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Feasibility study of CO_2 accumulation

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

This study analyses the influence of cold thermal energy storage (CTES), using carbon dioxide as working fluid.

Theoretical aspects are explained, a system concept is presented and industrial applications are discussed. Since fishing industry is a field of great interest, the example of a tunnel freezer, freezing 30t fish per day, is further explained. The tunnel freezer for pelagic fish is used as a base case for the modelling. 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 applied.

CTES is a promising technology. Using carbon dioxide for storage of cold energy offers a new temperature level for a wide range of applications. The proposed system offers a way to improve the performance of industrial applications as for example tunnel freezers.

To design and operate a CTES system working with the natural working fluid CO_2 further research in freezing of CO_2 is required.

KEYWORDS

SELECTED BY AUTHOR(S)	Cold energy thermal storage	
	Carbon dioxide	

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1 INTRODUCTION

In a time of fewer resources and rising energy prices savings in energy costs are an important goal. This study analyses if cold thermal energy storage using an indirect carbon dioxide system can help to achieve that goal. Therefore theoretical aspects are explained, a system concept is presented and industrial applications are discussed. Since fishing industry is a field of great interest for Norway, the example of a tunnel freezer freezing 30t fish per day is further explained.

2 COLD THERMAL ENERGY STORAGE (CTES) USING CARBON DIOXIDE

2.1 CO_2 for CTES

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 used 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 flowing on the tube side.

2.2 Storage tank

A modified tube and shell heat exchanger should be used as storage tank, as shown in Figure 2.1 . The shell side contains liquid carbon dioxide at constant pressure and temperature. The carbon dioxide will change its phase from liquid to solid and solid to liquid according to supplied or removed heat quantities.

During the charging process, carbon dioxide flows 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. The ice inside the tube sublimates while the liquid at the shell side freezes (see part A of Figure 2.1). This process continuous until most carbon dioxide on the shell side is converted to ice.

During discharge CO_2 gas flows at a different pressure level at tube side. Because of a cooling effect caused by the ice on the shell side the gas condenses, which results in a liquid film inside the tube (Part B of Figure 2.1). The ice melting starts around the tube. This process continues until all ice is melted.
The thermal resistivity of liquids is lower than in solids. It can be assumed that the discharging time is significantly shorter than the charging time. To calculate an exact duration of charge or discharge knowledge about the ice growing velocity is necessary.
As shown in Figure 2.1 the tank has a cylindrical shape and contains a number of tubes. It is required to orientate the tank in a vertical position. The tubes are covered with liquid carbon

dioxide. The liquid supply tank ensures that the CTES-tank is completely filled with liquid. This is important to realise nearly isobaric operation conditions.

