Energy saving potential in freezing applications by applying cold thermal energy storage with solid carbon dioxide

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ABSTRACT

In a time of fewer resources and rising energy prices savings of primary energy is an important goal for the food industry. This study analyses the potential of cold thermal energy storage (CTES) applying an indirect carbon dioxide system to reduce the electrical power needed by the freezing plant and to minimize the part load operation of the main compressor unit.

Theoretical aspects are explained, a system concept is presented and industrial applications are discussed. As an example from the fish industry, a tunnel freezer is applied as a base case for the modelling, it freezes 30t fish per day. A cascade process of ammonia and a carbon dioxide (CO_2) cycle is calculated for a 24 hours period. The calculation indicates that up to 30% less electricity is required for the equal freezing capacity, when CTES is utilized.

CTES is a promising technology and offers new temperature levels (below -50°C) for a wide range of applications. The proposed system offers a way to improve the performance and the efficiency of industrial applications as for example tunnel freezers.

The final design and operation of CTES systems applying the natural working fluid CO_2 requires further research in the behaviour of solid CO_2.

Keywords: cold thermal energy storage; carbon dioxide; solid carbon dioxide; improved efficiency

INTRODUCTION

Cold thermal energy storage is a method with a wide range of applications. Water ice baths, salt solutions and phase changing materials are used for a variety of industrial processes. One of the challenges when dealing with water ice slurries and salts are the temperature ranges of the applications. It is not possible to reach temperatures lower then -40°C, i.e. for applications below that temperature other substances have to be found. If temperatures of -50°C are required the use of carbon dioxide as storage medium is a feasible solution. The latent heat of the phase transition between solid and liquid CO_2 can be utilized to store cold energy at a low temperature level

The proposed indirect storage system is based on a tube and shell heat exchanger tank where pressurised liquid carbon dioxide is subcooled and becomes solid on the shell side, cooled by refrigerant (CO_2) inside the tubes.

MATERIALS & METHODS

During the charging process, carbon dioxide evaporates as gas or gas-solid mixture inside the tubes. The gas-solid stream has a lower temperature than the surrounding liquid CO_2, it is cooling the liquid phase on the shell side. The ice inside the tube sublimates while the liquid at the shell side freezes. This process continuous until most carbon dioxide on the shell side is converted into solid state as shown in part A of Figure 1. Part B shows the discharging, when the solid CO_2 is used to condense the working fluid of the low temperature circuit, shown in Figure 2

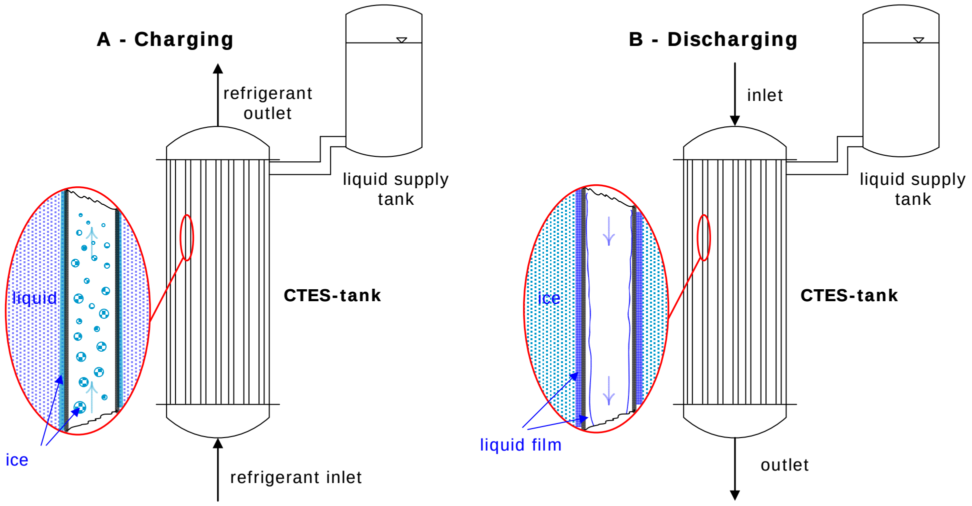

Figure1: Schematic sketch of a Cold Thermal Energy Storage tank for solid CO_2 storage.

