Cavern Thermal Energy Storage for District Cooling

Feasibility Study on Mixing Mechanism in Cold Thermal Energy Storage

Rami Alfasfoss
Master of Science Thesis EGI-2017-038

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ABSTRACT

There are studies available on stratification methods used for storing cold water in thermal energy storage (TES), however there are few studies that discuss alternatives. The purpose of this research is to discuss the feasibility of using a non-stratified (mixed storage) mechanism for storing cold water for district-cooling systems.

Understating the needs for district cooling technology will be discussed in the introduction chapter, where an overview of buildings’ energy consumption and EU regulations on inside temperature in relation to expansion of the district cooling network will be presented. Before researching the technologies that are used for storing cold water, a general understanding of different types, benefits and challenges of Thermal Energy Storage (TES) technology will be discussed, followed by a study on the district cooling market in Sweden and technologies used for storing cold water. Moreover, reasons and challenges for expanding this technology will be assessed in this country.

An abandoned underground oil cavern in Stockholm city is used in this study; therefore, using Computational Fluid Dynamic (CFD) for simulating a process will be a practical and economical solution to perform feasibility studies. The methodology chapter will discuss, in steps, the use of COMSOL Multiphysics software to simulate the storing process of cold-water in the underground cavern. After presenting the analysis of simulation results, the outcome will be discussed and presented in both theoretical and numerical approaches, finally, conclusions and future implementations will be drawn.
Det finns studier på stratifieringsmetoder för att lagra kallt vatten i värmeenergilagring (Thermal Energy Storage, TES), men få som diskuterar alternativ. Syftet med denna studie är att diskutera möjligheten att använda en icke-stratifierad mekanism för lagring av kallt vatten för fjärrkyla.

Behovet av fjärrkylteknik diskuteras i inledningskapitlet, med en översikt över byggnaders energiförbrukning och EU-regler om inre temperatur, i förhållande till fjärrkylnätets expansion. Innan man undersöker tekniken som används för att lagra kallt vatten diskuteras allmänt olika typer, fördelar och utmaningar för termisk energilagringsteknik (TES), följt av en studie av fjärrkylningsmarknaden i Sverige och teknik som används för lagring kallt vatten. Därutöver kommer förutsättningar och utmaningar för utökad användning av denna teknik i Sverige att bedömas.

I would like to express my gratitude to my supervisor Justin Chiu for his guidance, support and valuable inputs, comments and swift communication throughout the learning process of this master thesis.

Furthermore, I would like to thank The Royal Institute of Technology KTH for providing the suitable learning atmosphere and materials to proceed with this project. I would like also to thank Hamidreza Rastan and Jean-François OLIVIER, for without their assistance I could not have accomplished this project.

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### NOMENCLATURE

#### Notations

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$A_c$</td>
<td>Cross-sectional charging process surface</td>
</tr>
<tr>
<td>$A_d$</td>
<td>Cross-sectional discharging process surface</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Total surface area of the cavern</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Pipes area surface</td>
</tr>
<tr>
<td>$C$</td>
<td>Specific heat</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Fluid heat capacity at constant pressure $(J/(kg\cdot K))$</td>
</tr>
<tr>
<td>$D$</td>
<td>Pipe’s Diameter (m)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat transfer</td>
</tr>
<tr>
<td>$k$</td>
<td>Fluid thermal conductivity $(W/(m\cdot K))$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Thermal efficiency for stratified TES</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Charging mass flow rate over a time increment $(m^3/s)$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Fluid density $(kg/m^3)$</td>
</tr>
<tr>
<td>$\text{Re}$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature $(^\circ C \text{ or } K)$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Absolute temperature of the surroundings $(K)$</td>
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<tr>
<td>$T_{in}$</td>
<td>Inlet temperature</td>
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<tr>
<td>$T_{out}$</td>
<td>Outlet temperature</td>
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<tr>
<td>$\Delta t$</td>
<td>Time increment</td>
</tr>
<tr>
<td>$t_c$</td>
<td>Charging time (s)</td>
</tr>
<tr>
<td>$t_d$</td>
<td>Discharging time</td>
</tr>
<tr>
<td>$V$</td>
<td>Cavern volume $(m^3)$</td>
</tr>
<tr>
<td>$V_{c-inlet}$</td>
<td>Water Inlet velocity flow rate during charging</td>
</tr>
<tr>
<td>$V_{d-inlet}$</td>
<td>Water Inlet velocity flow rate during discharging</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Average fluid velocity flow (m/s)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Water viscosity $(pa\cdot s)$</td>
</tr>
<tr>
<td>$u$</td>
<td>Fluid velocity field (m/s)</td>
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilating and Air-Conditioning</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Energy Storages</td>
</tr>
<tr>
<td>UTES</td>
<td>Underground Thermal Energy Storage</td>
</tr>
<tr>
<td>BTES</td>
<td>Borehole Thermal Energy Storage</td>
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<tr>
<td>CTES</td>
<td>Cavern Thermal Energy Storage</td>
</tr>
<tr>
<td>CCTES</td>
<td>Cold Cavern Thermal Energy Storage</td>
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<tr>
<td>ATES</td>
<td>Aquifer Thermal Energy Storage</td>
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1. INTRODUCTION

In the last few decades, the quality of buildings has improved and is expected to continue as such, due to strict regulations on the materials used in construction as well as on indoor temperatures. As a result, efficient cooling systems maintaining the indoor temperature in a pleasant zone are needed. There are different technologies to deliver cooling for buildings; one of them is a district-cooling system, which has been expanding especially in developed countries. This triggers an increase on the demand for cold thermal energy storages (CTES) as they are an essential part of district cooling networks. The ability of CTES for storing cold water enables the system to balance between supply and demand for cooling, which enhances the overall system efficiency and reduces cost on district cooling companies. Since the oil crises in the seventies, Sweden has been trying to invest in cleaner energy so as to limit the dependency on fossil fuel based energy sources, this approach was clear also on the first conferences suggested by the Swedish government to the United Nations to discuss the relation between human, economy and environment which later on led to the concept of sustainability, this conference was held in Stockholm in 1972.

Reduction in oil demand has led to a number of unused underground oil caverns, these caverns are an investment opportunity for use as cold water storage for shifting peak load from demand. Traditionally, stratified mechanisms have been used in district cooling network for storing cold water in CTES. However, stratified mechanisms for underground thermal energy storage require an installation for sets of pipes in both the top and bottom sides of a cavern. Installing pipes for stratified storage requires special mechanical and manufacturing preparations. It may also need professional divers or robots to adjust the number of pipes inside the underground storage.

These requirements add a high initial cost, as well as being potentially life-risking for the technicians. As for an investment, the initial cost for using a stratified method for storing cold water in an underground cavern can be high considering the low storage capacity of storing cold water for district cooling purpose. Thus, this study will investigate a non-stratified (mixed) storage mechanism as an alternative mechanism on abandoned underground oil caverns to substitute for the stratified one. Storage capacity can be defined as the ability of the cavern to store cold water during daily operational hours. In addition to other factors such as safety, storage capacity will be used as a key factor for concluding the feasibility of a mixed storage method as alternative mechanism for storing cold water in underground caverns.
1.1 Background

Building and services related sector is one of the major energy consumers, this makes them very attractive to invest in for energy reduction due to global demand for reducing energy consumption and increasing the energy efficiency in both private and public sectors. According to statistics, building and service sector has on average 40% total EU energy demand and is responsible for a similar percentage of greenhouse gas emissions (Ardente, et al., 2010). These statistics urge governments to focus on implementation plans as well as different sets of regulations that aim to increase the energy efficiency in buildings and to reduce greenhouse gases. (Geller, et al., 2006)

Moreover, EU regulations on buildings are considered a major driving factor for expanding District Cooling Systems (DC). Buildings have become more insulated and have less energy demand especially due to lower levels of heat loss. Heat radiation from electrical equipment such as lighting, computers and screens, as well as heat generated from human bodies inside office buildings are some of the main reasons for increasing indoor temperature. As a result, cooling these spaces has become a necessity due to EU regulations that obligate the indoors temperature of a building to be within the comfort zone. As recommended in EN15251: 2007 for instance, minimum 20°C in the winter season and maximum 26°C in summer (Berlih, 2013). Banning CFC that was used as refrigerant in heat pump and refrigeration for environmental concerns has increased the need for alternative cleaner solutions for cooling. (Werner, 2017)

Trapped heat causes a constant increase in the inside temperature during the day, adding on the passive heating that is gained from the sun radiation. Without recycling the heat gained during the day, the indoor temperature will exceed the acceptable limit for room temperature and it will cause an unpleasant feeling for the occupants. A cooling system is required to keep the living spaces within a desired temperature range. Alternative solutions to reduce and balance energy demand for both heating and cooling especially for public buildings such as hospitals, shopping centres and work spaces were necessary, aimed to achieve a higher energy efficacy and more environmental friendly buildings, at the same time taking into consideration the well-being of the residences.

Thermodynamically speaking, cooling in fact is extracting heat from a medium. This would lead to the conclusion that the gained heat during the day needs to be expelled from the space so as to keep the space within the desired temperature.

Since the early nineties, demand for district cooling has been increasing in Sweden; the reason behind was the shifting of the government strategy to have more independence from fossil fuel as an energy source, after the oil crises in the seventies. In addition, other reasons were the environmental commitments that the country had signed for, to invest more in alternative cleaner energy. This action had started much earlier, dating back to the first conference held by the United Nations in Stockholm in 1972, where the relationship between humans, economy and environment was discussed (United Nations, 2017). However, the shift towards more environmental friendly technologies such as district cooling over the traditional ones for cooling took over two decades, since cooling was mainly based on heat pumps and HVAC systems.

Higher energy efficiency in buildings can be reached using different techniques: starting from the material types used in construction, energy saving equipment, and even the inside building design and its orientation. The main energy consumption in buildings especially in public buildings is due to HVAC systems (Heating, Ventilating, and Air-Conditioning). According to EU studies, HVAC is responsible for almost 50% of the total energy demand in a building. (Danielski, 2014) However,
the EU regulations for the indoor temperature make the dependency on HVAC higher due to high cooling demand during summer and high heating demand during winter to keep the indoor temperature within the comfort zone for the occupants.

Different technologies have been tested and used for cooling residential and public buildings. It can be mechanically driven cooling such as HVAC system, heat pumps and refrigeration cycles or passive cooling, which can be either preventing heat entering the building or removing the heat from inside buildings. For example, by painting roof tops, solar shading and natural ventilation (Kamal, 2012). Preventing the heat from entering a building could be one of the best approaches for reducing cooling demand but it cannot alone stabilize indoor temperatures year-round. Moreover, mechanical cooling consumes a large amount of energy and can lead in some cases to environmental problems, while dumping heat outside instead of recycling it as useful energy could also lead to extra heating demand during the colder time of the day. Nevertheless, wasting energy by dumping heat outside is contradicting the concept of energy and environmental conservation and may increase the expenses for buildings to sustain their indoor temperature within the allowed limits.

District cooling networks were established widely in Sweden since early nineties. In 2015 DC networks stretched to 544 km in length achieving total sales of almost 1TWh making Sweden the leading country in Europe for delivering district cooling. (Euroheat, 2017) The national statistic estimated 45 KWh/m² as the national demand for cooling in 2014. (Sköldberg & Rydén, 2014)

The national statistic estimated 45 KWh/m² as the national demand for cooling in 2014. (Sköldberg & Rydén, 2014)

1.2 Scope of the Study

In this project, a district cooling company aims to use an abandoned oil cavern for cold water storage as part of the district-cooling network extension in Sweden. There are two TES mechanisms used to store cold water: (Geller, et al., 2006):
Stratified
Non-stratified (Mixed storage)

Studies on district cooling storage systems are rare in general; the stratified storage mechanism is still the most common method used for district cooling and there are more studies and research material conducted on mixed storage.

Storing cold TES relies mainly on the stratification method, which is less economically feasible for underground caverns and may lead to construction complications in some cases due to the complexity of the installations of the piping system. Expanding the market of cold thermal energy storages would require searching for alternative technologies to stratification that are more cost and capacity competitive. Any technology proposed as an alternative should be able to cover the peak cooling demand hours, as well as minimising the dependency on external chillers that are expensive to operate and require larger spaces above the ground.