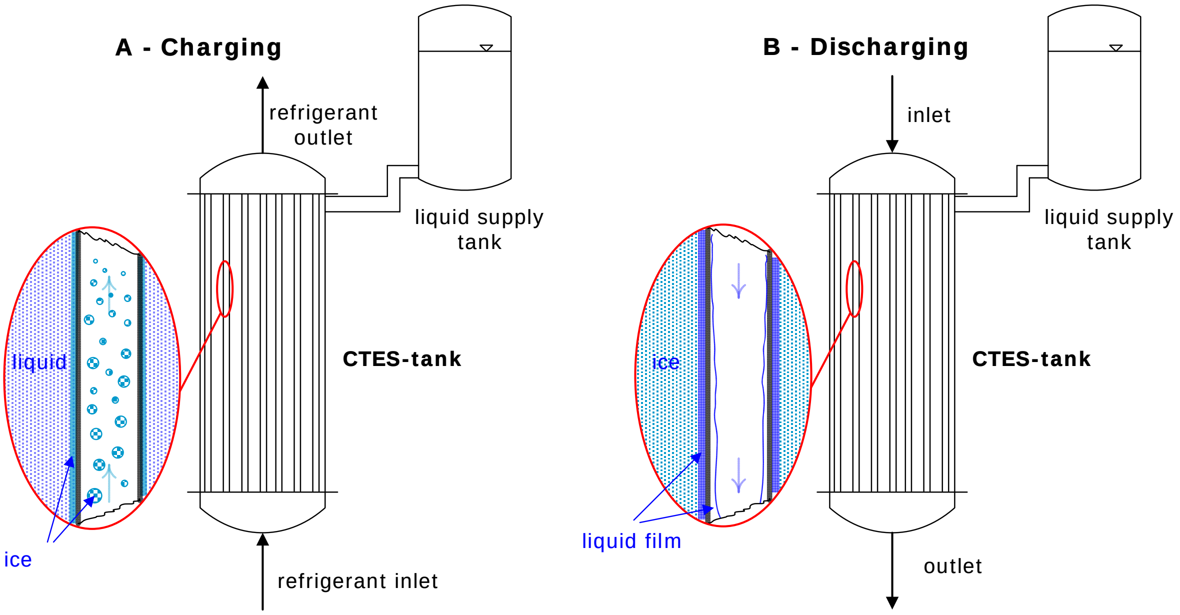

Figure 2.1: Schematic of a Cold Thermal Energy Storage tank

The phase change results in relevant volume contraction (28%). In an isochoric or mass constant operation mode this would lead to high mechanical stress in material, particularly in fittings. Therefore is it advisable to use a compensation tank. The liquid level in this tank changes with the volume change in the CTES-tank. To ensure that the liquid is able to flow inside the CTES-tank not all carbon dioxide in the tank can be frozen. Figure 2.2 shows the CTES-tank from the top in different operation modes. In the beginning (1) all the CO_2 in the tank is liquid (green colour: liquid). Then (2) refrigerant flows through the tubes at temperatures below triple point, which results in ice formation around the tubes (blue: ice).

After some time the tank is completely charged (3). It is important that not all liquid is turned to solid (green spots). This can be influenced by the position of the tubes and the cooling capacity. The flow direction of the refrigerant is important, too. Cold refrigerant enters in the lower part and ice formation starts at the bottom of the tank. Solid CO_2 has a higher density than liquid. Because of the volume contraction the liquid level in the CTES-tank would decrease but this effect is compensated by liquid from the liquid supply tank. To ensure that the pressure is constant in the CTES tank all ice has to be covered by a liquid film.

The pressure compensation works best when the tank has a vertical position. In case of a horizontal position less ice could be formed and additional tubing is required to guarantee liquid exchange inside the tank.

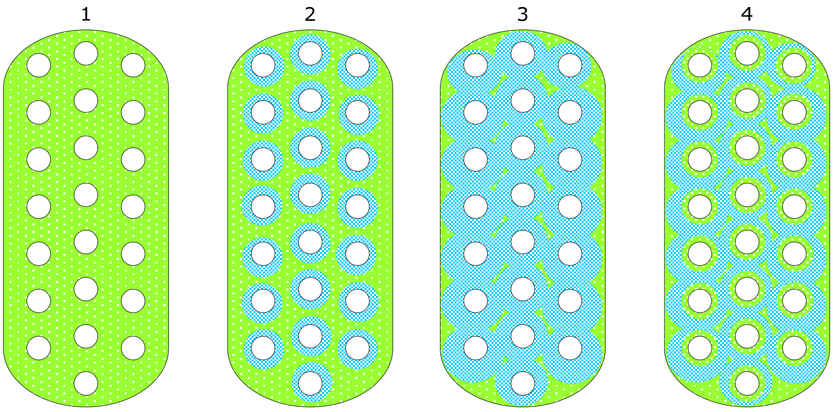

Figure 2.2: top view of tank; 1-4: unloaded, charging, loaded, discharging

During discharge (4) the ice next to the tubes melts first. The volume increases and liquid is flowing back to the supply tank. The discharge starts in the upper part of the tank because the flow direction on the tube side was reversed (see Figure 2.1).

