers (PPHXs) have received increased attention for thermal storage applications (Mastani Joybari et al., 2022a; Selvnes et al., 2021a; Sevault et al., 2022a). Further details are presented in Section 2.2. The current paper conceptually presents the use of the solid-liquid phase change of carbon dioxide as a cold thermal energy storage medium in low-temperature refrigeration systems. The application of these systems is mainly in freezing processes around -40 °C in the food processing industry. The rest of this paper is organised as follows: Section 2 discusses the system description, while Section 3 presents the potential system layout. In Section 4, the main challenges are presented followed by the conclusions and description of future work in Section 5.

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2. SYSTEM DESCRIPTION

In this section, first the principle of thermal energy storage in CO_2 is elaborated and then PPHXs, which can meet the requirements for this application, are introduced.

2.1. Principle

The concept of low-temperature thermal energy storage utilising the solid-liquid transition of CO_2 can be visualised in a pressure-enthalpy (*P-h*) diagram, shown in Figure 3. The CO_2 *P-h* diagram shown in the figure indicates the operational envelope for the suggested thermal energy storage system. The intention is to let CO_2 swing between the saturated solid and saturated liquid lines and avoid going beyond the liquid region. The reason is that if the temperature is rather high, then CO_2 will cross the saturated liquid line and enter the liquid-vapour region. This vapour formation is undesirable for thermal energy storage applications as it needs a higher volume (due to its very low density compared to the liquid and solid phases). According to Figure 3, if the thermal storage operates at 10 bar, then temperatures above -40 °C should be avoided. In practice, however, this is impossible to achieve due to the unavoidable heat gain from the environment. Suggestions on how to mitigate this challenge are presented in Section 4.3.

Another inference from the figure is that another refrigerant should be used to charge the storage (i.e., for CO_2 solidification). Ethane (R170) is commonly used in the lower stage of cascade industrial refrigeration systems due to favourable normal boiling point of -88.8 °C and can be used for this purpose.