This project will proceed with a feasibility study on a non-stratified (mixed storage) mechanism based CTES as an alternative solution to stratification, for thermally storing cold water for shifting cooling load as a case study dedicated to one of the major district cooling companies in Stockholm. The water storage for this study is an abandoned underground oil cavern, as an essential part of the district cooling system in Sweden. This study will compare the results with other conducted studies carried out on the same storage using stratified technology as a method to store water for DC system. We will also provide detailed documentation on using CFD software for modelling and simulating a non-stratified mechanism for (mixed) storing cold water in cavern thermal energy for the district cooling system.
2. LITERATURE REVIEW

Thermal storages for district cooling are necessary to keep the heating/cooling balance in a building during the day and night and also during the peak periods of the year. Cooling demand is increasing during the day and it reaches its peak especially with spaces that have a large number of occupants and equipment. This would require transferring some of the excess heat through a liquid medium, usually water and transporting it through a distribution network of pipes. Different stations might be necessary for cooling the medium to the desired temperature such as chillers and heat exchangers.

According to the EU commission, half of the EU’s energy consumption is from heating and cooling in residential buildings and industry, and while almost 70% of energy consumption was used for space heating, 3% was used for cooling these spaces. Thus in 2015 EU has launched a strategy plan to cut energy used from the heating and cooling sectors. (EU commission, 2017)

The market trend is expected to expand when it comes to cooling demand in Europe, as well as the need to reduce the use of energy while providing cooling, for example, through using compressors, as according to a district cooling paper review (Wenjie, et al., 2016).

2.1 Introduction to District Cooling and TES

District cooling is the technology that allows delivering chilled water that is produced in a separate location, other than the building that requires cooling. It is similar to district heating, and both aim to achieve a comfort zone inside buildings. This new technology is an early system, where very few statistics have been collected on the subject. However, statistics show that there is a trend towards using district cooling and it shows a sharp increase due to the positive effect of using this technology for both the environment and the economy (Poredos & Kitanovski, 2011).

According to Bo Nordell, twenty-one DC-systems are used traditionally in Sweden where cold water from sea or lakes is used to supply cooling systems in buildings. However, there is slow progress on the awareness of the benefits and potentials of this technology, and it is currently used in only a few countries, mostly Europe, Emirates, India, Qatar, Canada and the US. (Nordell & Skogsberg, 2002)

The first district cooling systems were installed in the US in the 60’s and the early system was the “pipeline refrigeration” in New York in 1890 (Nordell & Skogsberg, 2002).

The purpose of district cooling system is to use energy at a lower cost during off peak hours to store cold water to used later during peak hours. This aims to substitute fully or partially the use of primary energy for cooling utilities, which will also contribute in increasing energy efficiency in buildings and reducing the environmental impact from using conventional energy sources for generation cooling in buildings.

District cooling can be produced by three different methods: free cooling, absorption cooling and heat pumps (Werner, 2017)

**Free cooling:** is a technology that circulates water from lower temperature outside sources, such as lakes, rivers or the ocean to cool the water in the district-cooling network. The temperature of
the free water should be no higher than 4 °C for it to be useful. This water is then returned to the water source at a temperature of around 14 °C. Furthermore, snow collected during the winter can also be used to provide cooling later through the use of snow and ice storage for later use as figure 2.1 below illustrates (Werner, 2017).

![Figure 2.1. Outline of a ground pit snow deposit for seasonal cold storage (Nordell & Skogsberg, 2002)](image)

**Absorption:** Is using heat instead of electricity as energy source for cooling proposes. A refrigerate can use various heat sources such as waste heat from factories, wasted hot water form District heating systems. Refrigerate boils at low temperature – around -18 °C. The cooling effect happens when the refrigerate evaporates that allow to heat extraction from the spaces that needed to be cooled.

**Heating pump:** can produce both cooling and heating, and they are the most used technology in Sweden for this purpose.

### 2.2 Technology Used for Storing Cold Water

Many technologies can be used to store cold water as daily or seasonal storages. These will be described below. In large-scale applications, underground and snow storage are the most promising alternatives.

Cold energy can be stored both in liquid water or ice form. While cold water can store around 10 kWh per cubic meter of storage, ice is more energy dense and can store up to 50 kWh of cold energy per cubic meter of storage, providing a higher energy density and reducing the volume of the system. (Irchima research, 2017) Water can store energy as sensible heat whereas ice does it by using latent heat.

#### 2.2.1 Thermal Energy Storage Technology (TES)

Thermal energy storage is one of the techniques for energy conservations used from the time of the early human, either by storing water in clays or even ice storing for later usages. In the current time, human interest to develop alternatives for conventional energy sources, triggers the need for thinking of practical and efficient energy storages as an essential part of any large or small-scale energy generation project. In some cases, not finding a suitable energy storage could be a stopping point for some of the energy projects.

Storing the energy, as mentioned in the first chapter, plays a leading role in enhancing energy conservation and also in balancing its supply and demand in a way that meets the social needs, as well as having a better effect on the environment.
Storing energy thermally could be very beneficial for cooling and heating systems as other applications. One of the major usages for thermal energy storages in highly populated cities is for district heating and cooling for residential buildings and offices.

Nevertheless, underground TES are divided into two main categories:

- **Closed System**: where heat exchangers are used to pump water into the ground through boreholes.
- **Open System**: where wells or underground caverns are used as storages and water is pumped out and into the ground.

Underground Thermal Energy Storages (UTES) are used for storing water or fluid thermally underground, most of these technologies have been developed since the 1970s. The following are currently the most commonly used ones. (Gehlin, et al., 2015):

- Aquifer Thermal Energy Storage (ATES)
- Borehole Thermal Energy Storage (BTES)
- Cavern Thermal Energy Storage (CTES)

This study will focus on the Cavern Thermal Energy Storage (CTES) as a technology for storing cold water for use in the district cooling system in Sweden, as the research will be done on an abandoned oil cavern. The following paragraphs will explain the UTES in Sweden.

### 2.2.2 Underground Thermal Energy Storage Systems (UTES)

#### 2.2.2.1 Shallow Geothermal Energy for Cooling in Sweden

Sweden is one of the leading countries in using geothermal energy for heating and cooling buildings. Statistics show that almost 20% of the buildings in Sweden use geothermal energy (Gehlin, et al., 2015). According to the country update of Sweden in regard to geothermal energy utilization in 2015, there are almost half a million-installed ground source heat pumps.

Geothermal energy extraction in Sweden is mostly a shallow type, rather than a deep type, due to the fact that Sweden lacks the both a deep geothermal condition, as well as realistic cost feasibility to carry out the deep type. The purpose of mentioning the geothermal condition in Sweden in this study is to understand the geological nature of the ground in Sweden, with its usually hard bedrock, as well as the average temperature of the ground, which is around +8 °C in the south. (Gehlin, et al., 2015) These conditions are very suitable for chilled water trap for cooling purposes.

#### 2.2.2.2 Borehole Thermal Energy Storage (BTES)

BTES is basically one type of geothermal energy storage and is usually used for seasonal heating or cooling purposes as figure 2.2 shows. BTES is made by drilling vertical boreholes in hard rock to extract energy from the underground for both heating and cooling purposes. As mentioned, usually, the drilled holes are not as deep as it is in southern European countries, however there is
a market trend to have them deeper for extracting a higher temperature. Horizontal loops of underground pipe networks could be installed for the same purpose in case of soft ground; however, vertical drilling is the most common in Sweden. Although this technology is used in Sweden it could be still considered expensive, depending on the type of the rock as well as the depth of the holes.

Figure 2.2. Operating BTES system during summer (Left picture) and during winter (Right picture) (Underground Energy, LLC, 2009).

2.2.2.3 Aquifer Thermal Energy Storage (ATES)

ATES are caves or aquifers that are naturally formed underground and can be used to store warm and cold water. This water storing technology is used in Sweden mainly as seasonal storage, where warmed water from a building is transferred to the location of the aquifer and pumped into one side of the underground water rocks trap during the summer.

Cold water that has been stored, or naturally exists on the other side of the aquifer as the figure 2.2 above illustrates, is pumped and transferred, passing through set of heat exchangers before it is released as cool air into the spaces that are needed. The shape of the aquifer and density difference between warm and cold water are the main key players for not mixing between the hot and cold side of the aquifer.

2.2.2.4 Cavern Thermal Energy Storage (CTES)

The use of CTES is limited and not as popular as the ATES and BTES, however, CTES uses water in large, underground caverns in the subsoil to serve as thermal energy storage. As it is known, caverns are naturally formed underground, however, it could also be man-made for the use of storing oil or natural gas. Abandoned mine tunnels and shafts could also be used as CTES.

The dramatic decrease in dependency on crude oil as a source of energy in countries such as Sweden has resulted in the abandoning of the man-made oil cavern, consequently bringing the use of cheaper thermal energy storages. According to studies, the CTES technologies are technically feasible but have limitations, being both complicated and requiring site specific conditions (Underground Energy, LLC, 2009).

Though water and oil have been stored in natural caverns for millions of years, it is worth mentioning that the first attempt to store oil in man-made caverns was by a Swedish geologist during WWII as a tool to save these resources from destruction. Researching this method cost the Swedish Government around 1 million SEK annually. Ph.D. Tor Henrik Hagerman led a
feasibility study on storing oil underground in man-made caverns without the need for steel plate lining and without leakages (see figure 2.3) (Morfeldt C. O, 1938). The awareness of the environmental damage that underground oil caverns might cause was present as environmentalists were aware that this technology might pollute underground water, or be hazardous due to the risk of explosions.

This study will focus on the cavern thermal energy storage (CTES) as a technology for storing cold water for the use in district cooling systems in Sweden, as the research will be done on an abandoned oil cavern.

![Primary design for oil cavern in 1938](image)

The use for these man-made caverns for oil storing has been a strategic action to be used in crisis or energy demand peaks. Slowly after the oil crisis in the seventies, these storages started to be abandoned either because of the lack of oil supply or due to the new approach to use an alternative energy supply. However, since these storages have been used to sort liquid then it was an attractive area to invest in storing water instead of oil, while the strategy of having Sweden to be the world’s first oil free country by 2020 encourages companies to think beyond oil stage. (Vidal, 2006)

As there are new large-scale oil caverns for large-scale oil disposal in Gothenburg port there also are several smaller scale man-made caverns that are closing up in the Stockholm region, and ready to be used as water storages to operate as an essential part in an already constructed district cooling network system. The aim of these storages is to achieve a daily basis cooling demand balance between the peak hours and off-peak hours for residential and office buildings in Sweden.

### 2.3 CTES Technologies Used in District Cooling

Stratification method is one of the most common technologies used for storing cold water in man-made cavern thermal energy storage, however as mentioned in the Study Scope chapter there is another technology called non-stratified (mixed storage).
2.3.1 Stratification in CTES for District Cooling

Stratification as a term is referring to a state of having many layers; it is used to describe the natural separation layers of water without any physical interference. Thermal stratification is accrued due to the different densities of warm and cold water inside the TES. (Merriam Webster, ei pvm).

Cavern thermal storage for district cooling can be described as mixed or stratified based on the used mechanism for storing water in it. A stratified storage usually stores water in vertical tanks where cold water is injected (charged) or extracted (discharged) from the bottom of the tank, while warm water is injected (discharged) into the top of the tank. As hot water is less dense than cold water, it tends to stay at the top layer of the tank while cold water goes naturally into the lower layers of the tank. This water property allows keeping water with different temperatures separated from each other naturally, while a layer in between called the thermocline is formed.

Capacity of storage increases based upon a larger difference in water temperature between the cold and the warm side of the tank. The thermocline layer is the key point to keep them from mixing; it is essential to maintain it still, and to avoid a heavy discharging flow rate from the top that might destroy this layer due to the possible turbulence. Stratification favours a low flow rate and vertical tanks for its stability as seen in figure 2.4.

![Figure 2.4 An illustrative diagram for stratification storage and thermocline layer (Poredos & Kitanovski, 2011)](image)

In the vertical stratification method for district cooling, the higher the thermocline from the ground base, the higher the capacity of cold storage. It is also important to keep the thickness of the thermocline constant; however, it may vary due to the following factors:

- Operating temperatures;
- Flow rate;
- Diffuser design.
- Duration of storing.

In case the thermocline disappears due to the factors mentioned in previous paragraphs, water with time, will follow the thermodynamics and will have a mixed temperature, with a higher average temperature than the initially charged chilled temperature. The Cold storage then becomes
unusable for district cooling, since it would require high capacity chillers to cool it down to the desired temperature. Adding to that, investing in the tank also becomes financially infeasible, as the following chapters will illustrate.

Figure 2.5 shows three stages of stratification in TES where only case (a), would be the preferable case for district cooling.

Figure 2.5 shows three stages of stratification in TES where only case (a), would be the preferable case for district cooling.