Operation of the tank

To realise the phase changes as described above, specific temperature and pressure levels have to be realised inside the tank. The shell side should be continuously pressurised on a level of 8 to 10 bar. At this pressure level CO_2 freezes at -56°C.

To obtain a temperature difference between shell and tube side refrigerant has to be evaporated at tube side. This refrigerant could be CO_2. If carbon dioxide is depressurised to levels below the triple point dry ice is formed. A pressure of 2 bar will for example result in a temperature drop to -70°C. As shown in Figure 2.3 liquid CO_2 is throttled by nozzles implemented in the bottom of the tank. For a working system it is required to choose nozzles and a mode of operation that result in a gas-particle-stream that can flow trough pipes without blocking them. An important parameter is the solid content of the two-phase flow.

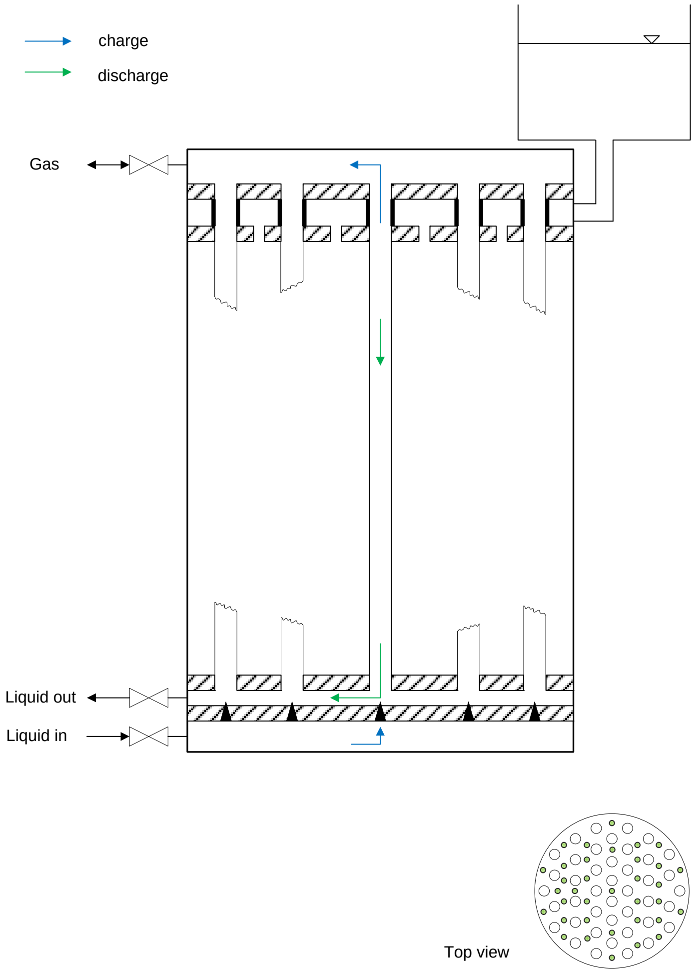

Figure 2.3: Sketch of CTES-Tank

During discharge, gas flows in opposite direction through the tubes. The pressure inside the tubes is above triple point pressure (>5 bar). Liquid CO_2 condenses inside the tube at the walls and flows to the bottom of the tank where it is collected and returned to the refrigeration cycle. The design of the bottom of the tank has to provide a way to implement nozzles for charge and liquid collection during discharge.
The upper part of the tank is applied as in- and outlet for gas streams on tube side. The shell side needs a connection to a liquid compensation supply tank. To guarantee that the liquid flow is not blocked by ice formation, the tubes have to be isolated in that part of the tank.

