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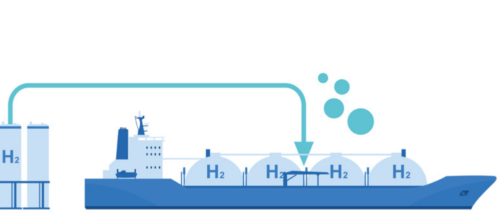
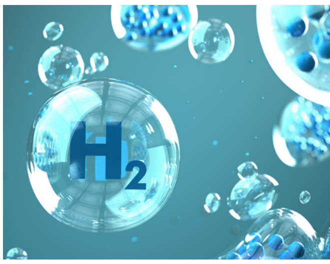
Large scale hydrogen filling

Challenges when filling large volumes of hydrogen in short time





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Challenges when filling large volumes of hydrogen in short time

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In cooperation with

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Summary

This feasibility study has been initiated and financed by Lighthouse and aims to increase knowledge about the use of hydrogen as a marine fuel, where it has good conditions to be a sustainable and efficient fuel in certain segments.

In the transition to fossil-free shipping, hydrogen has potential to be a non-fossil solution for certain segments of shipping. However, the possibility to use hydrogen is limited by the fact that hydrogen has a low volume density, which limits how much hydrogen can be stored on board. In addition, the use of hydrogen is also limited by challenges related to the handling of hydrogen. This report studies one of those the challenges, the filling of hydrogen from storage in the port to on-board the ship. Specifically, the filling of the next generation Gotland ferries is being studied, up to 16 tons of hydrogen must be filled for each round trip between Visby and Nynäshamn. Furthermore, to enable three round trips per day, the ferry needs to be turned around in less than one hour, which is a challenge for the filling, from both a thermodynamic and a regulatory perspective.

In this report, the large-scale filling of hydrogen gas is studied, a thermodynamic simulation model and an overview of relevant regulations are presented.

The thermodynamic simulation shows that the temperature in the hydrogen cylinders on-board the ship will rise to 130°C if no cooling of the hydrogen takes place. The maximum temperature allowed in the cylinders is 80°C, why it is absolutely necessary to introduce some form of cooling in the filling process.

When filling vehicles, the hydrogen is cooled down to -40°C before filling to avoid the temperature rising above the allowed limit. However, there is a big difference between filling of vehicles and filling of the ferry; a vehicle refuels up to 50 kg, while the ferry must be filled with 16,000 kg. Cooling these volumes requires a lot of energy, why in this report we have developed and tested an alternative method with active cooling inside the cylinder.

This active cooling is done with the help of seawater that flows through a heat exchanger inside each cylinder on-board the ship. The thermodynamic simulations show that this active cooling keeps the temperature inside the cylinders below 60°C.

To evaluate the concept of active cooling of hydrogen cylinders, a research project has been initiated where a cylinder with active cooling will be manufactured. The project is financed by the Swedish Transport Administration. The cylinder is a down-scaled version of the hydrogen cylinder planned to be installed in the future Gotland ferry. The temperature will be monitored both inside the cylinder and on the outside of the metal-liner. The laboratory tests will be carried out in cooperation with Research Institutes of Sweden (RISE) during quarter 3 in 2024.

The report also presents a compilation of the regulations relevant to the handling of hydrogen in ports.

The work on the feasibility study has been done by Björn Samuelsson, (project manager), Jim Allansson and Kenneth Friberg at Uppsala University and Kumail Marnate and Stefan Grönkvist at KTH. The work has taken place in collaboration with Christer Bruzelius, Gotland Tech Development; Harald B Hansen, Hyon; Per Wimby, Stena Teknik and Jens Berge, Norwegian Hydrogen.

Sammanfattning

Denna förstudie har initierats och finansierats av Lighthouse och har som syfte att öka kunskapen kring användning av vätgas som ett marint bränsle, där vätgas har goda förutsättningar att inom vissa segment vara ett hållbart och effektivt bränsle.