![Figure 2.5](image)

Figure 2.5 Differing degrees of stratification within a storage tank with the same amount of stored heat (Hallera, et al., 2009)

Figure 2.5 describes three situations of a stratified storage where pictures from left to right are classified as:

a) The picture on the left side describes highly stratified cold storage, where the thermocline layer is obvious and has a reasonable thickness for storing cold water in the cold zone.

b) The picture in the centre of the figure describes a lower level stratification, where the zone of the cold water is shrinking due to the expansion of the thermocline layer. The capacity of the cold storage is at its minimum level.

c) The right-side picture shows a fully mixed condition of a stratified storage, as mentioned in the previous paragraphs, a storage that has a fully mixed temperature cannot be used for storing cold water for district cooling.

Mixed water temperature in stratified storage can cause a loss in terms of useful stored energy; it is caused by heat transmission through storage walls as a result of not good insulations. Mixing in stratified storage could be also caused by high flow rates that could potentially cause turbulence near the inlet diffuser during charging and discharging processes.

However, there is another type of positive mixing, where water from inlets mixes with the one in the storage in both cold and warm regions without distorting the thermocline layer. Positive mixing can be achieved by allowing low flow rate on water inlets, adjusting the direction of pipes openings inside the storage. (Hallera, et al., 2009) It can slow down the heat transfer process and work as an obstacle for water to flow from one side to another as figure 2.6 below illustrates.
Figure 2.6. Hypothetical charging and discharging experiments with full mixing at the top (Charging) or at the bottom (Discharging). (Hallera, et al., 2009)

According to Sharp and Loehrke, stratification used for storing heat in the solar system could improve the overall performance by 5–15% compared to fully mixed storage (Bahnfleth & Musser, 1998). Mixed storage refers to a full mixture of stratified storage as in case (c) in the upper figure 2.5.

The efficiency of stratified chilled water storage could be calculated numerically using the first law of thermodynamics, where in full cycle of charging and discharging a TES could be illustrated as Wildin and Truman expressed in equation (1) (Bahnfleth & Musser, 1998):

\[
\eta = \frac{\text{Cooling capacity delivered during a complete discharge}}{\text{Capacity absorbed during a complete charge process}}
\]

Which equals to:

\[
\eta = \frac{\sum m \cdot C_p (T_{in} - T_{out}) \Delta t}{\sum m \cdot C_p (T_{in} - T_{out}) \Delta t}
\]

Where:

\[m\] : Mass Flow rate over a time increment
\n\[C_p\] : Specific heat
\n\[T_{in}\] : Inlet temperature
\n\[T_{out}\] : Outlet temperature
\n\[\Delta t\] : Time increment

**2.3.2 Mixed Mechanism for Sorting Cold Water in District Cooling System**

The non-stratified or mixed storage method for storing chilled water in man-made CTES is not a popular method in the market; therefore, it is rare to find any documentations or scientific papers on this technique. Usually a mixed storage in TES refers to fully mixed storage after failure of storage stratification as explained in case (c) from figure 2.5 above.
Mixed storage in this study refers to the mechanism of injecting the water, and towards an expectation of how the water would react inside the storage. In stratified storages, cold water is injected in the bottom of the tank or the cavern, while hot water is injected in the top, through a set of diffusers.

In mixed storage, cold/hot water is to be injected from the sides of the cavern, which in this case it has a horizontal geometry. It is not sure how the water would react inside the storage, however, it is predicted that water might tend to mix in both sides due to the turbulence, caused by the flow at inlets, and will slowly start to follow heat transfer principles to move from the hot side toward the cold side.

Mixed storage could to some extent have a similar functionality to the one underground ATES has, where water is stored seasonally to be used later for heating/cooling large spaces. As the figure 2.7 illustrates an ATES in a naturally formed cavern in Sweden, where cold water is injected to one side of a rock cavern trap during the winter, to be used in the summer, and the other way around for hot water during summer.

Figure 2.7 below shows that water does not mix fully even if it is stored for a long-time period. A diffusion zone, similar to the thermocline layer in stratified storage is also formed due to the difference in densities of water in each side of the cavern. In the same figure, there is also a natural obstacle (ramp) that is helping the separation of the water with different temperatures.

This method is in use for assisting the cooling and heating at Arlanda airport in Sweden. (Andersson, 2007)

![Figure 2.7. Illustration of ATES system used for seasonal storing warm and cold water. (Andersson, 2007)](image)

### 2.3.3 Integration with thermal energy storage

In order to increase energy efficiency, reduce operation cost and limit the power at peak hours, the DCS can be integrated with storage technologies. The idea is to store cold energy in periods of lower demand to be used when the demand is higher. The guidelines are defined by the ASHRAE in 1997. (Bahnfleth & Musser, 1998)
2.4 Introduction to The Study on Mixed Mechanism used in CTES for District Cooling

Stockholm is one of the top ranked cities in respect to the environment and human living standards. Operative temperature range inside a building is one of the standards that were issued by the Work Environment Authority in 2009, and Public Health Agency in 2014 following the International Organization for Standardization ISO 7730. They specified that the minimum acceptable indoor operative temperature cannot be below 18 °C and in some special conditions it cannot be even lower than 20 °C. (SIS, 1994)

Cooling demand since then has been increasing; as a result, TES has been introduced as a solution to balance the demand and supply of energy during the cooling operational time.

Cooling could be supplied to the end user and back to the TES using district heating and cooling networks (DHC). Distribution networks can be used as a carrying medium, which is usually hot or cold water to transport the heating or cooling energy into/from the end users. Figure 2.9 is illustrating the general procedure of how a district cooling system operates with the use of TES. (Ortiga, et al., 2013)

Figure 2.8. Diagram of DCS integrated with thermal energy storage. (a, b and c) (Wenjie, et al., 2016)

Figure 2.9. Illustration of district cooling system operates with the use of TES. (Ortiga, et al., 2013)

District cooling systems; consist of two major components (Ortiga, et al., 2013):
• Chillers: they are used for cooling both recycled water from DCS or from an external source to a certain temperature before sending it back to the cooling systems of a building.

• Distribution network, which consists of pipes that transport the chilled water, from the chillers to the cooling system in the building, also returning the warmed water back for cooling.

2.4.1 Advantages of Cold Thermal Energy Storage (CTES) in DC system

A district cooling system could work without the need for storage, by applying a closed circulation loop and by using chillers for cooling and a distribution network. However, this would require a large number of chillers to cover the cooling capacity demand during the peak hours of a day, while a number of these chillers might be out of work during the off-peak hours. Therefore, using the cold TES is essential for a balance between the supply and demand during the peak and off-peak hours in a daily cooling system. (Dincer, 2002)

Ibrahim Dincer added in his book “Energy and Building” (Dincer, 2002), that cold TES could also have a potential reduction in the operative costs by cutting some of the unnecessary expenses when TES is used. He summarized them in the following three points:

• Reduced pipe and pump sizes for chilled water distribution.
• Reduced duct and fan sizes for low-temperature air distribution.
• Correspondingly reduced operating costs.

2.4.2 Cold Thermal Energy Storage (CTES) Operating Principles

Advantages of using CTES are also related to the generation capacity, whereas the heating and cooling demand is rarely constant over a long period of time. Cooling demand off-peak hours starts late afternoon and lasts normally until following morning of a day. There is no need for cooling when occupancies of offices have left the building and electrical equipment is turned off, in some buildings heating and HVAC systems are also reduced or turned off.

Cold water is then sent through the distribution network to be stored into a CTES. During the peak hours that are usually the working hours in a building, cold water is then extracted from the CTES and sent back to provide cold air for that building. Having a CTES assures the balance between the supply and demand for cooling, and also allows the system to use smaller energy units during the off-peak hours and save the rest to be used during the higher demand period.

Operation hours for the cooling system are directly related to the cost; less operating hours during the off-peak hours can make more profits or at least less expense for the suppliers. However, the cost could also be reduced if the cooling demand is purchased during the lower cost period and then used during the peak hours where CTES with suitable capacity is needed to store cold water to be used at the desired time. (Dincer, 2002)

Cold TES could have both full and partial operational strategies as the figure 2.10 illustrates. Partially operating CTES is more popular than the full one, since in most cases it can handle a sudden sharp peak demand for cooling, without the need to put extra chillers in operation. The following graphs in figure 2.10 introduce three different cold CTES operation strategies:

a. Fully charged storage
b. Partially charged for load levelling

c. Partial-storage demand limiting

![Figure 2.10. Different operation strategies for cold CTES where: (a) full-storage; (b) partial-storage load leveling and (c) partial-storage demand limiting. (Dincer, 2002)](image)

Partial storage strategy for CTES is also more ecumenically feasible according to Dincer, since it has a lower initial cost able to deliver a balance between the demand/supply load curve. Also, it covers the missing capacity for cooling during the highest peak hours in case chillers in full operation fail to deliver the full supply (Dincer, 2002).

### 2.5 Underground Cold Thermal Energy Storages and Sustainability

In Sweden, as a leading country in the topic, sustainability is used as an indicator for project evaluation. This concern starts to take its shape in the country after holding the first conferences discussing the relationship between human and environment in 1972 in Stockholm, the city that also welcomed the World Commission on Environment and Development (WCED) in 1987 where the concept of sustainability was formed by Gro Harlem Brundtland. (United Nations, 1987)

Three main factors are considered of any entitled sustainable project: social, environmental and economic factors. Applying these sustainable indicators on underground CTE storages that will be used for district cooling will assist in measuring the sustainability level to invest in this technology. Environmentally speaking, utilizing abandoned oil cavern for storing cold water for district cooling have major benefits; since firstly, it would minimize the need to construct new underground caverns which would reduce harming the underground ecosystem and it would also reduce the needed recourses for such operations. Secondly, underground CTES would replace various refrigerating systems that use harmful refractors or energy sources to run the cooling generators. Thirdly investing in CTE storages would also allow to store the extracted heat from buildings instead of releasing them into the atmosphere.

Underground CTES could also be considered as a solution that affects the structural appearance of the city, to deliver the same cooling capacity for buildings that CTES is expected to provide, many chillers would be required to be installed close to the buildings’ surrounding or at least cooling towers which would occupy large spaces that
could be used for the residences but it would also disturb the aesthetic appearance of the city.

The ability to balance between daily supply and cooling demand would not only save costs for cooling companies but also it could generate profits, as CTE storages can store cold water during off-peak hours and provide it during the cooling demand peak hours without the need to run extra chillers.

It can be concluded that investing in underground CTES is not only environmental friendly but also it could be considered as sustainable project since it would also be affecting the social aspect and it would be economically feasible.

2.6 Classification of the Study Case

A major district cooling company in Sweden is investing in an abandoned oil cavern for storing cold water as part of its DC system in Stockholm. The company already has a set of chillers in operation for cooling the incoming warm water from office spaces and circulates cold water back to cooling systems for these offices. However, the company is seeking to use the cavern as cold CTES to work in partial strategy during the peak hours.

The aim of this investment has two main targets: firstly, operational; to meet the cooling demand during the peak time period of the year. Secondly, financial: to cut costs and expenses, since operating cold CTES would reduce the need for the company to buy extra chillers, which require extra space. Moreover, as mentioned earlier, using CTES for storing cold water during the off-peak hours, and then extracting it during the higher cooling demand would make the district cooling system meet the capacity demand at a lower cost since usually, the chillers would work at their full capacity during the peak hours when the energy cost is at its highest.

Any purchase of energy during peak hours would be translated into a very high cost for the company, while selling the excess energy at the same time would lead to extra profits. Therefore, the company is also trying to avoid any need to buy extra energy during the peak hours, while aiming to sell any excess energy during the same period of time.

Moreover, the company has decided to have a feasibility study on which technology they should invest in to be used for storing cold water in the abandoned cavern: the stratification technology or mixed storage technology. Important aspects have to be taken into consideration in order to be able to make a decision, however the financial aspect, which is the trade of the possible capacity expected from the storage is a primary concern for the company. It is mentioned that the company has already done a study on using stratified storage; this study will focus on calculating the possible capacity of using mixed storage to be compared later with the stratified study results.
This chapter will illustrate the procedures that were conducted by the researcher to reach the results that will lead to the conclusion whether to invest in Stratification mechanism or mixed storage for storing cold water. The methodology chapter will start with an overview analysis of the district cooling cycle and the processes of charging and discharging the cavern. Afterwards an introduction of the software that was used in this study will be shown as well as an illustration of the process in steps for modelling the cavern, which simulates the operating processes of charging and discharging. This chapter will then continue to the results analysis for drawing a better picture before the conclusion and recommendation for future work chapters.