Calculation of the storage tank

Geometry and freezing time are important information concerning the storage tank. To calculate the geometry it is important to know how much ice has to be stored. The capacity of the storage gives the mass of ice, which gives information about volumes.

$$m_{ice} = \frac{C}{h_F} \qquad V_{ice} = \frac{m}{\rho_{ice}} \qquad V_{liquid} = \frac{m}{\rho_{liquid}}$$

With assumptions for the number of tubes, tube diameter and length, the geometry of the tank can be calculated.

$$V_{tank} = m_{ice} + N_{tube} \cdot \pi \cdot r_{tube}^2 \cdot l_{tube} + m_{ice} \cdot F_{save}$$

$$d_{tank} = \sqrt{\frac{4 \cdot V_{tank}}{\pi \cdot l_{tank}}}$$

Freezing time is a critical information. It can be calculated using the assumption of a growing ice layer around a single tube. The volume of ice around a tube is the ratio between total volume of ice and number of tubes. With the tube diameter the thickness of the ice layer in the end of the freezing process can be calculated [1].

$$s_{ice} = \sqrt{\left(\frac{\frac{V_{ice}}{N_{tube}}}{\pi \cdot l_{tube}} \right) - r_{tube}^2}$$

With thermodynamical properties of CO_2 the freezing time can be estimated. The calculated values will be lower then the actual freezing time [1].

$$t = \frac{h_F \cdot \rho_{ice} \cdot s^2}{2 \cdot \lambda_{ice} \cdot \left(\vartheta_F - \vartheta_0 \right)} \cdot \left[\left(1 + \frac{1}{s^+} \right)^2 \cdot \ln\left(1 + s^+ \right) - \left(1 + \frac{2}{s^+} \right) \cdot \left(\frac{1}{2} - \beta \right) \right]$$

$$s^+ := \frac{s}{r_{tube}} \qquad \beta = \frac{\lambda_{ice}}{\lambda_{wall}} \cdot \ln \frac{r_{tube}}{\left(r_{tube} - s_{tube} \right)} + \frac{\lambda_{ice}}{\left(r_{tube} - s_{tube} \right) \cdot \alpha}$$

2.3 State of the art

The design and construction of a tank with the proposed abilities is combined with a number of challenges. The heat transfer is complex due to the phase changes, the two-phase mixture can cause plugging and the ice growing at shell side is difficult, too.

Therefore good knowledge about behaviour of carbon dioxide during phase transition is desirable. However, only a few literature resources describing the behaviour of CO_2 at the required temperature and pressure levels are available. A side effect is that most programs dealing with data for substances and refrigeration cycles (like Rnlib, Refprop or CoolPack) are not able to calculate values for solid carbon dioxide.

If talking about solid carbon dioxide or dry ice the basic sources of information is the book “Die feste Kohlensäure”[2].

However, 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 but the results have not been published jet.

2.4 Further research

Freezing parameters of CO_2 are significant information for the design of the tank. So research in that field is necessary. Some sources report about subcooling, an effect that can influence the temperatures for freezing. Other parameters are freezing time and behaviour, influence of pressure differences, sublimation rate of dry ice particles, heat transport properties (ice layer), volume contraction, etc..

Also heat transport inside the tank is combined with some challenges. The question which surfaces are necessary to grow CO_2-ice on it or how tubes and nozzles have to be designed to sublimate dry ice particle and realise two phase flow are important, too.

A number of parameters have to be analysed before a tank for solid carbon dioxide storage can be designed and operated.

3 EXPLANATION OF THE MODEL SYSTEM

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 3.1 shows the cascade system. Three different cases can be analysed.

For case one and two only the ammonia cycle is calculated. This cycle consist of a compressor, a throttling nozzle 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.
Pressure levels in the process vary depending on the different temperature levels inside the freezing tunnel.