I omställningen till en fossilfri sjöfart har vätgas potential att vara en icke-fossil lösning för vissa segment av sjöfarten. Den möjliga användningen av vätgas begränsas dock av att vätgas har låg volymdensitet, vilket begränsar hur mycket vätgas som kan lagras ombord. Utöver detta begränsas även användningen av vätgas av utmaningar kring hanteringen av vätgas. Denna rapport studerar utmaningar relaterade till fyllning av vätgas från lager i hamn till ombord på ett fartyg. Specifikt studeras fyllningen av nästa generations Gotlandsfärjor, där upp till 16 ton vätgas ska fyllas för varje tur och returresa mellan Visby och Nynäshamn. För att möjliggöra tre tur- och returresor per dygn krävs att färjan kan vändas på mindre än en timme, vilket innebär en stor utmaning såväl ur ett termodynamiskt som ett regulatoriskt perspektiv.

I denna rapport studeras den storskaliga fyllningen av vätgas, en termodynamisk simuleringsmodell och en genomlysning av relevanta regelverk presenteras.

Den termodynamiska simuleringen visar att temperaturen i vätgascylindrarna ombord på fartyget kommer att stiga till ca 130°C om ingen kylning av vätgasen görs. Högsta tillåtna temperatur i cylindrarna är 80°C, varför det är absolut nödvändigt att införa någon form av kylning i fyllningsprocessen.

Vid fyllning av vägfordon kyls vätgasen ned till -40°C innan fyllning, för att undvika att temperaturen stiger över den tillåtna gränsen. Det finns dock en stor skillnad mellan fyllning till fordon och fyllning till färjan; ett vägfordon tankar upp till 50 kg medan färjan ska fyllas med 16 000 kg. Att kyla dessa volymer kräver stora mängder energi, varför vi i denna rapport har utvecklat och testat en alternativ metod med aktiv kylning i cylindern.

Denna aktiva kylning görs med hjälp av sjövatten som flödar genom en värmeväxlare inne i respektive cylinder ombord på fartyget. De termodynamiska simuleringarna visar att denna aktiva kylning håller temperaturen under 60°C.

För att utvärdera konceptet med aktiv kylning av vätgascylindrar har ett forskningsprojekt initierats där en cylinder med aktiv kylning ska tillverkas. Projektet finansieras av Trafikverket. Cylindern är en nedskalad version av den vätgascylinder som planeras att installeras i den framtida Gotlandsfärjan. Temperaturen kommer att övervakas både inuti cylindern och på utsidan av metallfodret. Laboratorieförsöken kommer att genomföras i samarbete med Sveriges Forskningsinstitut (RISE) under tredje kvartalet 2024.

Rapporten presenterar även en sammanställning av de regelverk som är relevanta för hantering av vätgas i hamn.

Arbetet med förstudien har gjorts av Björn Samuelsson, (projektledare), Jim Allansson och Kenneth Friberg Uppsala universitet samt Kumail Marnate och Stefan Grönkvist KTH. Arbetet har skett i samarbete med Christer Bruzelius, Gotland Tech Development; Harald B Hansen, Hyon; Per Wimby, Stena Teknik samt Jens Berge, Norwegian Hydrogen.

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1 Introduction

Green hydrogen has potential to be a good fossil-free alternative maritime fuel for certain segments and can be used either with fuel cells, internal combustion engines (ICE) or in a gas turbine. A major advantage using green hydrogen is that there will be no CO_2-emissions and the energy content per weight unit is high, 1 kg of hydrogen contains as much energy as 3.4 liter of diesel.

However, hydrogen has not yet been used in large scale as ship fuel. The cost of hydrogen compared with fossil fuels is an obvious a reason for this, but there are also other hurdles for the implementation of hydrogen to the maritime sector.

A major problem is the volume, at 200 bar pressure 1m^3 of hydrogen has a weight of 17 kg, which will have a significant impact on the space needed on-board for storing the fuel. Furthermore, the low volume density will create certain difficulties when fuelling the ship due to high volumes to be filled in short time. In particular in ferry operations, it is of high importance to be able to fill fuel in a short time. Due to the very specific thermodynamic properties of hydrogen, there is a high risk that the temperature will increase above the allowed 80°C during such a fast filling.