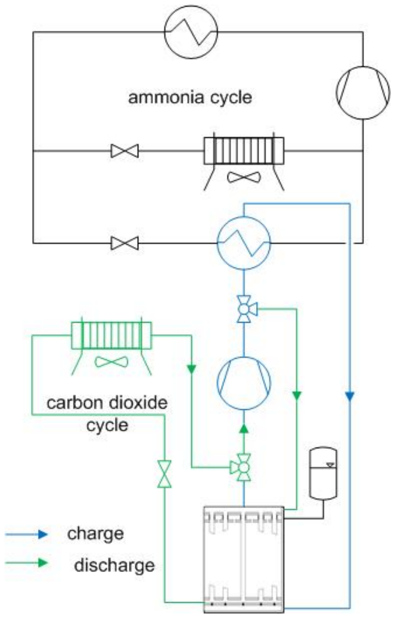

Figure 2: System layout.

An ammonia refrigeration cycle is used as reference system for the calculations. To calculate the effect of a carbon dioxide storage system an additional evaporator is added to the ammonia refrigeration cycle, i.e. the cascade heat exchanger transfers heat from the bottom carbon dioxide cycle into the ammonia cycle. Figure 2 shows the cascade system. Three different cases are analysed.

For case one and two only the ammonia cycle is calculated. This cycle consist of a compressor, a throttling device and two heat exchangers. The condenser is assumed to be cooled with (sea-) water at 15°C. The evaporator is cooling the air inside the freezing tunnel.
Suction pressure levels in the process vary depending on the different temperature levels inside the freezing tunnel.

Case study

The model considers a 24 hours period based on average values calculated for every 15 minutes.

Cooling capacity

A required cooling capacity for the tunnel freezer is assumed based on a heat flux curve for fish, as show in Figure 3. The heat flux curve is based on mackerel frozen in boxes of 20 kilogram. An assumption for intake of heat due to fans circulating air inside the tunnel (assumed to be constant) and additional heat through the walls are considered. The long period of very low cooling demand during the last hours should represent the standard mode of operation applied for most industrial tunnel freezer plants. These systems run for 24 hours to ensure that the storage temperature is reached in all parts of the product.

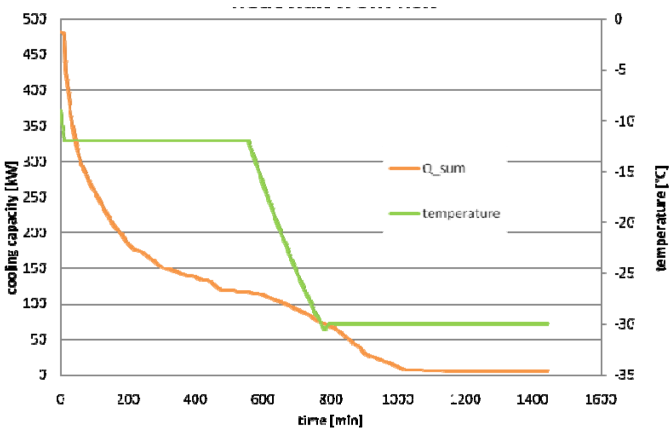

Figure3: Assumption for required cooling capacity

Temperature profile

Three different phases can be described for fish freezing. During pre-cooling the temperature of the fish is reduced to the initial freezing temperature. During freezing temperature is assumed to be constant and when the fish is frozen it is subcooled to storage temperature.

Case 1:

The airtemperature inside the tunnel freezer should remain constant at – 30°C during the whole freezing process. Therefore the compressor runs at full load in the beginning of the process. During freezing the compressor load is reduced due to reduced cooling demand during subcooling.

Case 2:

The airtemperature inside the tunnel freezer should remain at a constant temperature difference to the product.

Part load operation is, from the point of energy consumption, a challenge for compressor operation in freezing tunnels. To maintain the higher power consumption in the beginning of the process a higher capacity has to be installed which operates on part load later in the process. In the modelled system the part load is less then 5% in the last 4 hours of the process. Figure4 shows a worst case scenario for the ideal compressor work and the energy consumption resulting from the part load effects.