3.1 District Cooling Cycle – Charging and Discharging Cold CTES

Discarding the technologies used for storing cold water in a cold CTES, the district-cooling cycle consists of two main processes:

- **Charging:** The process where chilled water is injected into the storage after passing through different cooling stations as chillers and heat exchangers. Charging is usually applied during the off-peak hours. It uses the excess available cooling capacity at a lower cost during the lower demand period to cool water down to the desired temperature.

- **Discharging:** The process where warm water works as a transportation medium to carry extracted heat from spaces during peak hours. Warm water passes similar stations as in the charging steps to lower its temperature, and is then carried through a distribution network and injected into the CTES.

3.1.1 Discharging Process During Peak hours

Discharging hours are the peak hours and the hours when cooling demand reaches its maximum, which is expected to be during working hours, which usually in Sweden are between eight o’clock in the morning until four o’clock in the afternoon. During discharging hours, heated water goes through half of the district cooling cycle to discharge the cold storage with warm water. The targeted spaces for cooling are heated up during the peak hours where excess heat needs to be expelled and replaced with cool air to keep the room within the acceptable temperatures.

The heat from the buildings is then transferred into a transportation medium, in this case water that has an average temperature of 14 - 15 °C, after that warm water is transferred through a constructed distribution network with a specific flow rate controlled by the size of the distribution pipes and by the capacity of the installed pumps in the DC system.

Warm water during the discharging hour passes through a heat exchanger to lower its initial temperature about one degree before it reaches the cold CTES. The discharged warm water is discharged from the top of the tank, simultaneously replacing a chilled one that has been stored during charging hours. Figure 3.1 below illustrates discharging process during peak hours.
3.1.2 Charging Process During Off Peak Hours

Charging hours are the off-peak hours when the demand for cooling starts to decrease until it reaches its lowest points during the night time. The cooling demand drops when the occupancies of a building leave from work, and the equipment and lights are turned off. During charging hours chillers should cool water to around 6 °C taking the advantage of the cheaper energy prices during that period of time.

Chilled water then also passes through the heat exchangers where it gains about one degree to reach about 6 °C. If the storage fails to provide chilled water with this temperature then water has to pass through reserved chillers to be cooled down to the desired one, however there are limitations for this option. Since it would require high capacity from the chillers to cool water to even one degree during the peak hours, it is important to assure that the cold CTES are capable of keeping water an acceptable cold temperature.

Chilled water has an average temperature of 5 - 5.5 °C. It is usually extracted from the bottom of the storage since cold-water density is higher and tends to naturally stay in the lower part of the TES. Cold water is then transferred back through a distribution network to the cooling system of a building and converted into cold air or other cooling purposes. Charging storage usually starts in late afternoon and lasts for twelve to fourteen hours. Figure 3.2 illustrates a charging process during off peak hours.

Figure 3.2. Diagram illustrates a charging process during off peak hours. (Wollblad, 2015)
3.2 Primary Data Collections and Classification of the Cavern Storage

The dimensions of the decommissioned oil cavern are 135 m*14 m*15 m. In the right side of the storage lays a ramp that occupies a space from the total volume of the storage, which is expected to disturb the fluid flow during the charge and discharge processes.

The cavern has a horizontal rectangular shape and is installed in the underground; this would increase the cost of the stratified method, as it would be necessary to install more pipes in the UCTES. It would also require special equipment and drivers for installation, which could also be a life risk for the divers.

Therefore, a study is needed to either prove that stratification method is still the valid technology to be used for storing chilled water in the cavern for the district cooling usage or the mixed technology as an alternative method.

3.2.1 Cavern Geometry

Figure 3.3 illustrates the dimensions of the cavern where the dominions in meter scale are as follows:

- Height (H) = 14 m
- Width (W) = 15 m
- Tall (L) = 135 m

![Figure 3.3 Blueprint of the dimensions of cavern](image)

Ramp Location and Dimensions

There is a constructed ramp inside the storage that occupies a space from the storage volume. The locations with the dimensions of the ramp are shown below:

- 7,770 mm from the right end of the cave
- 8,350 mm at its highest point
- 5,000 mm in width
- 12,000 + 62,045 – 7,770 mm = 66,275 mm ramp’s length in the storage base
Charging and Discharging Temperatures Arriving at The Cavern

- Charging cold water temperature: 5 °C ≈ (278 K)
- Discharging warm water temperature: 14 °C ≈ (287 K)

Assumption for Input Data

- Initial Cavern storage temperature: 9 °C ≈ (287 K)
- Heat loss due to walls conduction or convection to be neglected in the following calculations.

Charging and Discharging Pipes

Two pipes with diameters (d) of 50 mm are to be placed on the storage’s side. One of the pipes will be used for cold water charging from the left side of the storage, while the other one is used for warm water discharging from the right side of the storage. However, the number of these openings will affect the flow and the turbulent behaviour of the water in the inlets regions, therefore, the exact number and location is to be discussed later in this chapter.

3.3 Modelling and Simulation Software

Investment in CTES generally amounts to high cost: the real challenge comes with the fact that there are not many available cases to serve as reference on this subject. This makes it high risk for companies to proceed with a project without having firm expectations of the outcome of an investment. Therefore, intensive studies on such projects and analyses are required, before proceeding with any decision.

Modern technologies have provided the market with useful and accurate software. Though sometimes the best way to test the workability of a model is to apply it in real case. Nonetheless, the expenses and risks limited this procedure where a prototype could be run in different simulations under real life conditions, which makes it much easier for the stakeholders to draw conclusions.

Two types of software were suggested for modelling and simulating discharging and charging processes during operational hours of the cavern:

- **ANSYS Fluent CFD**: is a Computational Fluid Dynamic (CFD) software used for modelling fluid flow and other physical phenomena such as hydrodynamics, mixtures of liquids/solids/gas, reacting flows and heat transfer. (CAEAI, 2017)

- **COMSOL Multiphysics**: is also is software for modelling and simulating physical phenomena based problems, but is more general and also connected to CAD, and ECAD software.

COMSOL Multiphysics software was decided to be used for modelling the cavern, due to its simplicity for use, not requiring complex steps, or large size modelling files necessitating a large
computational power. Adding to the advantages of its usage, the CTES storage has a fairly simple geometry and a not too complicated testing process.

3.4 Introduction on COMSOL Multiphysics Software and Simulation Steps

COMSOL Multiphysics as defined by the producers “is a general-purpose software platform, based on advanced numerical methods, for modelling and simulating physics-based problems” (COMSOL, 2017). Adding to the mentioned advantages of using Comsol software, it is also easy to learn and has access to an online forum, where a user can contact the software builder and other users on a formed community-based platform in case a question or challenge appears. Comsol software is regularly updated and has various versions. This study will proceed with Comsol 5.2a version that has more available features and less manual input calculations. The study will start by creating a model of the cavern as a preparation step for inputting the cavern. Simulating storage starting with 3D geometry might be unfitting, therefore, modelling and simulating for the cavern will be carried in steps from 2D to eventually 3D, as follows:

Primary Data Collections:

- Cavern 2D Modelling and Simulating
- Primary Result Analysis and Conclusion
- Cavern 3D Modelling and Simulating
- Secondary result Analysis

This procedure was decided since there is no firm opinion on how the fluid inside the cavern would act during the charging and discharging processes, therefore different tests and variable changes are to be conducted, aimed to draw a primary understanding of the process.

3.4.1 Primary Data Collections on the Caverns

Charging/Discharging Time and Flow Rate

Figure 3.4 below illustrates the usual time for charging and discharging the cavern as provided form the district cooling company, where discharging is based on pipes dimensions and available pumps power. This process might change with the changing of consumer demand, however as mentioned earlier the consumer demand is related to the occupancy of the building during the working hours.
Figure 3.4 Charging/Discharging curves for the cavern during the peak and off-peak demand hours in respect with flow rates.

The graph in figure 3.4 shows that charging the storage with cold water starts approximately at 19:00 during off peak hours. The charging process has constant fluid flow rate of 500 kg/s, and ends the following morning around 6:00 am.

Discharging the storage usually starts at 7:00 am by injecting water with higher temperature into the storage. Discharging flow rate is not as constant as the charging one and it fluctuates depending on the consumers’ cooling demand, as figure 3.4 shows. The discharging starts smoothly with low water flow rate of 116 kg/s and it escalates to reach its peak around midday. It stays at its peak until the end of usual working hours in Sweden. Discharging peak hours as the graph shows are in the time period between 11:00 and 16:00, where the water flow rate injected to the cavern reaches its maximum of about 300 kg/s. Discharging flow rate then starts slowly, and declines as a response to the decreasing of the customer cooling demand. However, the process continues even after the working hour, until approximately 18:00 with an average flow rate of 200 kg/s.

Table 1 illustrates the data for charging and discharging processes during a full day. The processes are in rest mode for about two hours a day: before charging and before discharging, where water flow rate is set to be zero as seen in the grey coloured cells in Table 1. It is also the same with the resting hours also marked in red in figure 3.4. In reality, it is not possible to set the flow rate to on and off easily, however, this step was taken for measuring the effect of the flow rate on mixing inside the cold CTES.

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<tr>
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<th>Charging Process</th>
<th>Discharging Process</th>
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<td>Charging Time</td>
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<tr>
<td>3</td>
<td>21:00</td>
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3.4.2 Modelling and Simulating the Cavern in Two-Dimensional Space

Two-Dimensional modelling (2D) is advised when the studied object has a simple or symmetrical shape, where running a simulation on a sectional part from it, would lead to an approximate result of full scale. 2D modelling is used for short time simulation or as a primary step before proceeding with third-dimensional modelling (3D) of a project.

The studied cavern has a simple shape as mentioned before, but it also has a fairly large volume to run a 3D simulation without having a primary understanding on the operational processes. Running 2D simulation on Comsol can take less time than full dimensional simulation. A simulation with more repetitive steps can achieve a higher quality and more accurate results. Having a shorter time per simulation allows for testing different variables such as the effect of gravity or density on fluid dynamic inside the cavern, it also allows time to modify cavern geometry by relocating pipe locations.

3.4.3 Cavern Numerical Calculations

Set of formulas and input data have to be prepared before proceeding with modelling cavern. Cavern formulas with more details are also found in the appendix A.

- Cavern Side Surface Area:

\[ A_s = L \times H = 135 \times 14 = 1,890 \text{ m} \tag{2} \]

- Pipes Cross Section Area:

\[ A_p = \frac{1}{4} \pi \times d^2 = 0.19 \text{ m}^2 \tag{3} \]

- Total Cavern Volume:

\[ V = W \times L \times H = 14 \times 15 \times 135 = 28,350 \text{ m}^3 \tag{4} \]

3.4.4 Charging and Discharging: Time Calculations

Required time for charging and discharging the cavern from table (1):

- 12 hours charging + 1 hour idling
- 10 hours discharging + 1 hour idling

Taking into account that:

\[1 \text{ Hour (h)} = 3,600 \text{ seconds (s)}\]

Fluid flow rate \(1 \text{ kg/s} = 0.01 \text{ m}^3/\text{s}\)

Required time to fill (charge) the cavern with 100% cold water during charging process is calculated by equation (5):

\[
t_c = \frac{\text{Cavern Volume}}{\text{Discharging Flow Rate}} = \frac{V \text{ (m}^3\text{)}}{\bar{m} \text{ (m}^3/\text{s})} = \frac{28250}{0.5} = 56,700 \text{ s} \approx 16 \text{ h}
\]  

(5)

Where:

- \(t_c\) = Charging time (s)
- \(V\) = Cavern volume (m\(^3\))
- \(\bar{m}\) = Charging mass flow rate over a time increment (m\(^3\)/s)

Equation (5) explains that the time to charge the cavern fully with cold water at a flow rate of 500 kg/s, would be around 16 hr. This case is unusual, except for zero cooling demand on holidays or weekends, since cooling thermal energy storages for district cooling is built to cover the daily cooling demand which has two processes: charging and discharging. Therefore, cold storage cannot stay completely chilled due to the injecting of warm water during cooling peak hours.