An additional hurdle is the lack of rules and regulations for handling hydrogen in maritime applications, both on-board the ship as well as in the port.

This report considers the system for handling and storage of hydrogen in the port. The system is schematical described in Figure 1. This system includes all hydrogen related operations from the moment the hydrogen arrives at the port until it is filled to the ship.

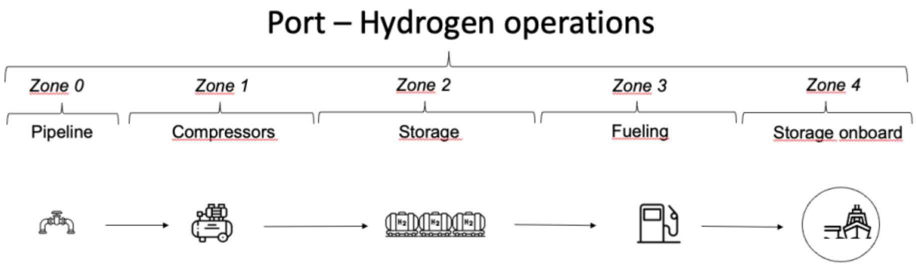

Figure 1: Schematic view of the system

The principal system is divided into five zones;

- in zone 0 hydrogen arrives in gaseous form at low pressure to the port via pipeline;
- using compressors in zone 1 the pressure is increased and
- further on stored at different pressure levels in zone 2;
- zone 3 handles the filling equipment and finally
- zone 4 relates to the hydrogen storage on-board the ship.

As a case-study we consider the handling and fuelling for the future hydrogen powered Gotland ferries. Two types of ferries are planned, a large-scale Ro-Pax (1900 passengers) and a large-scale catamaran (1600 passengers), where the Ro-Pax requires 16 ton of hydrogen per each round trip between Gotland and mainland Sweden and the catamaran correspondingly requires approximately 12 ton of hydrogen.

2 Case-study

The Swedish island Gotland is located in the Baltic Sea, the island is 52 kilometres wide and 176 kilometres long and has a surface area of 3,140 square kilometres. Slightly more than 60,000 people are permanently living on the island, and during summertime the population is approximately doubled. With no road connection to mainland Sweden, travelling by ferry or air are the only available options. The shortest distance to mainland Sweden from the main city Visby is 50 nautical miles (to Västervik). The ferries operate from two ports on mainland Sweden; Oskarshamn, 70 NM and Nynäshamn, 80 NM distance from Visby.

At peak-season a ferry can do up to three roundtrips per 24 hours, and with a cruising speed of 28 knots it requires that the ferry must leave port within one hour after arriving.

During year 2022, 1.8 million passengers, 575,000 cars and 843,000 lane meters of goods was transported in the ferry system, operated by Destination Gotland (Destination Gotland 2023).

RESEVOLYMER

Transporterade enheter

Utfall år	2020	2021	2022
Längdmeter gods	794 383	839 221	843 023
Fordon	437 564	594 705	574 204
Passagerare	1 235 481	1 723 082	1 799 168

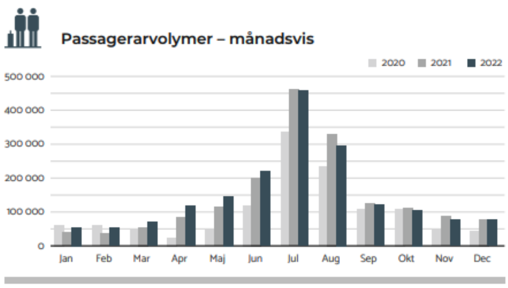

Figure 2: Travel volumes, 2020-2022

The ferry traffic between mainland Sweden and Gotland is a public procured operation, where the current contract period ends by the end of 2026. The new contract period starts by 2027 and is for 8 + 2 years. Current operations are run by Destination Gotland using three Ro-Pax ferries. Two of them have a capacity of 1,650 passengers and run on liquid natural gas (LNG), the third one has a capacity of 1,500 passenger and run on marine gas oil (MGO).