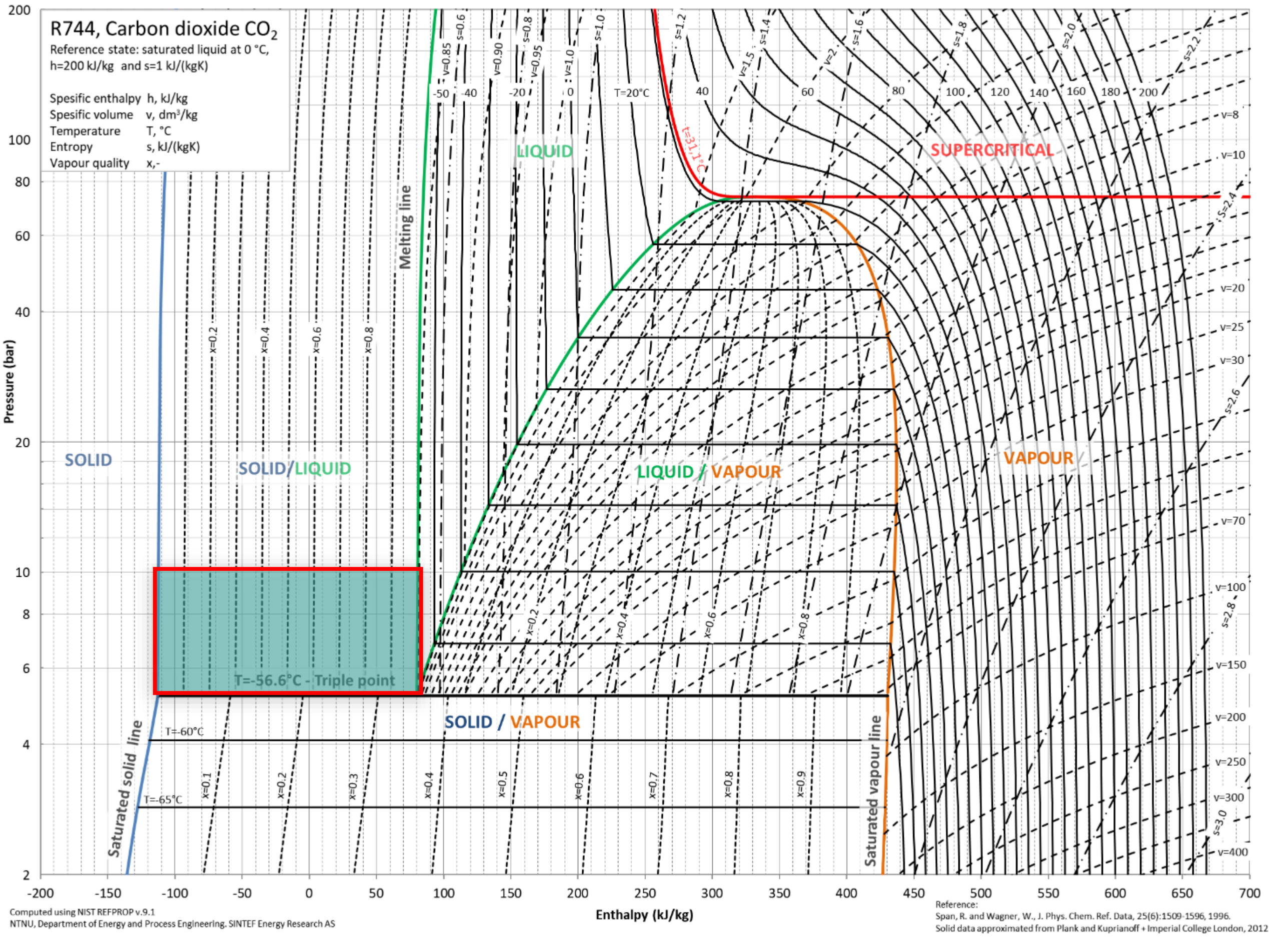

Figure 3: Pressure-enthalpy diagram of CO_2 indicating the envelope for thermal energy storage

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2.2. Heat exchanger

As mentioned, in this study, CO_2 was considered as the PCM (solid-liquid phase transition), which needs a heat exchanger that can withstand operational pressures around 10 bar, as shown in Figure 3. A pillow-plate heat exchanger (PPHX) can be used for this purpose (see Figure 4a).

Simply, a PPHX is manufactured by superimposing two metal sheets of the same thickness and then spot-welding them in a certain pattern (using laser welding). Then the edges are seam welded except for the inlet and outlet (not shown in Figure 4a) which are used to send a pressurised incompressible fluid (such as water) into between the plates. This high internal pressure causes the plates to get deformed (in a process known as hydroforming). In this way a single pillow-plate is manufactured. In the next step, several pillow-plates are stacked together to form a heat exchanger. Consequently, two passages are created, one within the pillow plates, and one between them, known as the inner and outer channels, respectively.

It should be noted that the manufacturing procedure as explained in the previous paragraph is used for the double-embossed single channel PPHXs (as shown in Figure 4b, top). If the same procedure is followed but using three plates, the resulting PPHX would be called double-embossed with two channels (as shown in Figure 4b, bottom). This means that there will be two inner channels and one outer channel.

For thermal storage applications, the outer channel is used for the PCM while the inner channel (s) are used for the refrigerant(s), either for charging or discharging the storage. Note that the hydroforming pressure is way beyond the operational pressure of PPHXs making them an ideal option for the low-temperature application using CO_2 as the storage material.