Required time to fill (discharge) the cavern with 100% warm water during discharging process is calculated by equation (6):

\[
t_d = \frac{\text{Cavern Volume}}{\text{Discharging Flow Rate}} = \frac{V \text{ (m}^3\text{)}}{\bar{m} \text{ (m}^3/\text{s})} = \frac{28250}{0.29} = 99,202 \text{ s} \approx 27.5 \text{ h}
\]  

(6)

Where:

- \(t_d\) = Discharging time (s)
- \(V\) = Cavern volume (m\(^3\))
- \(\bar{m}\) = Average discharging mass flow rate over a time increment (m\(^3\)/s)

The time that is required for discharging the cavern fully is longer than the one for charging it with cold water. This is because the discharging process has an average flow rate of 290 kg/s which as equation (6) shows, would take over than 27 hours to have the cavern fully charged with warm water. This scenario is also unlikely to happen, due to the need for charging and discharging in one day, which is equal to 24 hours. Discharging regular time is round 10 hours per day as table 1 shows. It is important to figure out the required time for fully charge or discharge the cavern for emergency situations such as chillers break down or as mentioned in time periods when there is no demand for cooling.
To explain this further, discharging the cavern fully in 10 hours, would require at least a constant flow rate of almost 780 kg/s, which would require special pipes and pumps that are not available for this project.

### 3.4.5 Cavern’s Filling Capacities for Charging and Discharging

The ideal case for a cavern is to be charged fully with cold water and then discharged fully with warm water within one day. This is also an ideal cooling capacity from a cold storage. However, this is not possible in a practical situation, as previously explained.

The following equations were used to calculate the maximum possible filling capacity for the studied cavern during operational hours.

- The maximum possible percentage for filling the cavern with cold water for 12 hours charging is 76% from the total volume of the cavern, as equation (7) shows:

\[
\frac{\text{Charging Flow Rate}}{(\text{Cavern Volume / Time for charging})} = \frac{\dot{m} \ (m^3/s)}{(V \ (m^3)/tc(s))} = \frac{0.5}{(28250/12+3600)} = 76\%
\]  

- During the discharging process, the maximum percentage for filling the cavern with warm water in 10 hours of discharging is 36%, as equation (8) shows:

\[
\frac{\text{Dicharging Flow Rate}}{(\text{Cavern Volume / Time for discharging})} = \frac{\dot{m} \ (m^3/s)}{(V \ (m^3)/tc(s))} = \frac{0.29}{(28250/10+3600)} = 36\%
\]  

### 3.4.6 Charging and Discharging in 2D Simulation: Time Calculations

Calculations in equations (7) and (8) prove that it is not possible to fully charge or discharge the storage during one day with the given flow rate, the same is also applied to 2D simulation. Calculating the required time for thesis processes, the 2D modelling takes different procedures as the following paragraphs will explain.

Calculations for 2D modelling should consider all physics and fluid dynamic processes in two-dimensional geometry, since it defers from calculating for a full-scale simulation.

2D calculations are based on a cross sectional surface area (A<sub>s</sub>). An assumption was made that a simulation surface area will be taken from the middle of the cavern. This layer of the cavern has the maximum possible fluid flow rate, because pipes should be in the middle top part of the cavern. Randomizing the sections selection for simulation would ensure more accurate results. However, the purpose from proceeding with 2D modelling is to understand the heat transfer and fluid dynamic inside the cavern, therefore basic assumptions were considered for the case of 2D modelling.
Equation (9) and (10) are used for calculating cavern filled space with cold and warm water during operational processes, based on calculations made in equations (7) and (8).

Total surface area of the cavern ($A_s$) equals to 1,890 m$^2$ (equation (1)), which is the surface area of the cross section of the cavern during the charging period ($A_c$) equals to:

$$A_c = A_s \times 76\% = 1,140 \text{ m}^2$$  
(9)

Similarly calculated for the cross-sectional discharging process surface area ($A_d$) with maximum discharging of 36% of the total cavern capacity gives:

$$A_d = A_s \times 36\% = 696 \text{ m}^2$$  
(10)

For calculating velocity flows at the openings of the cavern, equations (11) and (12) were used. ($A_p$) is pipes’ surface area is a cross sectional area of pipes it is an essential step before proceeding with operational time calculations:

**Velocity flow for charging:**

$$v_c = \frac{\text{Flow Rate m}^3/\text{s}}{\text{Pipes surface Area m}} = \frac{\dot{m} (\text{m}^3/\text{s})}{A_p (\text{m}^2)} = 2.5 \left(\frac{m}{s}\right)$$  
(11)

**Velocity flow for discharging:**

$$v_d = \frac{\text{Flow Rate m}^3/\text{s}}{\text{Pipes surface Area m}} = \frac{\dot{m} (\text{m}^3/\text{s})}{A_p (\text{m}^2)} = 1.5 (\text{m/s})$$  
(12)

Based on equation (11) and (12), charging and discharging flow rates were calculated using equations (13) and (14):

**Flow rate for charging process in two-dimensional section of the cavern ($\dot{v}c$):**

$$\dot{v}c = v (\text{m/s}) \times d (\text{m}) = 1.27 (\text{m}^2/\text{s})$$  
(13)

**Flow rate for discharging process in two-dimensional section of the cavern($\dot{v}d$):**

$$\dot{v}d = v (\text{m/s}) \times d (\text{m}) = 1.27 (\text{m}^2/\text{s}) = 0.74 (\text{m}^2/\text{s})$$  
(14)
Combining equations (9) and (10) with (13) and (14), leads to calculated time needed for charging and discharging the cavern with cold and warm water, for 2D simulation on Comsol by equation (15) and (16).

\[ t_{C=A_c} = \frac{v_c}{1,131} \text{s} \quad (15) \]
\[ t_{D=A_d} = \frac{v_d}{942} \text{s} \quad (16) \]

3.5 Introduction for Modelling Cavern in Comsol 5.2a

This section will discuss the actual modelling steps of the cavern using Comsol Multiphysics. Each step will be explained to be as a follow up report for the future research. Modelling step is the base form for data entry before running a simulation.

3.5.1 Choosing the Right Comsol Version

Comsol has different updates with different features, choosing a right Comsol version would save time, effort and also it is recommended for better communication between the team working on the same project. It should be noted that the downloaded version of Comsol could only open the same version files or earlier but not newer versions. For example, if a file is on Comsol 5.2 it can only be read with same version or any older ones, but it can't open with Comsol 5.2a for example. Therefore, it is important to check that all the used computers for a study have the same version of Comsol.

3.5.2 Choosing Geometry’s Space Dimension for Study

The first thing that appears after selecting (Model Wizard) on Comsol is different space dimensions as figure 3.5 illustrates, for this stage of study 2D. This study as mentioned will start with the 2D space dimension.

![Figure 3.5. Different space dimensions as it shows in Comsol 5.2.a](image-url)
3.5.3 Selecting Physics for The Study

Understanding fluid dynamics and heat transfer of stored fluid and cavern is one of the key points to have good simulation results. Comsol has predefined physics on its software that a user can choose from. Each physics option has also a set of pre-programmed equations that control calculations and determine fluid behaviour during simulations. Comsol delays in details the functionality for each selected physics, by pointing at it with the mouse of a computer, which makes it much easier to choose suitable physics for study. See figure as 3.6 below.

Clicking on the selected physics interfaces will add them to the study and then it is ready to proceed with modelling. There are two important physics to be chosen for this study:

1. Fluid Dynamics (Fluid Flow)
2. Heat Transfer

![Select Physics Interface](image)

Figure 3.6. Selecting physics on Comsol software 5.2a

3.5.3.1 Fluid Dynamics (Fluid Flow) for Cold Cavern TES

Fluid flow was selected to be a Non-Isothermal, based on the fact that the studied fluid has non-constant temperatures during processes. Non-isothermal flow is open for fluid’s changes, also in velocity and density, which is the case during the charging and discharging processes of the fluid. Moreover, selecting a non-isothermal fluid flow on Comsol adds automatically predefined equations for both turbulent and laminar fluid flows as one of them was selected. (Comsol, 2017)

3.5.3.2 Turbulent –Laminar Transition Fluid Flow

Deterring fluid behaviour inside an underground cavern during discharge and charge processes is challenging, especially without references or simulations on this subject. However, there is a set of predefined data such as flow rate at the inlets, average velocity fluid flow, which can help to have a primary assessment. The large-sized underground cavern is most likely to have turbulent fluid flow at the inlet regions of the cavern, during operational hours, while the cavern’s middle section will most likely be having a laminar flow since the effect of the flow rate will vanish slowly away from the inlet region. Nevertheless, calculating Reynolds number in the following paragraph will make the decision on the fluid flow more accurate.
3.5.3.3 Reynolds Number and Flow Regime

Reynolds number is a ration that describes inertial forces to viscous forces of flowing flow, by using multiple correlations to describe the boundaries of a flowing fluid as defined at Neutrium platform. (Neutrium, 2012). Based on the result of these correlations that are calculated by Reynolds numbers ration, it is decided whether the fluid falls under one of these three main categories:

- Laminar flow occurs at low Reynolds numbers,
- Turbulent flow occurs at high Reynolds numbers.
- Transitional flow occurs in between scale of the two previous Reynolds numbers

These rations are defined using numerical measurement scaling the fluid as shown below: (Neutrium, 2012):

- Laminar Flow is Reynolds number (Re): Re<~2,100Re<~2,100
- Transitional Flow: ~2,100<Re<~4,000~2,100<Re<~4,000
- Turbulent Flow: ~4,000<Re<~4,000<Re

Fluid flow inside pipes scales is calculated by Reynolds numbers equation (17):

\[
Re = \frac{\rho vD}{\mu} = \frac{1000\times2.5\times0.5}{1} = 2,500 \text{ Re}
\]

(17)

Where:

Re: Reynolds number
\(\rho\) : Water density (kg/m\(^3\))
\(v\) : Average fluid velocity flow (m/s)
\(D\) : Pipe’s Diameter (m)
\(\mu\) : Water viscosity (pa.s)

Calculating Re in equation (17) for the cavern confirms that the general fluid flow inside the cavern will be in the turbulent regime. However, there is still a space for arguing whether or not the flow regime should be a laminar.

3.5.3.4 Heat Transfer Equations for Cold Cavern Thermal Energy Storage

Heat Transfer is a movement process of thermal energy (heat) from one subject into another. This process requires a temperature difference between the interactive objects or mediums, where naturally heat flows from a higher temperature medium into a lower one, through different physical mechanisms such as conduction, convection, and radiation, until they both reach into the thermal equilibrium phase in case of an isolated system.
This study is dependent mainly on heat transfer measures before, during and after charging and discharging the caverns. Expected storage capacity of cold-water is calculated by measuring heat transfer in a defined time period. Equation (18) is used to measure the heat capacity of the storage.

\[ Q = \dot{m} \cdot c_p \cdot \Delta T \text{ or } Q = \rho \cdot c_p \cdot V \cdot \Delta T \quad (18) \]

Where:

- **Q**: Heat transfer, (Heat capacity of the storage)
- **\(C_p\)**: is the specific heat of water
- **\(\Delta T\)**: Temperature difference
- **\(V\)**: Total volume of water inside the cavern
- **\(\rho\)**: density of water.

Heat transfer will be used to explain how fast heat is flowing from the discharging side of the cavern towards the colder side at a given time; it will also identify the formation of a thermocline layer in between.

There are three different heat transfer interface options on Comsol for this study as listed:

- Heat Transfer in Solids, (Walls and boundaries of the cavern)
- Heat Transfer in Fluid, (Fluid inside the cavern, which is water in this case)
- Heat Transfer in Pipes, (Inlet pipes inside the cavern)

The assumption made was that heat transfer between boundaries of the cavern will be neglected, due to the minimal effect on the process. According to studies only 1% to 2% from UTES capacity would be caused by transmission losses between walls of the cavern and fluid. (Bahnfleth & Musser, 1998). Mixed storage technology for storing cold water in cold CTES in this study will use two main pipes with a fairly small surface area; therefore, heat transfer in pipes inside the cavern will also be neglected in this study.

By selecting heat transfer interface for a study on Comsol software, the predefined heat transfer equations (19) and (20) are added automatically into the simulation. These equations are based on Fourier’s.

\[ q = -\kappa \nabla T \quad (19) \]

\[ \rho C_p \frac{\partial T}{\partial T} = \nabla \cdot (k \nabla T) + Q \quad (20) \]

Where as defined in Comsol software:

- **\(\rho\) (kg/m³)** : Fluid density.
- **\(C_p\) (J/(kg·K))**: Fluid heat capacity at constant pressure.
- **\(k\) (W/(m·K))**: Fluid thermal conductivity
- **\(u\) (m/s)** : Fluid velocity field
- **\(Q\) (W/m³)** : Heat source
Model boundaries should also be defined as a necessary input data for charging and discharging processes, such as temperatures at the inlets and the cavern’s water initial temperature.