Rederi AB Gotland, the owner of Destination Gotland, are currently developing the next generation hydrogen powered Gotland ferries. Two different ferries are being developed, a traditional Ro-Pax (1,900 passenger) and a high-speed catamaran (1,600 passengers) (Gotlandsbolaget 2023). The ferries will be equipped with gas turbines in a combined cycle with steam turbines, which will give an efficiency above 50%. The hydrogen will be stored on-board in gaseous form at 200 bar pressure in composite cylinders of type IV.

It is assumed that so called cascade filling will be used, which means that hydrogen is stored on dockside at higher pressure compared with the on-board cylinders. This method eliminates the need for a compressor between dockside storage and the ferry. The dockside storage will roughly need to be twice as much as the hydrogen to be filled, i.e., 30-35 tonnes. This storage is divided in three pressure levels, low, medium and high.

2.1 Challenges

Hydrogen has a good potential to replace the fossil fuels, although it has its limitations and challenges. A first major challenge is the low volumetric density; 1 kg of hydrogen contains the same energy as 3.4 litres of diesel, but 1 m^3 at 200 bar pressure has the weight of only 17 kg. This gives that, compared with diesel, hydrogen needs about 15 times more volume on-board for the same amount of energy. Per necessity this will limit the use of hydrogen as a maritime fuel, the combination of distance and energy consumption will set the limit when and where hydrogen can be used.

A second challenge is that even though the weight of the hydrogen is quite low, the volumes to be bunkered will be quite high. The future Ro-Pax in the case-study will consume 16 tonnes of hydrogen for round-trip. Due to space limitations on the ship, the on-board storage will be maximised to approximately 25 tonnes, hence bunkering, or re-fuelling, must take place once every round-trip.

The 16 tonnes of hydrogen to be filled means that approximately 1,000 m^3 should be transferred from the dockside to the ferry. Further, as discussed above, the hydrogen needs to be filled in approximately 45 minutes to allow for three roundtrips per 24 hours during peak-season, which gives us the third challenge. Due to the thermodynamic properties of hydrogen (further explained in chapter 3), there will be a significant increase of the temperature inside the hydrogen storage cylinder, which will require some kind of temperature control system.

Finally, so far hydrogen has not yet been used in large scale for the maritime sector, hence there is a lack of experience as well as an adapted regulatory framework, which adds a fourth challenge.

This report focuses on the two latter challenges, including a thermodynamic simulation of the hydrogen filling and an overview of the existing regulatory framework with relevance to hydrogen operations in the port.

3 Thermodynamic modelling

Filling large volumes of hydrogen in short time has certain challenges. The following chapter describes the thermodynamic challenges that will be faced. Furthermore, a thermodynamic simulation model is presented and used to evaluate the filling process from a thermodynamic perspective.

3.1 Introduction

Hydrogen has a Joule-Thompson (JT) coefficient inversion temperature of 200 K, above which the gas heats up on expansion due to a negative JT coefficient, as opposed to some other gases, e.g., natural gas, which have positive JT coefficients under such conditions. This contributes to significant heating of the gas in a tank during its filling (Tietze & Stolten, 2016; Zhao et al., 2010). The other thermodynamic principle, that contributes to the heating, is the compression of the gas within the cylinder (Li et al., 2021). For fuel-cell electric vehicles (FCEV), especially those that require hydrogen storage at higher pressures of up to 700 bar, this necessitates a pre-cooling system for hydrogen at the refuelling station in order to ensure that the filling can be performed quickly, and with temperature evolution not breaching safety limits (US D.O.E, 2009). In comparison to a FCEV, the tank sizes in this case are significantly larger as each cylinder must be filled with approximately 150 kg hydrogen (kg_{H2}) within 45 minutes. Therefore, it becomes necessary to thermodynamically analyse the filling process to identify issues with heating of the gas and potential solutions to counter them.