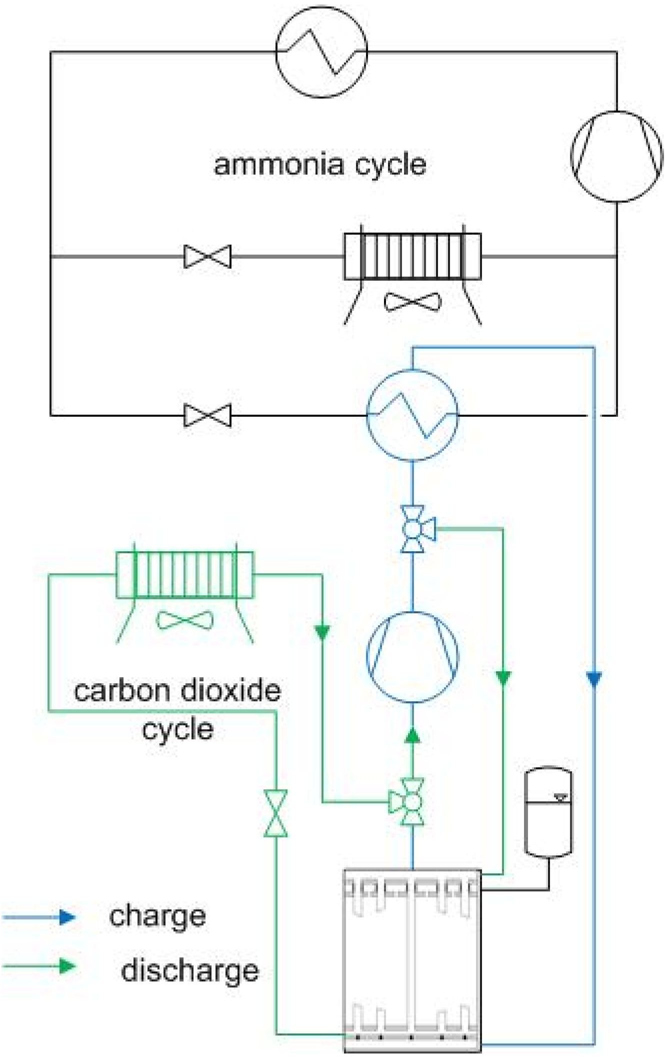

Figure 3.1: schematic of cascade process

3.1 Case study

The model is based on a 24 hours period of time and based on values calculated for steps of 15 minutes.

Cooling capacity
A required cooling capacity for the tunnel freezers is assumed. The assumption is based on a heat flux curve for fish. The heat flux curve is based on mackerel frozen in boxes. An assumption for intake of heat due to the ventilation systems blows inside the tunnel (assumed to be constant) and a temperature dependent heat lost due to environmental influences is added to obtain a total required cooling capacity.
The long period of very low cooling demand during the last hours should represent the mode of operation in industrial tunnel freezer plants. These systems run for 24 hours to ensure that the storage temperature is reached in all parts of the product.