### 3.5.3.5 Brief About Computational Fluid Dynamics (CFD) Modelling for Turbulence Flow

Fluid Turbulence defined by ANSYS is a dynamic phenomenon, where quantities move in irregular patterns and fluctuate in time and space (Ansys, 2006) Reynolds number (Re) scale is used as mentioned to detect the turbulence in flowing fluid using equation (17). Various modeling for turbulence could be applied in CFD, choosing the suitable one depends in availability of computing software also the fluid dynamics proprieties and conditions. However, Eddy-Viscosity-Models (EVMs) are the most turbulent models used for Computation Fluid Dynamics. The following lists from CFD online are for the most, turbulence models used in CFD (CFD Online, 2013):

1. **RANS-based models**
   a. Linear eddy-viscosity models
      i. Algebraic models
      ii. One and two equation models
   b. Non-linear eddy viscosity models and algebraic stress models
   c. Reynolds stress transport models
2. **Large eddy simulations**
3. **Detached eddy simulations and other hybrid models**
4. **Direct numerical simulations**

Comsol software mainly uses Reynolds-Averaged Navier-Stokes (RANS), which is able to model a wider range of turbulent length scales. Comsol also has a (Help) function that allows the user to read a brief on each model before. RANS based, one and two equation models on Comsol are: k-ε, k-ω, low Reynolds number k-ε and SST. Figure 3.7 is a snap shot image from Comsol software, which shows the list of available RANS models for turbulence flow.
Models k-ε, k-ω, low Reynolds number k-ε and SST are two educational models meaning, that they use two main equations to solve for two variables, they differ one to another from the specific functionalities, but it could also be said that these models from left to right are organized respectively from the simplest to the most complex. This is also valid in regard to time, computing space and computing cost, as they are also available in Comsol for Heat Transfer Module (25).

3.6 Cavern 2D Modelling

Simulating charge and discharge processes will be time dependent, and therefore transient, the initialization study function on Comsol software will be selected as the last step before proceeding with modelling the cavern.

This chapter will discuss the procedure of modelling cold CTES using Comsol Multiphysics software 5.2a as a computing tool for this study. After a primary data collection and assumptions, the actual modelling of the cavern geometry will start, followed by data entry.

3.6.1 Sketching e Cavern on Comsol Software

Modelling the cavern starts with sketching the cavern in 2D space using the Geometry tool on Comsol (Geometry node). The overview geometry of the cavern should be clear before starting the data entry. However, including the ramp in figure 3.8, the location of the pipe openings in the 2D cavern model are also important to have a clear decision on.

Dimensions of the ramp inside the tank were discussed in the Cavern Geometry chapter. Figure 3.3 shows that the ramp is taking space from the far-left side corner of the tank. The ramp is 5 m in width, which equals to one-third of the total width of the cavern; it is also over 8 m in height which is over than half of the height of the cavern, and a base of 66 m in length. The large occupying area of the ramp on the side of the cavern makes it debatable whether the ramp should be included into the 2D model for simulation or not.

Testing attempts were made to visualize the effect of the ramp on the simulation and it was concluded that the ramp would have a major effect on the fluid dynamic if it is carried in 2D.
Another reason for not considering the ramp is based on the reason for carrying out 2D simulation, which is, as previously mentioned, is intended to understand fluid behaviour inside the cavern during the charging and discharging processes. Therefore, there will be a final conclusion of the feasibility of using the mixed storage based on 2D simulation. Moreover, as mentioned in the 2D calculations chapter, the 2D cross-section of the cavern to be modelled is located in the middle part of the cavern; therefore, there is no need to include the ramp in this part of 2D modelling.

![Figure 3.8. Cavern 2D geometry on Comsol 5.2a including the ramp (inside the red box)](image)

### 3.6.2. Placing Charging and Discharging Pipes in 2D Simulation

Pipes positioned in the cavern geometry can affect fluid flow inside the cavern, which would also affect heat transfer and the storing capacity of the cavern. Deciding pipes’ location in a 2D model is much easier, and is less time consuming than when using a 3D model. However, several attempts were made for modelling and simulating with different pipe positions. Figure 3.9 illustrates the final decision on pipe position inside the cavern in 2D geometry, which was based on comparisons between different results from pipes positions.

Pipes ought to be placed on the top layer of the cavern, where their openings should be positioned towards the walls on each side of the cavern. The opening of the inlets should have a distance of about 3 m away from the cavern’s wall about 7 meters in depth from the top middle part. In Comsol **Difference** function is used to make the pipes’ inlet.

![Figure 3.9. Cold cavern 2D geometry model with pipes inlets pointing towards the walls (blue and red boxes)](image)
### 3.6.3 Data Entry for 2D Simulation on Comsol: Global Definition

**Global Definitions** is the first function for data entry on Comsol software, where parameters, variables and functions are defined for the model builder. There are four major inputs in Global Definition node to be filled for this study, as listed in table 2 below:

<table>
<thead>
<tr>
<th>Global Definition Input</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Inlet velocity flow rate during charging</td>
<td>( V_{c\text{-inlet}} )</td>
<td>2.5 m/s (constant)</td>
</tr>
<tr>
<td>Water Inlet velocity flow rate during discharging</td>
<td>( V_{d\text{-inlet}} )</td>
<td>1.7 m/s (fluctuating)</td>
</tr>
<tr>
<td>Water Initial temperature of the storage</td>
<td>( T_{\text{in}} )</td>
<td>9 °C</td>
</tr>
<tr>
<td>Water charging inlet Temperature</td>
<td>( T_{\text{inlet}} )</td>
<td>5 °C</td>
</tr>
<tr>
<td>Water discharging inlet Temperature</td>
<td>( T_{\text{outlet}} )</td>
<td>14 °C</td>
</tr>
</tbody>
</table>

Step function is used to add temperature inputs on Global Definition node. While for \( V_{c\text{-inlet}} \) and \( V_{d\text{-inlet}} \) an **Interpolation** function are used to define values for velocity flows that could be imported from external files or inserted manually.

### 3.6.3.1 Material Definition for Cold Cavern 2D Simulation

The global definition step is followed by cavern materials’ definition. Neglecting wall and pipe material to make this simulation deal with the fluid inside the cavern. Water was specified as fluid for this study and it was defined on Comsol by **Materials** nodes. This function allows users to automatically add predefined materials, while it is also possible to be added manually by choosing the user-defined material option. Material function specifies the selected material properties by using a set of functions, values, and expressions. A video tutorial is available on the Comsol website which explains the material selection in detail. (Comsol, 2017). It is important to define the geometry and the material boundaries for simulation; in this case, everything inside the Cavern is considered water except the pipes.

### 3.6.3.2 Heat Transfer Boundaries Definition for Cold Cavern 2D Simulation on Comsol

The Heat Transfer node on Comsol was used for boundary definitions for a model and it is the step that follows selecting materials on Comsol software. Clicking the right click on the icon of heat transfer will display a branch of predefined Multiphysics functions that are added automatically by selecting them. A set of heat transfer interfaces were selected for Cold cavern 2D simulation, the following list was defined from the metaphysics branch on Comsol software 5.2a:

- a) Fluid: Has been described in equation (19), (20). Surface area that is covered by fluid has to be defined manually on the modeled geometry of the cavern.
b) Initial Values: In heat transfer, initial values refer to the initial temperature of the cavern before the charging and discharging processes. Initial temperature domains on the cavern’s geometry have to be defined.

c) Thermal Insulation: Boundaries with no heat flux across them, such as walls boundaries for this simulation.

d) Temperature: Charging and discharging are continuous processes in this simulation. Temperatures are selected from the heat transfer node on Comsol. Inlets/outlets initial temperatures for cold and warm water on each side of the geometry have to be defined manually.

e) Outflow: inlet flow in the discharging side is considered as an outlet flow during charging process and vice versa.

### 3.6.3.3 Fluid Flow Boundaries Definition for Cold Cavern 2D Simulation on Comsol

Water is the fluid that is used for storing cold energy in the cavern. The fluid has a turbulent flow during operational hours as explained in the fluid flow chapter. Turbulent flow, k-ε interface was used for this simulation, the reason behind that will be discussed later in the following chapters. Velocity flow for charging and discharging were defined in similar steps to heat transfer, selecting temperature boundaries in the last paragraph.

A gravity feature was added for the fluid flow section by selecting (Include gravity) option from fluid flow node. This option will add automatically presented equations to the simulation. Since water has a respectfully high density that is also temperature dependent, gravity is necessary while running a simulation. Including a gravity option on Comsol defines the gravity forces from the acceleration of gravity value, where \( (\text{SI unit m/s, default value } -g_{\text{const}x} \text{ in 2Daxi and 3D and } -g_{\text{const}y} \text{ in 2D}) \) are used to define the gravity forces as classified on the software. (Comsol, 2017)

### 3.7 Meshing in Comsol

Meshing is a term in computing means adding elements to grid-points, called 'nodes' or ‘elements’. There are equations that govern fluid flow and heat, transferring larger-sized domains of geometry. When meshing geometry, these dominoes are divided into smaller subdomain or nodes, where each one of these cells has a relevant governing equation. Meshing basically helps to understand how each of these cells in geometry is connected to another, by applying numerical calculations for each of the nodes.

Governing equations for the elements are driven by partial differential equations from the Finite Element Analysis (FEA) software. It could be concluded that the finer mesh size is the number of solved equations leading to a closer result for the true one. (Comsol, 2017). There are three main methods, which are used to solve the governing equations: finite volumes, finite elements, or finite differences. FEA is using a finite element method.

Different geometries for 2D and 3D models can be selected in Comsol, while hexahedral and tetrahedral are used in 3D models, quadrilaterals, and triangles used for 2D ones. Figure 3.10 explains how cells are generated in simple 2D and 3D models; dividing the larger dominoes in cells as the figure shows, increasing the accuracy of simulation’s results.
Figure 3.10. Meshing a domain into smaller subdomains in 2D and 3D geometries. (Bakker, 2006)

3.7.1 Mesh Size

Meshing size is dependent on the purpose of simulation, as well as the geometry of the model. Comsol’s software guide advises the users to start meshing with coarse elements size, in case the model has simple geometry. Mesh size is selected by Size node on Comsol software. It is good to point out that Comsol has predefined sizes for meshing, starting with normal sized elements and scale up to extremely coarse and down to extremely fine-sized element. Mesh size can either be automatically added or manually selected, depending on the nature of model geometry and its needs.

Larger element sizes lead to faster simulation results, with a possibility of having a lower accuracy, higher level of errors. Additionally, simulations with large element size might stop before it reaches the result due to the lack of convergence. However, extremely fine elements’ size might require a long time to complete one simulation, thus it is advised to choose larger element sizes and apply mesh analysis to investigate the results’ dependency on element size.

Mesh analysis is used for mesh refinements, and it can save much time and effort for models that require a reparative simulation. Analyzing mesh dependency does not require less than three solutions that have three different element sizes. (Comsol, 2017).

3.7.2 Cold Cavern Meshing in Comsol 5.2a

Before starting the actual meshing of geometry, it is essential to understand the complexity level of the structural model. Figure 3.10 shows the geometry of the cavern in 2D, as simple geometry that does not require complex meshing. Geometry in Comsol is represented as CAD model, where the meshing process starts by dividing the cavern into domains based on their complexity. The 2D cavern model was divided into 3 main sub-domains as shown in figure 3.11, where subdomain number (2) has a very simple geometry while (1) and (3) are subdomains that would require finer meshing, due to the presence of corners and pipe inlets.
Different meshing nodes for the selected domains are shown in figure 3.11 where **Mapped** node was used for the middle part of geometry with domain number (2). This meshing function is used to create structured logical quadrilateral cells that are suitable for extremely simple geometry. It can be used for both 3D and 2D models. Finer customized elements’ size was applied on domain (2) which has a maximum element size of (0.32 m). Figure 3.12 is a snapshot of a zoomed in section from domain (2), where it shows a structural mapped mesh with fine element sizes and quadrilateral cells.

**Figure 3.12.** Snapshot of zoomed in section from domain (2) with mapped mesh and finer quadrilateral cells.

Different refining tools were applied on domains (1) and (3) for increasing mesh quality, Corner **Refinement** node was added to the mesh, causing a decrease in the elements’ size at sharp corners and around pipes’ inlets while **Free Triangular** node, which is another refining tool, was used to create an unstructured triangular mesh on boundaries.

**Free Triangular** node allows more freedom in filling the gaps around difficult areas such as pipes and corners. Figure 3.13 shows nicely formed triangular cells around pipe’s inlet in a domain (1). Element sizes for both domains (1) and (3) were customized to be extremely fine with maximum size of 0.07 m. Extreme size element was applied in areas around the pipes and corners to ensure the quality and accuracy of results since these regions have a more complex structure than the middle domain. Moreover, considering also that the simulation is for a 2D model with simple geometry, it did not require much time to run and complete simulations.
Figure 3.13. Illustrative view of a section for two mesh sizes, elements with green colour are from domain (2) and the grey ones from domain (1).