Thermodynamic modelling of hydrogen filling and discharge cycles are extensively covered in the literature. While computational fluid dynamics analyses give a more accurate depiction of how the temperature varies spatially within the tank (de Miguel et al., 2015; Heitsch et al., 2011; Liu et al., 2020; Melideo et al., 2017), they significantly enhance the required computational effort and complexity of the model. These analyses have, however, exhibited temperature homogeneity to a certain extent, especially for Type III hydrogen vessels and therefore, zero-dimensional lumped parameter models for filling of hydrogen vessels have become a common practice in the literature (Bai et al., 2021; Caponi et al., 2021; Deng et al., 2023; Tietze & Stolten, 2016; J. Xiao et al., 2016; Zhou et al., 2019). A lumped parameter model assumes that the hydrogen in the vessel is well stirred and, thus, the thermodynamic properties are spatially uniform. Temperature uniformity has also been demonstrated experimentally by Monde et al. (2007). Caponi et al. (2021) have also found the Type III vessels to satisfy the conditions for using a lumped parameter model. The same modelling approach is considered in this study.

3.2 Method

A zero-dimensional lumped parameter thermodynamic model for the filling process has been developed based on a simplified bunkering system, as shown in Figure 3. Hydrogen is to be filled on-board into 120 type III cylindrical vessels and stored at a maximum pressure of 250 bar. Each cylinder is 12 meters long, has an outer diameter of 1.2 meters with a storage capacity of 150 kg_{H2}. As mentioned, it is assumed that the hydrogen is well-stirred and its' temperature, along with other thermodynamic properties, evolves in a spatially uniform manner during the transient filling process, a characteristic of 0-D lumped parameter models. The thermodynamic state properties for hydrogen are obtained from the CoolProp database (Bell et al., 2014).

3.2.1 Buffer refuelling

The bunkering takes place from a large hydrogen storage facility at the port. The dynamic modelling of the port storage is not considered in this study. It is assumed that the port storage is either significantly large or constantly filled through a compressor system and, therefore, the temperature and pressure of hydrogen delivered during filling remains constant.

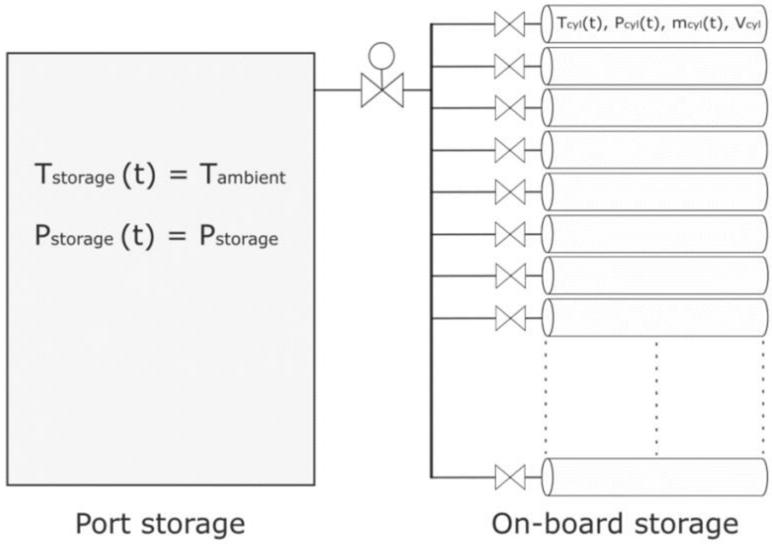

Figure 3: Simplified overview of the filling system. On the left is the storage of hydrogen at the port, while on-board storage is depicted on the right.

With constant temperature ($T_1 = T_{ambient}$) and pressure ($P_1 = P_{storage}$) considered for the port storage, the model is fundamentally based on the mass and energy balance over two components, as shown in Figure 4: (i) pressure reducing valve and (ii) storage vessels on-board. The pressure reducing valve, also known as the JT expansion valve, allows for an adiabatic and isenthalpic throttling of the incoming hydrogen (Yang & Huber, 2008). This will cause the temperature of gas to rise, proportional to the pressure difference ΔP_{1-2}. The pressure at 2 ($P_2(t)$) depends on gas pressure in the on-board hydrogen vessel, which rises during the filling process and, consequently, ΔP_{1-2} becomes smaller with time. The specific enthalpy, however, remains the same ($h_1 = h_2$) before and after the expansion.