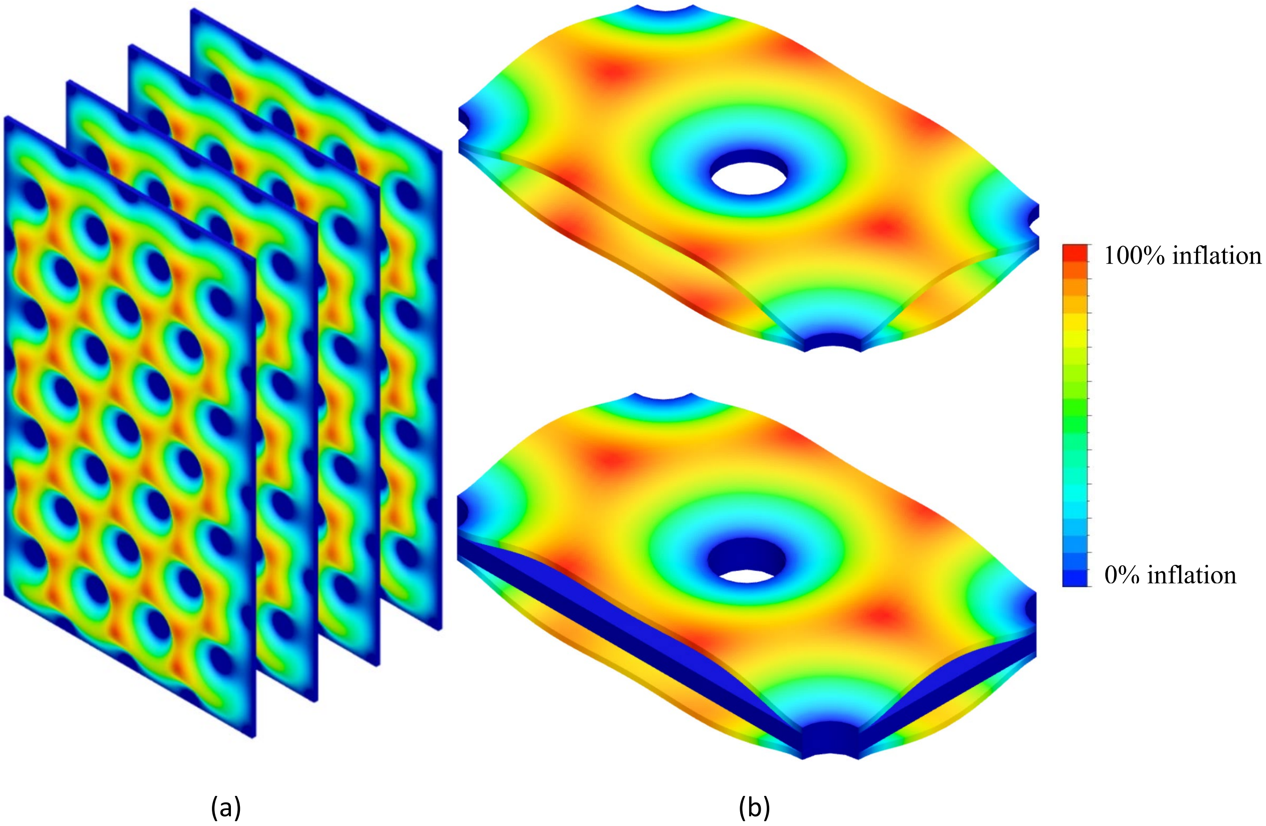

Figure 4: (a) the conceptual view of pillow-plate heat exchangers and (b) their different types

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2.3. Planned testing to verify system operation

To verify the concept of using CO_2 as a PCM (by cycling it within the solid-liquid two-phase region), there are numerous points that needs to be addressed. Firstly, a small test section has to be established for verifying the operational principle of solidifying CO_2 in an increasingly thicker layer on a cold surface. This method is the most commonly used method for operating traditional PCM heat exchanger units. The preliminary testing could be executed by using a tube-in-tube arrangement, where the inner tube accommodates the low-temperature refrigerant (e.g., ethane) while liquid CO_2 (used as the PCM) is kept within the outer tube. This test should include a visualisation of the phase front for instance through a sight glass on the outer tube. This experimental feasibility study will confirm the possibility of cycling CO_2 between the solid and liquid phases in the marked blue area in Figure 3. Furthermore, it will provide important knowledge on the behaviour of the mixture of solid and liquid CO_2 during the discharging process (i.e., during melting). An important point to be addressed is the expansion of CO_2 due to the density difference between its liquid and solid phases, which determines the strength of natural convection within the solid-liquid mixture.

After successful demonstration of the concept on the small scale, a lab-scale pilot unit should be tested, accommodating the proposed pillow-plate heat exchanger design presented in the previous section. The challenge is to design a suitable pressurised vessel that could hold both the CO_2 storage medium and the pillow plate heat exchanger. The detailed design will depend on the outcome of the proof-of-concept test campaign.