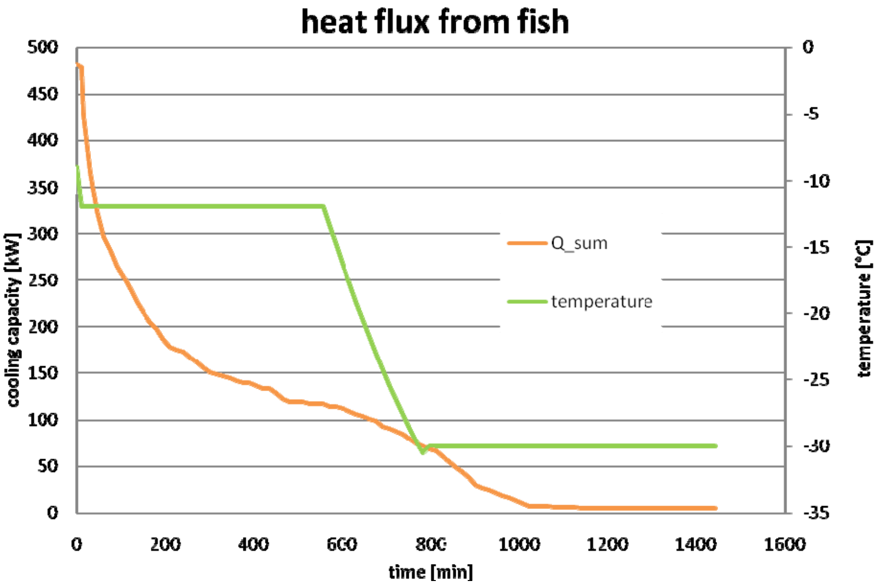

Figure 3.2: Assumption for required cooling capacity

Temperature profile
Three different phases can be described for fish freezing. During precooling 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 temperature 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 temperature 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. Figure 3.3 shows a worst case scenario for the ideal compressor work and the energy consumption resulting from the part load effects.
For calculating the part load effect information of the program Comsel were used. 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.

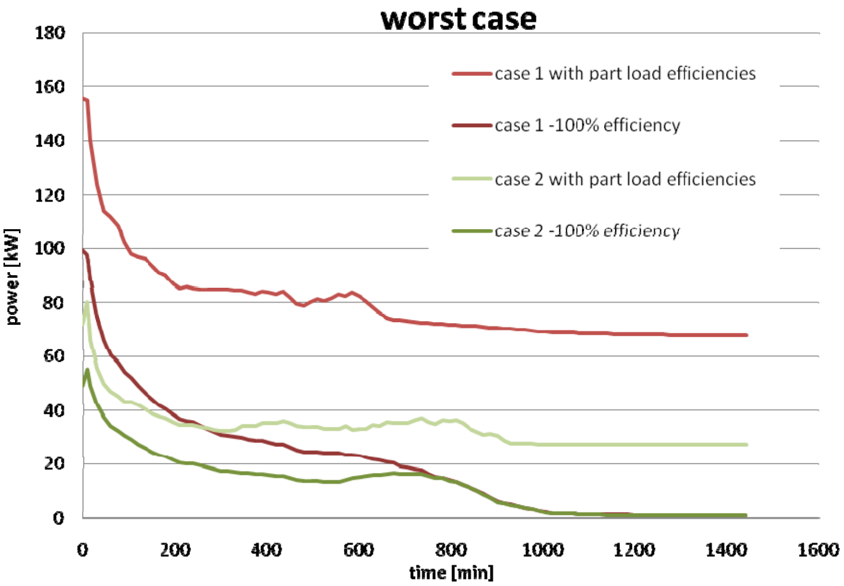

Figure 3.3: influence of part loads on energy consumption

Case 3:

For that case a carbon dioxide cycle is added in a cascade arrangement to the ammonia cycle as shown in Figure 3.1. 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.

Than 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.