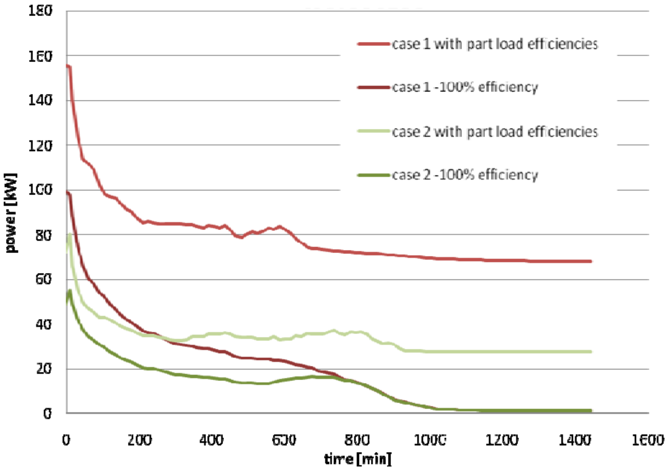

Figure 4: Influence of part loads on energy consumption

A commercial tool from Grasso is applied to calculate the performance of the ammonia plant, it is assumed that the process is operated with a Grasso screw compressor (PR-P2240S-28) giving a maximum refrigeration capacity of 237 kW at -30°C.

Case 3:

For this case a carbon dioxide cycle is added in a cascade arrangement to the ammonia cycle as shown in Figure 2. The carbon dioxide cycle consists of a compressor, the storage tank and two heat exchangers. It has two modes of operation charge and discharge.

For charging the tank, CO_2 is condensed by the cooling capacity of the ammonia cycle, which is available since the system is able to maintain the temperature in the tunnel freezer. Condensed liquid CO_2 can then be throttled by the nozzles inside the storage tank (CTES-Tank). The dry ice particles of the resulting two-phase stream are sublimated inside the storage tank. Then carbon dioxide gas can be compressed. A two stage compression with intermediate cooling by (sea-)water is used.

During discharge carbon dioxide is condensed inside the storage tank. Liquid CO_2 can than be throttled and evaporated in a heat exchanger cooling the air inside the tunnel freezer. The gas stream is compressed and flowing back into the storage tank.

Figure 5 shows the cooling capacities. The cooling capacity provided of the compressor is constant. The compressor is turned of after 675 minutes. Cooling capacity (number 1 in Figure 5) provided by the ammonia system is stored (number 2) and later used to provide the required cooling capacity during the last hours of the process (number 3).

In the beginning the total amount of capacity provided by compressors is lower then the required which is substituted by a higher amount later in the process. After 135 minutes the provided amount are higher then the needed cooling capacity and after 345 minutes extra cooling capacity is available which can be stored. The storage is filling and starts to unload when the compressor is turned of. This mode of operation avoids low part loads for the compressor operation, because the compressor is operating on full load most of the time.