3. POTENTIAL SYSTEM LAYOUT

Figure 5 shows an example of the proposed system layout of a CO_2 refrigeration system for brine freezing of fish at around -35 °C, combined with storage room cooling with a temperature requirement of -25 °C. A ULT thermal energy storage using CO_2 as the storage medium is included, along with a dedicated ethane (R170) circuit for charging the storage. In the figure, the solid lines indicate CO_2 refrigerant (R744) while ethane refrigerant (R170) is shown with the broken lines. The ULT thermal energy storage is designed for peak shaving of the refrigeration load during brine freezing of the fish to reduce the power consumption of the compressors in the CO_2 refrigeration plant. This section discusses the four operating modes of the system which are (1) no storage, (2) storage charging while meeting the demand, (3) storage charging only, and (4) storage discharging. Note that the system concept can be applied to other ULT applications and fish processing was selected merely as an example to present the system layout and its operational modes.

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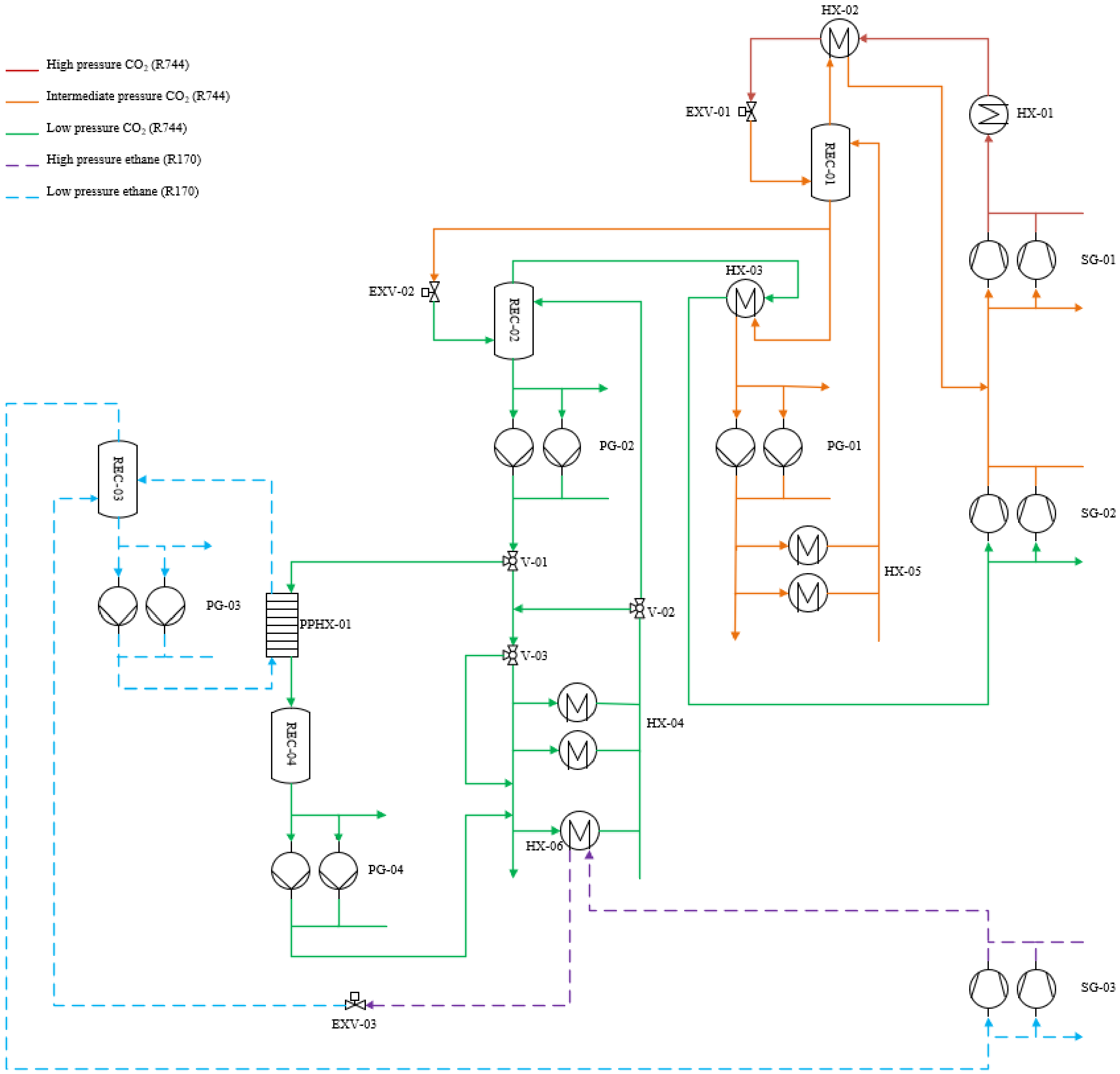