A statistic tool is also used for checking mesh quality; by illustrating the mesh numerically as colored plot by selecting **Statistics** and **Plot** tools on Comsol software. Figure 3.14 below illustrates mesh quality analyses on a section from cavern geometry. Based on the colored legend on the right side of the figure, the average mesh quality is high which approves the suitability of the chosen mesh element size for all domains.

Figure 3.14. Illustrative view of plot mesh quality analyses on Comsol software 5.2a

### 3.7.3 Cold Cavern 2D Simulation

Cold-water storing process in CTES using mixed mechanism is rarely simulated. In fact, there is almost no study that has been found about it. Therefore, the expectation of how the fluid flow would react during operation hours is based on heat transfer and fluid dynamics and not on practical testing. Assumptions have been made for the initial values such as an initial temperature of the cavern before starting the simulation, as well as the position of pipes inside the cavern shown by figure 3.11. Consequently, there is a need for multiple iterations for this simulation to verify these hypotheses and to minimize possible error.

Numerous attempts were applied to finally find a suitable input data for the simulation to run and complete the first solution with successful conversion. Afterwards, six solutions for charging and discharging processes were performed, where solutions (results) from one computing attempt were used as initial values for the following one. This procedure was repeated one after another for the six computing attempts. Results were then compared with the initial attempt to verify the validity of the cavern 2D simulation results. Figure 3.15 illustrates the results’ branches from cavern 2D simulation used for this study. Compute button on Comsol software is used for the simulation to run.
3.8 Results and Discussion of 2D Simulation

This chapter is a primary results’ analysis of 2D. The objective of this chapter is to draw an elementary conclusion on how fluid is flowing during operational hours in the cavern. It aims to also have an expectation on the possible capacity of storing cold water in cavern TES using mixed technology. The discussed results will be based on the first, third and fifth solutions from the charging process and the second, fourth and the sixth solutions from the discharging process. The results will go briefly through heat transfer and fluid dynamics reasoning, based on the theoretical knowledge that was discussed in earlier chapters.

The Results branch on the COMSOL Multiphysics allows analyzing data numerically and visually by using a set of static and dynamic plots of simulation results. When clicking the right button on results, various options for data analysis appear, where results could also be exported as animations, tables, excel files and plots. Furthermore, result branch setting enables one to choose any period of time of a simulation and easily maneuver from one solution to another.

3.8.1. Charging: Surface Temperature Analysis

The simulation, as mentioned was repeated six times to ensure accuracy. Simulation started with a charging process where cold water with 5 °C was injected into the cavern that has an initial temperature of 9 °C. Figure 3.16 illustrates surface temperature of the cavern during a process of charging, over different time periods. The figure helps to understand how cold water would really flow inside the cavern. Picture (a) from the figure shows water with lower temperature is pushed out from the inlet against the water with a velocity flow rate of 2.5 m/s, which caused the water turbulence and bouncing force that disturbed the initial temperature of the cavern, marked in light red in the same picture. Picture (b) shows the cavern after a moment from charging. It is clear that cold water starts to mix with warmer water causing a discerning of that region temperature in total.

Picture (c) is from the middle time period of the charging process shows clearly that cold water tends to flow into the lower part of the tank due to its higher density, while the mixing of water with two different temperatures continues. Cold water then starts to flow toward the warmer side of the tank as the charging process continues, however, due to the not natural flow of water form cold side to the warm side a thermocline layer starts to form, in at least the upper side of the cavern.
while the temperature of that region also starts to drop gradually. Picture (d) illustrates the last stage of the charging process in the cavern with cold water; it is clear that injecting cold water into the tank has disturbed the initial temperature and caused purely cold temperatures in the left side of the cavern, while in the middle one is water with mixed temperature that is ranked between 6.5 °C from right to 8.5 °C on the left side.

Warm water tends to stay in the top side of the tank, for the density reason. It is also noticed from the figure below that cold water occupies only a small part from the tank, which gives an indication of a low storing capacity of cold water using the mixed mechanism. However, this will be decided after, based on the cold outlet after temperature after the last discharging simulation.

Figure 3.16. Cavern surface temperature illustrations during a process of charging in three different time periods.

Charging solutions comparison should proceed before moving into a discharging analysis; this step is done to make sure that the repetitiveness of the process would not have a major effect on the results. Figure 3.17 illustrates the surface temperature of the cavern after three complete cycles of charging, the legend on the right side of the figure shows that there is not a major variation between the three results, which would confirm the accuracy of the results.
Figure 3.17. Cavern surface temperatures comparison, after three complete cycles of charging processes.

However, exported surface temperature has also been numerically considered in figure 3.18 where the chart is based on the three charging simulation solutions of the temperature at the warm side outlet. The purpose of taking the warm side outlet temperature is to understand how the cold water flows during charging, as well as how it would affect the initial temperature of the warm side of the tank, which will be discharged with warm water after each charging process. It is concluded from figure 3.18 that the repeatability of the simulation would have a minor effect on the results in a way which can be neglected.

Figure 3.18. Cavern warm side outlet temperature from three charging simulation solutions.
3.8.2 Discharging: Surface Temperature Analysis

Discharging process starts when warm water at 14 °C is injected into the cavern during daytime after charging process is completed. It lasts for approximately 10 hours with fluctuating flow rate. Temperature at the inlet in the cold side of the cavern would determine the feasibility of the mixed storage mechanism for storing cold water in this cavern. Three discharging simulations were applied.

Figure 3.19 illustrates surface temperature of the cavern after the third discharging. Warm water is going from the inlet pipe and hits the wall with an average velocity of 1.7 m/s and bounces back to the flow toward the colder side of the cavern, causing a turbulence in discharging region on the right side of the tank. It is easier for warm water to flow from the warmer side into the colder side since it is natural heat transfer process.

However, warm water tends to initially at first rise into the top of the cavern as the figure shows due to its lower density. If charging and discharging figures were compared, it would be noticed that thermocline layer does not really form during discharging process, and it looks more like water mixture with different temperatures along the cavern.

Temperature at the cold outlet starts to increase gradually during cavern’s discharging, figure 3.20 shows that the initial temperature at the cold outlet is 5 °C and by the end of the discharging process it reaches up to 6.5 °C. These results indicate that there is no clear separation between the two sides, which also gives a primary signal mixed storage option that might not be feasible for this purpose of storing.
Nevertheless, calculating storage capacity will define whether it is feasible to use this mechanism to store cold water for district cooling or not.

![Figure 3.20. Temperature changes over time of discharging process at the outlets of cold side of the cavern.](image)

### 3.8.3 Cold Cavern 2D Simulation: Capacity Calculations and Conclusion

The capacity of CCTES means in practice, that the cavern can keep the temperature at the cold side of the storage, low enough to the use of district cooling system, after a couple of cycles of the discharging processes. It was mentioned earlier in the study that the most desired cold temperature to be extracted from the cavern during discharging process is the same as the initial charging temperature, any increase on that temperature should be cold down by chillers outside the storage, which they can also tolerate a level of temperature increase.

Temperature increase here is measured by decimals, since cooling extracted chilled water to one full Celsius degree would require double the capacity of the used chillers. Table 3 illustrates the cooling capacity of the cavern that was calculated by equation (18); it is clear that a higher flow rate and lower extracted temperature results in higher expected storing cooling capacity. From table 3 it could be concluded that, with current flow discharging rate and expected extracted temperature, the mixed storing mechanism for cold water failed to reach the needed capacity for district cooling where from table 3 the average cooling capacity that the storage is required to deliver entitle to be feasible to invest in is around 10 MWh, while the calculations of the storage with current features expected to deliver less than 8 MWh cooling capacity.

This would require extra cooling alternatives to cover the gap between the demanded and delivered cooling capacity from the cold storage, such as extra chillers.
It is not easy to have a confident conclusion based on 2D simulation, since many other factors are neglected in comparison to the realistic results that 3D simulation can provide. Therefore, the final conclusion will be presented after the 3D simulation for the operational processes of the cavern will be completed.

### Table 3. Cooling capacity of the cavern 2D model in relation with temperature at the cold extraction, time and discharging flow rates.

<table>
<thead>
<tr>
<th>Real Time</th>
<th>Discharging Time</th>
<th>Cold Extraction $^{3\text{ed}}$</th>
<th>Discharging Mass Flow Rate</th>
<th>Cooling Capacity</th>
<th>Needed Cooling Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00</td>
<td>1</td>
<td>5.3</td>
<td>116</td>
<td>4.2</td>
<td>-4.0</td>
</tr>
<tr>
<td>09:00</td>
<td>2</td>
<td>5.3</td>
<td>280</td>
<td>10.1</td>
<td>-9.7</td>
</tr>
<tr>
<td>10:00</td>
<td>3</td>
<td>5.8</td>
<td>277</td>
<td>9.2</td>
<td>-9.6</td>
</tr>
<tr>
<td>11:00</td>
<td>4</td>
<td>6.1</td>
<td>300</td>
<td>9.7</td>
<td>-10.4</td>
</tr>
<tr>
<td>12:00</td>
<td>5</td>
<td>6.2</td>
<td>305</td>
<td>9.8</td>
<td>-10.6</td>
</tr>
<tr>
<td>13:00</td>
<td>6</td>
<td>6.2</td>
<td>306</td>
<td>9.8</td>
<td>-10.6</td>
</tr>
<tr>
<td>14:00</td>
<td>7</td>
<td>6.2</td>
<td>369</td>
<td>11.8</td>
<td>-12.8</td>
</tr>
<tr>
<td>15:00</td>
<td>8</td>
<td>6.2</td>
<td>374</td>
<td>11.9</td>
<td>-13.0</td>
</tr>
<tr>
<td>16:00</td>
<td>9</td>
<td>6.3</td>
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<td>10.4</td>
<td>-11.5</td>
</tr>
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<td>10</td>
<td>6.4</td>
<td>201</td>
<td>6.3</td>
<td>-7.0</td>
</tr>
</tbody>
</table>

### 3.9 Cavern 3D Modelling and Simulation

This chapter will discuss modelling and simulating the cold cavern in 3D. The purpose of which, is to confirm or reject the feasibility of using mixed mechanism for storing cold water in the cavern for district cooling network in Stockholm. The same Comsol 5.2a software will be used, and similar steps to 2D modelling and simulation will be carried out. The chapter will start by aggregating and calculating input data, followed by cavern modelling. Simulating operational processes on the 3D modelled cavern will be the last step, before results, analysis and conclusion. Proceeding with modelling is much easier after understating how it is done with 2D. First step is to choose the 3D space on Comsol as figure 3.5 shows and follows the same steps in choosing the same heat transfer and fluid dynamics for the simulation. However before starting any data input, geometry for the cavern which has to be made using geometry tools for 3D modelling, is also the
same procedure as 2D but here, block and different layers are selected. The geometry tree that was applied for 3D cavern model is illustrated in figure 3.21.

![Geometry Tree](image)

**Figure 3.21.** Comsol geometry tree used for 3D modelling of the cold cavern.

Block node is used to draw the outer geometry of the cavern, as explained previously in the meshing 2D chapter, Work Plans were used to draw the pipes, ramps, and also divide the cavern into three different regions for meshing. Figure 3.22 illustrates the 3D geometry on Comsol software, where pipes are located as concluded in 2D on the upper middle side of the cavern, and the pipes’ opening is pointing toward walls of the cavern.

![3D Geometry](image)

**Figure 3.22.** Illustration of the cavern 3D geometry on Comsol software.

Charging and discharging input data will be based on the real-life data. Starting from the global definition where temperatures will be defined as in 2D, while in 3D a flow rate in (m$^3$/s) will be imported from an external Excel file as table (2) shows. Simulation time will correspond as well as the real time for charging and discharging processes calculated in seconds instead of hours where one hour equals to 3,600 seconds, therefore:
Charging simulation time:

\[ 13 \times 3,600 = 46,800 \text{s} \]  

(21)

Discharging simulation time:

\[ 11 \times 3,600 = 39,600 \text{s} \]  

(22)

All other inputs will be the same as it is explained in the 2D chapter except meshing the cavern, which has a special procedure; this is what the following paragraph will discuss.

### 3.9.1 Meshing 3D model of Cold Cavern in Comsol 5.2a

The cavern was divided into three subdomains to make it easier and more effective for meshing. The meshing node which was used in 2D is the same one used in 3D; meshing will also follow the same procedure.