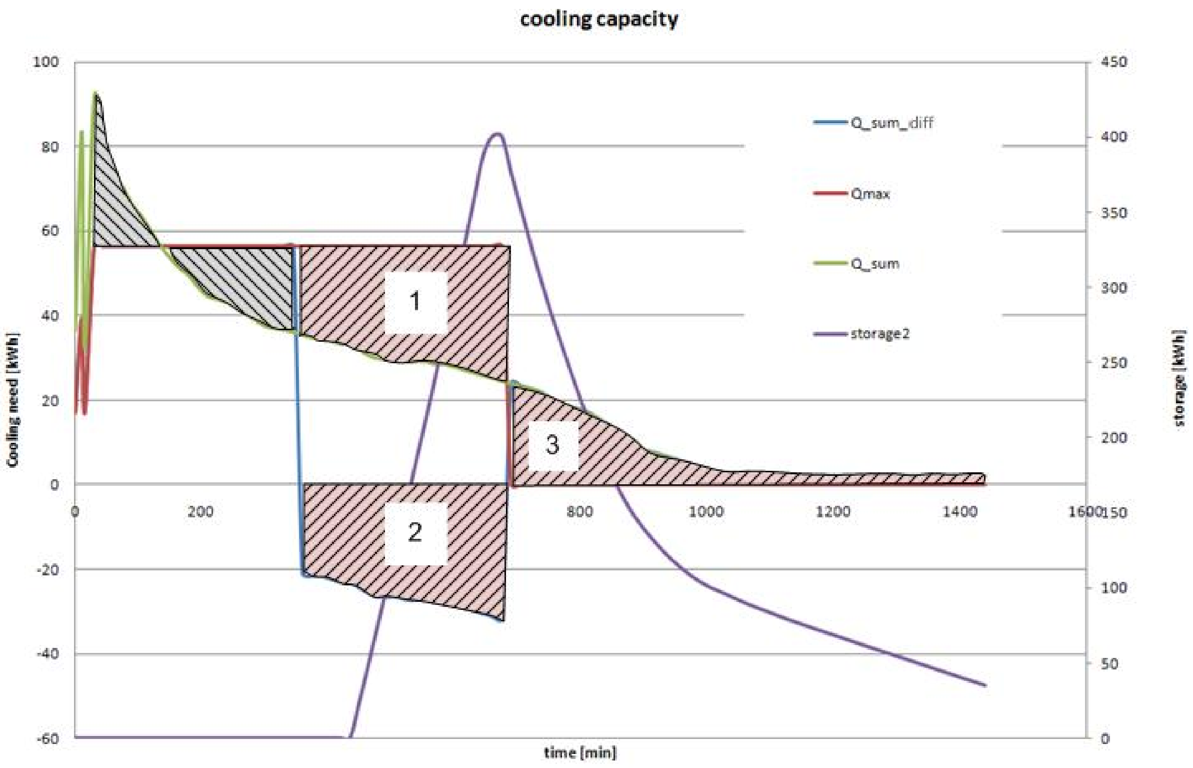

Figure 3.4: Cooling capacities

Figure 3.4 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 3.4) 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.

For a process as shown in Figure 3.4 a storage with a capacity of 400 kWh is needed. This equals to 7200 kg of CO_2 which results in 4.8 m^3 of ice. Therefore a storage tank of 7 m in length has to be approximately 1.2 m in diameter and should contain about 500 tubes. 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 reduce the total amount of 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 Figure 3.5.