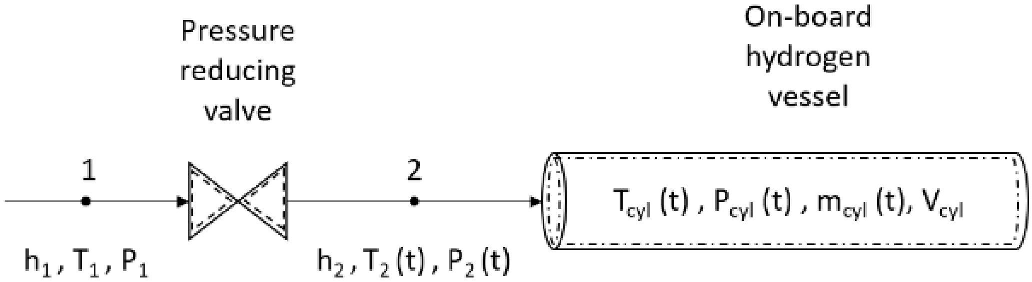

Figure 4: The components considered for the thermodynamic modelling. Point 1 represents the state of hydrogen as obtained from the port storage, while point 2 is the state of hydrogen after isenthalpic pressure reducing valve.

As the ship will be powered by a gas turbine, it is assumed that an empty on-board hydrogen vessel has a minimum storage pressure of 25 bar ($P_{cyl}(t) = 25\ bar\ @\ t = 0$), a typical fuel pressure required for gas turbine engines (Magnusson & Andersson, 2020). The temperature of the remaining gas in the cylinder is also assumed to be equal to the ambient temperature ($T_{cyl}(t) = T_{ambient} \quad @\, t = 0$). The density and consequently the mass ($m_{cyl}(t) = m_{cyl,0} \quad @\, t = 0$), of the gas before refuelling, may then be obtained from the CoolProp database at these conditions. The mass balance over the vessel can be written as equation (i) below:

$$m_{cyl}(t) = m_{cyl,0} + \dot{m}_{in} * t \tag{i}$$

where $m_{cyl}(t)$ is the mass of gas in the vessel at time t and $\dot{m}_{in}$ is the constant mass flow rate entering the vessel. In some other works, e.g., Caponi et al. (2021), a constant pressure ramp rate has been considered to govern the refuelling process instead of a constant mass flow rate, as an optimization strategy; however, only a constant mass flow rate has been considered here. The energy balance over the vessel can be written as equation (ii) below:

$$u_{cyl}(t) = \frac{m_{cyl,0} * u_{cyl,0} + \ h_2 * \ \dot{m}_{in} * t - Q(t)}{m_{cyl}\ (t)} \tag{ii}$$

where $u_{cyl}(t)$ is the specific internal energy of the gas in the vessel at time t, $u_{cyl,0}$ is the specific internal energy at time $t = 0$ and $Q(t)$ is heat transferred from the vessel to the surroundings at time t. As an adiabatic thermodynamic refuelling model has been considered in this study, the heat transfer term may be ignored. This will yield results for an extreme case. While in reality, where some heat will be transferred to the surroundings, the vessel will heat up slower than as predicted by the model and the cooling needs may be reduced.

3.2.2 Cascade refuelling

As an energy efficiency measure, the hydrogen storage at the port may also be divided into different storage reservoirs at different low-to-high pressure levels. This technique, known as cascade refuelling, is practiced at hydrogen refuelling stations (Sadi & Deymi-Dashtebayaz, 2019), where the tank is first filled with the low-pressure reservoir (LP), followed by the medium (MP) and then the high-pressure (HP) reservoir. In this way, all hydrogen stored in the port would not have to be compressed to the highest pressure, thereby minimizing both operational energy and costs. The Joule-Thompson effect will also be reduced in a cascade filling system, as the ΔP_{1-2} over the expansion valve will be reduced while the vessel is being filled with the low and the medium-pressure reservoirs.