Meshing in 3D will define how long the simulation would take to complete one process, while the difference between meshing levels could take many hours or even days; therefore, it is wiser to start with a large mesh size and carry a mesh analysis, and then refine the mesh to a smaller size.

Study also carried the same procedure as meshing in 2D, where the side subdomains were mashed into smaller element sizes, in comparison to the middle one. After the mesh refining process, it was discovered that there is no significant difference in the simulation results with the last used mesh size, which was 0.4 m minimum element size for the side subdomains, while it was 0.6 m as minimum element size for the middle subdomain.

![Figure 3.23. Meshing the cavern geometry on Comsol.](image)

Figure 3.23 illustrated cavern geometry after meshing; it is also observed that the average quality of the mesh is at its highest level, as the coloured legend shows. Figure 3.24 below shows also that
corner refinement and free triangular functions were applied on the model mesh as seen round the pipes inlet marked in blue in the figure.

Figure 3.24. Applying Corner Refinement and Free Triangular functions to increase the quality of cavern geometry meshing on Comsol.
4. RESULTS AND DISCUSSION

This chapter will discuss the results of the simulation processes on the 3D model of CCTES. Charging process’ results will be illustrated in figures to see how the fluid in the 3D simulates will act during the charging process and also during discharging, afterwards capacity calculations will be carried out, through which a consolation on the feasibility of mixed storage mechanism will be discussed.

4.1 Simulation of Cavern 3D Charging Process

Charging the cavern in 3D starts as table 1 shows at 7pm by injecting the cavern with cold water at 5°C with a constant flow rate of 0.5 (m³/s) and it last for 12 hours. Figure 4.1 illustrates different stages of the charging process, where (a) is the cavern at its initial temperature where it shows cold water is hitting the wall and behave exactly as in 2D simulation, where water tends to go to the lower area of the cavern due to its higher density and start mixing with higher temperature water of the cavern in (b). While picture (c) from the figure shows the cavern after the charging process is completed, where it is seen as an almost homogeneous complete mix of water at a temperature of between 5-6 °C, remains in the cavern. A full tank with cold water at this temperature would be an optimum situation for district cooling.

![Figure 4.1 3D solid surface temperature illustration of three different stages of charging process; a) One hour of charging; b) Six hours of charging, c) Twelve hours of charging.](image-url)
4.2 Simulation of Cavern 3D Discharging Process

The discharging process in the 3D cavern model has a similar fluid flow as the one in the 2D, as seen from figure 4.2. Water with higher temperature is injected toward the cavern’s wall where it causes a turbulence that pushes part of the coming water to mix with colder water in the cavern. Mixed water in the warm region then has a higher average density, which makes it flow toward the lower part of the cavern. However, the discharging process lasts almost ten hours, causing water temperature in the right side of the cavern to rise, and to gradually float toward the upper part of the cavern due to its lower density.

![Figure 4.2 Simulating of discharging process of 3D cavern model on Comsol.](image)

After multiple simulations of charging and discharging processes, the temperature from the outlet from the colder side of the cavern was measured during the last simulation attempt of the cavern 3D discharging process. This was intended in order to analyse the effectiveness of mixed mechanism in keeping water with two different temperatures separated during operational hours.

Figure 4.3 shows that temperature at the cold outlet does not remain constant and starts to increase gradually from an initial temperature of 6.5 °C after last charging, until it reaches up to almost 9.5 °C, which is much higher than usable extraction cold water average.

![Figure 4.3. Mentoring of cold temperature at the outlet after discharging process over time.](image)
Understanding fluid dynamics is an essential step towards a conclusion in this subject; it is easier to interpret quantitative figures by visualising a presentation rather than numbers. Comsol as mentioned has different physics for result analysis, where Isosurface node is used to visualise water flow from one side into another. Figure 4.4 illustrates water behaviour in the cavern after five hours of discharging, which would also explain the increase in water temperature at the cold outlet. As it is seen from the figure, incoming water with average flow rate of 290 kg/s, hits the cavern wall and starts to diverge after part of it start mixing. The ramp shows that it can work as an obstacle to slow down the flow, however, as it is seen from the figure 4.4 below, that the water keeps migrating towards the colder side, causing the increase of average water temperature in that region.

![Figure 4.4. Illustration of water behaviour in the cavern after five hours of discharging using Isosurface node on Comsol.](image)

### 4.3 Cold Cavern 3D Simulation: Capacity Calculations and Results Analysis

Calculating storage capacity is important to confirm or reject the results from the previous chapter; though it is obvious that water with almost 9.5 °C cannot serve its purpose in district cooling as discussed in earlier chapters. However, table 3 shows the related capacity per discharging hours and compares it with the demanded capacity for district cooling. The results did not defer much from what it is in table 2 for the 2D model, where it could be concluded from both tables that extracting water from the cold side at these temperatures would not fulfil the demanded capacity.
Table 3. Cooling capacity of the cavern 3D model in relation with temperature at the cold extraction, time and discharging flow rates.

<table>
<thead>
<tr>
<th>Real Time</th>
<th>Discharging Time</th>
<th>Cold Extraction 3rd</th>
<th>Discharging Mass Flow Rate</th>
<th>Cooling Capacity</th>
<th>Needed Cooling Capacity</th>
</tr>
</thead>
<tbody>
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<td>-7.0</td>
</tr>
</tbody>
</table>

4.4 Sensitivity Analysis and Discussion

This research study is a *de novo* study. Due to the lack of similar studies and reference experiments for Underground CTES and documentation, a repeated modelling and analysis were performed to obtain reproducible and representative results. Modelling the cavern in 2D was performed to visualize the cavern during operational processes to optimize the geometry of the cavern before running the simulation of 3D modelling. Though the actual geometry cannot be changed, however inlet pipes locations could be optimized. Therefore, various iterations with different pipes positioning were applied where pipes position that is shown in figure 3.11 were optimum. The simulation could be affected by factors such as system boundaries, ramp size and location inside the cavern. However, system boundary was neglected since the cavern was considered as adiabatic system where we assumed that transmitting losses to the surrounding is around 1% to 2% from UTES capacity as mentioned in the methodology chapter. (Bahnfleth & Musser, 1998)
Figure 4.4 shows that the ramp, even though it occupies large space in the cavern total volume, it does not stop migration of water from one side to another. Obviously, adding obstacles to slow water migrations would not lead to a significant difference in the results.

Analysis of figure 4.1 and figure 4.2 shows that no obvious thermocline layer was formed as a natural separation between the warm and cold sides of the cavern which indicates that a full separation between water with different temperatures (densities) is not possible in horizontal mixed storage mechanism.

![Graph](image.png)

**Figure 4.5 Capacity Calculations of Mixed Cold CTES Compared with Needed Cooling Capacity**

Based on table 3, figure 4.5 was generated where the green line illustrates required cooling capacity during a day which implies that any other considered cooling technology as alternative should match or exceed the required cooling demand. The red line in the same figure illustrates the expected cooling capacities of the underground CTES after during a discharging process, where it is shown that using the mixed storage failed to deliver the required cooling capacity for the district cooling system.

From table 3, the average required cooling capacity that is needed to be covered or exceeded for the studied district cooling is around 10 MWh while the average excepted cooling capacity from the underground CTES using mixed mechanism is less than 8 MWh.

Finally, any implementations on this underground cavern as CTES such as adding obstacles would lead to extra costs and/or less expected cooling capacity output, therefore the given results were considered optimized and carefully considered for the nature of this project.
5. CONCLUSION AND FUTURE IMPLEMENTATIONS

The importance of cold thermal energy storages has been clear throughout the study. Different factors, such as fluid dynamics, heat transfers must be considered carefully and understood to proceed with any decision related to thermal energy storages. Using software modelling and simulation is a very efficient way for saving costs and time, as well as enabling the study of different scenarios and conditions for a given subject. This study used two steps of modelling and simulation to reach a conclusion on feasibility of using mixed mechanism for storing cold water in the abandoned oil cavern for district cooling system.

The first step was modelling the cavern in 2D for the purpose of understanding fluid behaviour inside the cavern during operational hours and also to choose the right input physics to be used later for 3D simulation. Due to the shorter time that 2D simulation takes to complete on district cooling water-sorting cycle, multiple attempts were made. However, the first conclusion provided information on unsuitability for using the mixed mechanism as an alternative for storing cold energy using stratification method, since the cavern capacity calculations showed that mixed technology cannot fulfil the cooling demand during peak hours. The second step was simulating real operational processes on a 3D model cavern, since in the 2D simulation factors were neglected due to the nature of the 2D geometry, such as the ramp, corners of the cavern, therefore it was necessary to perform a 3D simulation to assure the accuracy of the result considering all factors. These results confirm that a stratified mechanism is a valid option to store cold water in the underground cavern, due to its higher cold water storing capacity that was estimated to be around 10 to 12 MWh as the company referenced adding to that the solid references in both practical and theoretical studies.

Repeated simulations can always increase the accuracy of the results however; in this case it is not expected to have a major difference in the result since it has already been tested multiple times with refined meshes. Nevertheless, adjusting water inlet positions as well as adding obstacles inside the cavern model Comsol can be tested in order to compare results.

Testing the feasibility of mixed storage on a real small-scale model can be recommended, since it can enable a better view on how water reacts during operational hours. Also, various adjustments could be tested, such as adding obstacles to slow water migrations from one side of the tank.


Nordell, B. & Skogsberg, K., 2002. *Snow and ice storage for cooling applications.* Aomori, Japan, s.n.


5. APPENDIX A: FORMULAE DESCRIPTION
<table>
<thead>
<tr>
<th>Formulas</th>
<th>Charging</th>
<th>Discharging</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V = W \times L \times H$</td>
<td>28,350</td>
<td>28,350</td>
<td>m$^3$</td>
<td>Volume of the cave</td>
</tr>
<tr>
<td>$1 \text{kg/s} = 0.01 \text{ m}^3/\text{s}$</td>
<td>0.5</td>
<td>0.29</td>
<td>m$^3$/s</td>
<td>Average Discharge flow rate</td>
</tr>
<tr>
<td>$t = \frac{\text{Volume m}^3}{\text{Flow Rate m}^3/\text{s}} = s$</td>
<td>56,700</td>
<td>97,759</td>
<td>S</td>
<td>Time it would take to fill the 3D cave 100%</td>
</tr>
<tr>
<td>$1 \text{*Hour} = 3,600 \text{s}$</td>
<td>15.75</td>
<td>27.5</td>
<td>h</td>
<td>Time it would take to fill the 3D cave 100%</td>
</tr>
<tr>
<td>$12 \times 3600 \times \frac{\text{Volume m}^3}{\text{Flow Rate m}^3/\text{s}} = 76%$</td>
<td>76%</td>
<td>36%</td>
<td></td>
<td>Maximum filling capacity for the cavern during Cold Charging is (83%) and warm Discharge is (40%)</td>
</tr>
<tr>
<td>$10 \times 3,600 \times \frac{\text{Volume m}^3}{\text{Flow Rate m}^3/\text{s}} = 36%$</td>
<td>1,890</td>
<td>1,890</td>
<td>m$^2$</td>
<td>This is due the flow rate in case of charging and the capacity of the chillers in case of discharge</td>
</tr>
<tr>
<td>$A_s = L \times H$</td>
<td>1,890</td>
<td>1,890</td>
<td>m$^2$</td>
<td>Surface area of the cave 2D</td>
</tr>
<tr>
<td>$A_c = A_s \times 76%$</td>
<td>1,440</td>
<td>696</td>
<td>m$^2$</td>
<td>The filled 2D cavern area during charging / Discharging</td>
</tr>
<tr>
<td>$A_d = A_s \times 36%$</td>
<td>0.5</td>
<td>0.5</td>
<td>m</td>
<td>Inlet/outlet pipe diameter</td>
</tr>
<tr>
<td>$\nu = \frac{\text{Flow Rate m}^3/\text{s}}{\text{Pipes surface Area m}^2} = \text{m/s}$</td>
<td>2.5</td>
<td>1.5</td>
<td>m/s</td>
<td>Velocity flow both 2D/3D</td>
</tr>
<tr>
<td>$\dot{\nu} = \nu \times d$</td>
<td>1.27</td>
<td>0.74</td>
<td>m$^3$/s</td>
<td>Flow Rate in 2D</td>
</tr>
<tr>
<td>$t_c = A_c / \dot{\nu}$</td>
<td>1,131</td>
<td>942</td>
<td>S</td>
<td>Seconds are necessary to fill 76% of the 2D cave with the same velocity as the 3D cavern during charging and 36% during discharging</td>
</tr>
</tbody>
</table>