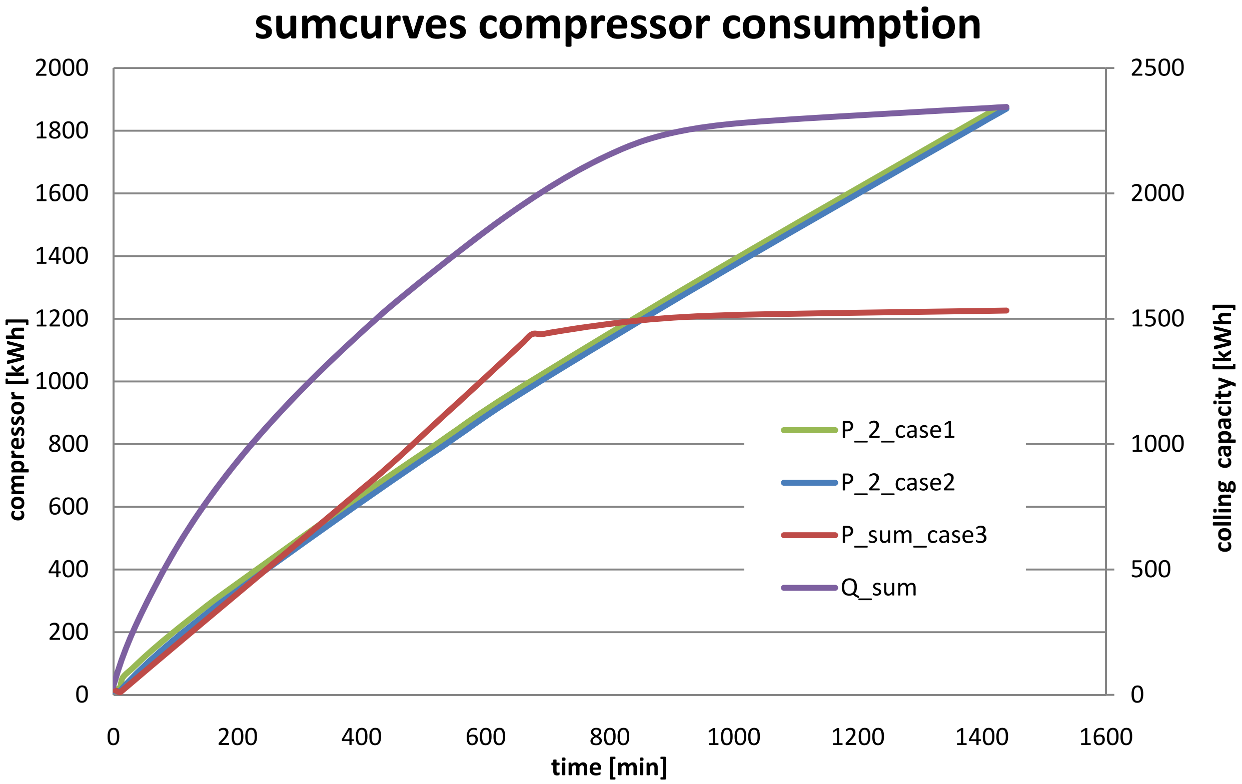

Figure 3.5: energy consumption by compressors

3.2 Evaluation of the model

The basic problem of the model is that the fish is not part of it. The assumption that the fish is not influenced by different temperatures in case study is not realistic. So it is not possible to obtain any information about the influence of temperature level variations on the freezing time of the fish. This information would be valuable to evaluate the influence of the lower temperatures from the storage on product and freezing process especially freezing time and capacity of frozen fish.
It can be that the lower temperatures lead to a reduced total freezing time which would lead to a significantly lowered energy consumption or a higher capacity for freezing of fish.

Another challenge is the simulation of the carbon dioxide cycle. Since no equations are available for solid carbon dioxide the values for the calculation are taken from a T-S-diagram. So it is not possible to calculate changes in pressure or temperature automatically.

The model can be improved by better assumptions for a number of parameters. The heat transfer is not implemented, the change in temperature levels and the resulting effects are not simulated and the operation of the system (ventilation, temperature in heat exchangers) is not part of the simulation.

The current model gives an idea how a storage system could work. To obtain valid information more measured values and specific information have to be added.

3.3 Further research

The current model was done with Excel. It would be interesting to apply modelling software like Modellica. There a model for the fish behaviour could be implemented to obtain values for influence of temperature levels and how to use the storage. A question is for example at which point of process it is best to use cold provided on a lower temperature level from the storage.

The simulation can be improved when more components in the ammonia cycle are added to represent a tunnel freezer plant in a better way. This would allow a more detailed conclusion, especially for reducing part load operation.

4 DISCUSSION

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 fishing 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 salmon rather then 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 site system effects can be important. It is possible to use the full capacity of compressors for loading storage instead of running compressors on part load. Then the stored cold can be used for cooling shipping or production storages, saving the energy for there 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 safe 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.

5 CONCLUSION

This feasibility study was performed to get an idea of the challenges and possibilities combined with CTES using CO_2 as working fluid. It shows the possibilities of that new application and gives an overview of research needed to get more insight on the topic.

CTES is a promising technology. Using carbon dioxide for storage of cold energy offers a new temperature level and with that new applications. The proposed system offers a way to improve the performance of industrial applications as for example tunnel freezers.
To design and operate a CTES system working with the natural working fluid CO_2 further research in freezing of CO_2 is required.

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