The storage system with three pressure levels has been found to be the most energy efficient cascade filling configuration (Rothuizen & Rokni, 2014); however, two-level cascade has also been investigated in the literature, e.g., Caponi et al. (2022). When considered for FCEV, where storage pressures of 880 – 950 bar is needed at the refuelling stations, cascade refuelling has also exhibited reduction in capital costs, as cheaper vessels may be employed for lower pressure storages (Heere, 2019). The pressure levels considered in this study are significantly lower; therefore, an economic assessment would be needed to ascertain the economic benefit of a cascade system, as only simple vessel may be needed for our case if cascade filling is not used. It also requires some optimization to identify the ideal pressure levels (Rothuizen & Rokni, 2014; L. Xiao et al., 2021).

In this study, we have considered storage pressures of 67 bar, 200 bar and 350 bar for the LP, MP and HP respectively, based on the equivalent pressure levels considered by the US Department of

Energy for a 700-bar vehicle tank refuelling (Parks et al., 2014). The only change in the thermodynamic model would be the varying pressure P_1 , temperature T_1 and enthalpy h_1 delivered to the on-board storage. The schematic of the filling system is shown in 5.

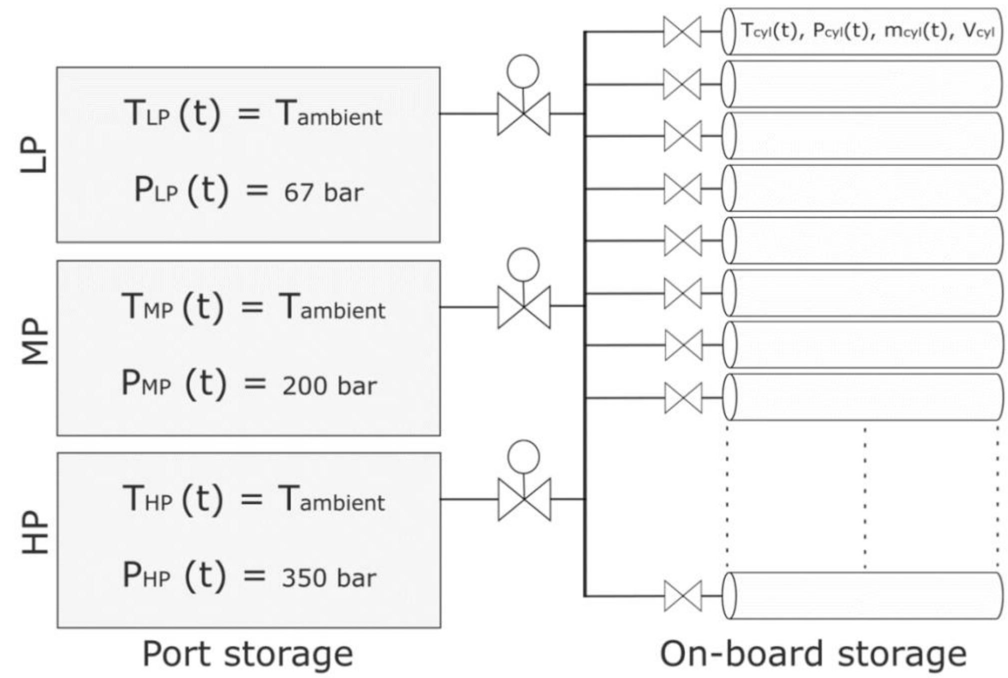

Figure 5: Simplified overview of a cascade filling system with three storage levels. On the left is the storage of hydrogen at the port, while on-board storage is depicted on the right.