Figure 5: Schematic circuit of a typical refrigeration system with a CO_2 thermal storage unit

3.1. Mode 1: No storage

As its name implies, this mode is equivalent to the regular operation of the system where there is no storage and/or peak shifting. In this mode, the R170 cycle does not operate at all. According to Figure 5, starting from Suction group 1 (i.e., the highest pressure indicated by SG-01), the refrigerant R744 exchanges heat in gas-cooler/condenser HX-01 which can be used for heat recovery or connected to a heat pump unit (if needed), and then goes through another heat exchanger, HX-02 for further subcooling. The subcooled refrigerant undergoes expansion in EXV-01 and ends up in receiver REC-01 to separate the liquid and vapour. The vapour portion goes back to HX-02 to get superheated prior to entering the suction of SG-01. The liquid portion is divided in two parts. The first part goes through HX-03 to get further subcooled before being pumped (in PG-01) towards a group of evaporators (i.e., HX-05). These evaporators are used for storage room applications (at around -25 °C). The evaporated refrigerant is returned to REC-01. The other liquid portion coming out of REC-01 undergoes expansion in EXV-02 and then enters a second separator REC-02. The vapour exits from the top towards HX-03 to get superheated prior to entering the suction of SG-02. The liquid is then pumped by PG-02 to the evaporators HX-04 (valves V-01, V-02 and V-03 are in “I” position). These evaporators are at a lower temperature which can be used for brine freezing applications (at around -35 °C). The exiting vapour

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from HX-04 returns to REC-02. Note that there is no heat exchange in the last evaporator in HX-04 (denoted by HX-06) in this mode as the R170 cycle is not running (i.e., SG-03 is OFF).

3.2. Mode 2: Storage charging while meeting the demand

In this mode, in addition to meeting the demand at the two evaporator groups (i.e., HX-04 and HX-05), the thermal storage is also charged. To this end, high-pressure R170 is sent from SG-03 to HX-06 as the condenser. Then the liquid R170 goes through expansion in EXV-03 and enters the receiver REC-03. The liquid portion is pumped by PG-03 to go through the inner channels of PPHX-01, the thermal storage unit. Consequently, in the outer channels of this unit pure CO_2 undergoes freezing. The exiting R170 stream from PPHX-01 is then returned to REC-03. The vapour portion of R170 exits the top of REC-03 to the suction of SG-03. On the R744 cycle, the valve V-01 is open in all directions (i.e., “T” position) in this operational mode, while V-02 and V-03 are in the “I” position.

3.3. Mode 3: Storage charging only

In this operational mode, only the storage PPHX-01 undergoes charging while there is no demand at the evaporator groups (i.e., HX-04 and HX-05). To do so, the R170 compressors (i.e., SG-03) are operational to charge the storage. On the R744 cycle, the valve V-03 is switched to its “L” position, essentially bypassing HX-04, while V-01 and V-02 are at “I” position. Note that the R744 suction groups (i.e., SG-01 and SG-02) could be turned OFF if another heat sink was connected to the R170 cycle instead of HX-06 (e.g., a condensing unit).