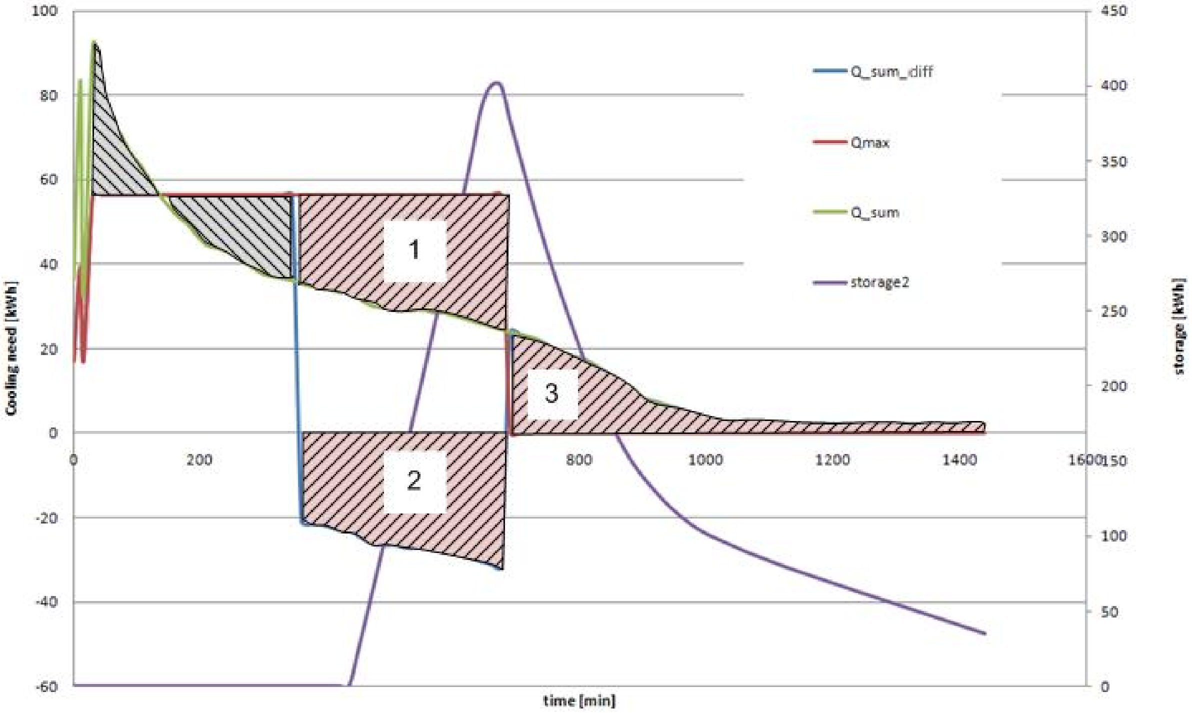

Figure 5: Cooling capacities and accumulated cold (solid CO_2)