3.4. Mode 4: Storage discharging

During discharging of the thermal storage, all the suction groups are switched OFF to avoid power consumption during peak hours. Instead, the storage PPHX-01 provides the cooling for the brine freezing and possibly storage room (not shown). To this end, the 3-way valves V-01 and V-02 are at their “L” position, while V-03 is closed. The evaporated R744 exits HX-04 and flows through piping towards PPHX-01 where it condenses by coming into contact with the thermal storage. The liquid keeps collecting in REC-04 where it gets pumped by PG-04 to continue the cycle.

4. CHALLENGES

4.1. Handling refrigerant channels

As shown in Figure 5, two refrigerants should be used, one for charging (R170) and another for discharging (R744). The challenge is how to use PPHXs for the two refrigerants as well as the thermal storage. For the refrigerants, the double-embossed two channel design (shown in Figure 4b, bottom) can be used so that each refrigerant can have its own channel. Another option is to use the double-embossed single channel design (shown in Figure 4b, bottom) but use the inner channels alternatively for the refrigerants.

4.2. Cost

As mentioned, the solid-liquid transition of CO_2 happens at high pressures (around 10 bar), above its triple point (see Figure 3). This means strict structural requirements for the heat exchanger as well as the pipework, which in turn can increase the cost. PPHXs are not very expensive but the main reason keeping their cost high at this moment is that they are usually custom-made. It is expected that their market share will increase over time, driving their costs down. It should be mentioned that the manufacturing process of each double-embossed two channel plate (shown in Figure 4b, bottom) is more expensive than the single channel design; however, the overall cost of the heat exchanger and the required surface area should be considered.

4.3. Vapour formation in the storage

CO_2 in the thermal storage unit remains liquid as long as the temperature remains below -40 °C (see Figure 3). However, in practice, due to the unavoidable heat gain from the environment some vapour will be formed in the storage. The problem is that the vapour has a very low density, requiring a large storage volume.

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Different approaches can be considered to deal with the formed vapour. For instance, in a large-scale installation, a dedicated storage unit can be used to condense the formed vapour. Another solution is to use a small refrigeration system to recondense the vapour (i.e., using a cold finger).

4.4. Control

A common challenge in thermal storage units is their control, especially when it comes to achieving a constant charge/discharge capacity. This is due to the fact that at the initial stage of the phase change process, there is a sudden release of capacity followed by a sudden drop which then asymptotically reaches zero after the phase change process is completed. Consequently, the refrigerant flow rate should be controlled to achieve a constant capacity.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

Industrial refrigeration plants operating at low temperatures are significant users of energy due to the required temperature lift of the refrigeration system. Thermal energy storage has been proposed as a measure to mitigate high peak power consumption in these systems; however, the lack of appropriate storage materials is hindering such low-temperature applications. There is a great potential for CO_2 to be used as the storage material for low-temperature thermal energy storage units. This paper has described the principle and design of a thermal energy storage unit utilising the solid-liquid transition of CO_2 in a specific heat exchanger design (i.e., pillow-plate heat exchanger). A potential system layout was also presented together with the challenges to be dealt with when using CO_2 as the storage medium.

The reported research on using CO_2 as a storage material for thermal energy storage to date is scarce and is currently limited to theoretical concepts and numerical investigations without validation based on experimental research. To increase the confidence in this promising technology, it is of key importance to demonstrate the feasibility of such thermal energy storage units at laboratory scale. An experimental test facility using CO_2 as the storage medium in the solid-liquid transition is currently under planning and development at the Thermal Engineering Laboratory at the Norwegian University of Science and Technology (NTNU). The aim of the test facility is to demonstrate and document the feasibility and performance of a thermal energy storage unit with a pillow plate heat exchanger and CO_2 as the storage medium. The charging and discharging performance will be investigated and the results from the experimental campaign will be used to design full-scale thermal energy storage units suitable for industrial refrigeration plants for freezing processes. Overall, due to the superior properties of CO_2 for such applications at low temperatures, it is expected that this topic would receive further research attention in the near future.

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DATA AVAILABLITY

Datasets related to this article can be found at https://doi.org/10.18710/MPL6FL, an open-source online data repository hosted at DataverseNO (Mastani Joybari et al., 2022b).

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