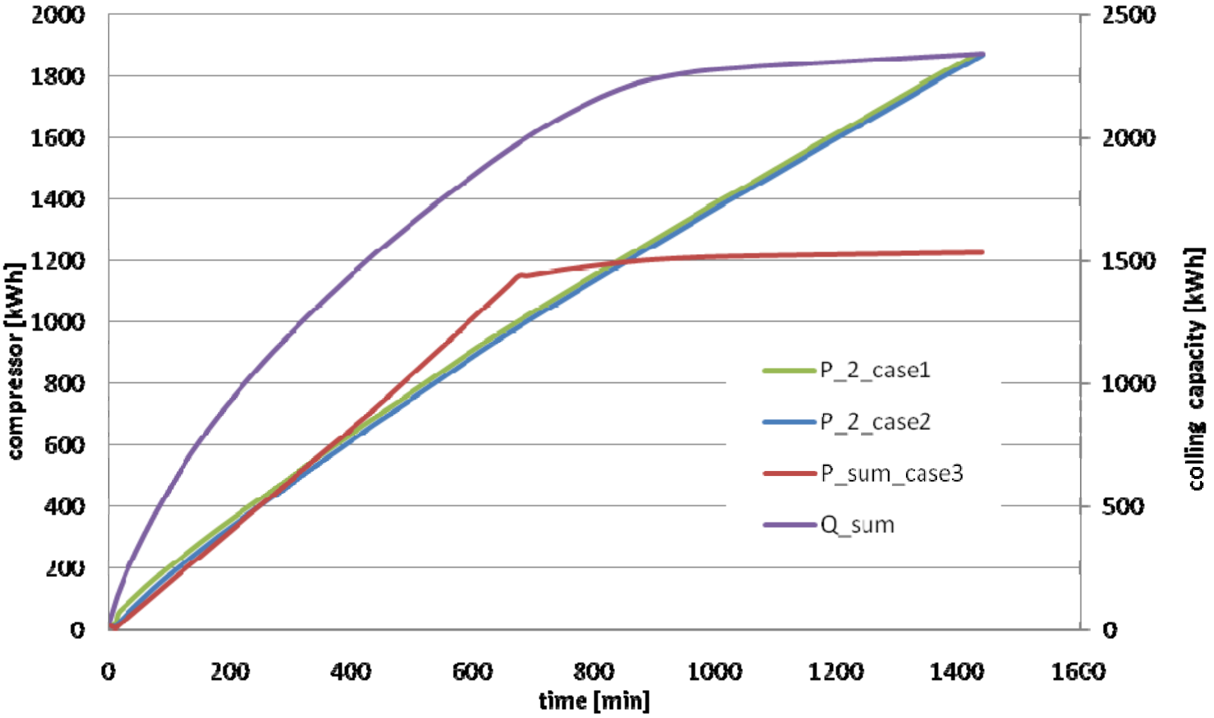

Figure 6: Accumulated compressor energy consumption

For a process as shown in Figure 5 a storage capacity of ~400 kWh is required. The approximately freezing time for the ice in the storage is 1.53 hours. The loading process in this examples takes more then 3 hours, hence freezing time is not a limiting parameter.
The capacity for fish of the tunnel freezer in this example is 30.000 kg mackerel with an initial temperature of 1°C. The storage temperature is -30°C. The energy consumption of the compressors is 0.09 kWh per kg fish.

The cascade process requires less energy. The main advantage of the proposed system is that less compressor capacity has to be installed and that stored cold is used to reduce the part load operation of the compressors in ammonia cycle. This results in a lower amount of required energy as shown in Figure6.

RESULTS & DISCUSSION

The design and construction of a tank with the proposed abilities is challenging. The heat transfer is complex due to the phase changes, the two-phase mixture can cause plugging and the ice growing on the shell side is difficult to predict. Therefore, new knowledge regarding the behaviour of carbon dioxide during phase transition (close to the triple point) is desirable. However, only a few literature resources are available which are describing the behaviour of CO_2 at the required temperature and pressure levels. The basic source of information related to solid carbon dioxide or dry ice is the book “Die feste Kohlensäure”[2]. Span and Wagner [3]described an equation of state for carbon dioxide in the fluid region, this equation is not covering the solid area. More research in the field of dry ice sublimation and modelling has been done by Prof. Span lately, however, the results have not been published jet.

Carbon dioxide for CTES provides a lower temperature level than state of the art storage applications. In food industry especially for frozen goods this can be an advantage, and applications for pharmacy products and cryogenic engineering may be possible. This form of cold storage can be used when temperatures lower then -50°C are required and it can give advantages in capacity, production time and product quality.

Tunnel freezers in the fish industry are not the best example for this application. During a year there are month where the plants are not running at all. Here applications for plants which run all year around may be better, for example plants dealing with farmed salmon rather than with pelagic fish.
For tunnel freezers working with pelagic fish another effect is disadvantage for the use for CTES. Due to the mode of operation the freezers are running 24 hours a day. So freezing time reduction of 3 hours is not helpful because the freezers will run for 24 hours anyhow. But simulations could show if it is possible to reduce the freezing time with storage to 12 hours and hereby double the capacity over a 24 hours period. Furthermore the cold produced and stored during freezing could be used for other applications on the site, for example after production storage. And it should be possible to increase the production rate and enhance product quality of the fish because of the lower temperature levels.

To gain more information on possible advantages and applications it is desirable to analyse a larger system. In a freezing plant effects can be important. It is possible to use the full capacity of compressors for loading coldstorage instead of running compressors on part load. Then the stored cold can be used for, saving the energy for the refrigeration cycles. In a plant more than one storage tank will be installed. So it is possible to unload one tank while another one is loaded at the same time.

Energy consumption and energy costs are an important topic for industrial plants. Using CTES the total installed compressor capacity can be reduced and part load operations avoided. So CTES gives the possibility to save costs during plant operation. To quantify that amount of money a more detailed model is required. Especially the influence of different temperature levels on the fish freezing behaviour has to be implemented in such a model. Then it is possible to quantify the change in freezing time, capacity, product quality and the resulting economic advantages.

To quantify the investment costs for a CTES tank and system more research has to be done on freezing parameters of CO_2.

CONCLUSION

The calculation indicates that up to 30% less electricity is required for equal freezing capacity, when cold thermal energy storage is applied to prevent inefficient part load operation of large ammonia refrigeration plant.

An idea of a novel cold storage system is introduced, however, further research on the behaviour of CO_2 around the triple point and a pilot system is required to identify the challenges which have to be overcome before an wide implementation of this technology can take place.

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