3.2.3 Cooling system

In cases where the thermodynamic models of the filling process yield temperature evolutions in breach of the safety limits, a cooling system would be necessary. At a hydrogen refuelling station, this is typically done by pre-cooling hydrogen down to -40°C with a refrigeration unit to cater for the high storage pressures and fast refuelling times. The electricity demand for the refrigeration unit is reported in the range of 0.3 - 50 kWh_{el}/kg_{H2} depending on the station utilization factor and the ambient temperature, as a significant amount of electricity is also be consumed to keep the heat exchanger at -40°C, even when no filling is being carried out (Elgowainy et al., 2017). For bunkering of several tonnes of hydrogen, such a cooling system would require a significant amount of electricity.

Due to a significantly larger size of the on-board vessel in comparison to typical FCEV tanks, higher refuelling times and availability of cold seawater at the point of bunkering, an alternative cooling solution is considered in this study. According to the Swedish Meteorological and Hydrological Institute (SMHI), the sea surface water temperature around Visby is around 11°C in summer, while even colder water can be obtained at a depth of 50 – 60 meters below sea level (SMHI, 2014). Therefore, it is assumed that cooling water will be available at 10°C, on a hot summer day, while the ambient temperature ($T_{ambient}$) is 15°C . The vessels are proposed to have active cooling during the filling process with internal cooling tubes, instead of pre-cooling to significantly low temperatures. The schematic of the filling process with active cooling is shown in 6 below.

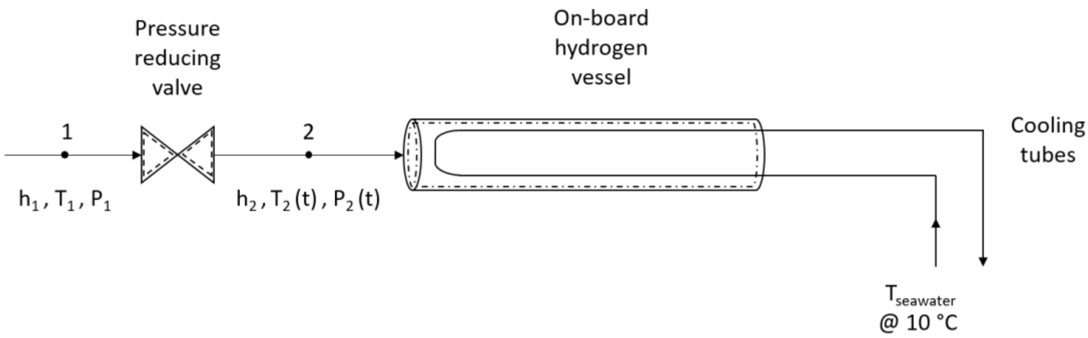

Figure 6: Schematic of components included in thermodynamic modelling of the filling process with active cooling.

The vessel with internal cooling tubes can be modelled and designed as a shell and tube heat exchanger. The two most commonly practiced methodologies for heat exchanger design are (i) the logarithmic mean temperature difference (LMTD) method and (ii) the effectiveness-number of transfer units (ε-NTU) method. Both these methodologies are adopted in this study, to ensure that the temperature evolution remains under control, regardless of the designing approach considered. A detailed description of the methods can be found in Coulson & Richardson (2005) and Incropera et al. (2007).

The design of the tubes is done according to British standard BS 3606 for steel tubes, as discussed by Coulson & Richardson (2005). In order to counter the impact of hydrogen embrittlement, austenitic stainless tubes should be preferred as tube material (Marchi & Somerday, 2014). Each tube is a two-pass U-tube (as shown in **Error! Reference source not found.**), with an outer diameter and thickness of 38 mm and 2.6 mm, respectively. The total considered length of each tube is 22 meters. The recommended range of cooling water velocity is 1.5 – 2.5 m/s, which must be high enough to avoid settling of any solid particles within the tubes but still limited to avoid erosion (Coulson & Richardson, 2005). The higher end of the range is considered for the model, while the design cooling water exit temperature is considered to be 20°C ($T_{seawater,out}$).

A minimum heat exchanger temperature difference (ΔT_{min}) of 20°C is considered. This implies that the cooling system starts operating when the temperature of the gas in the vessel exceeds 40°C ($T_{H2,target}$) and can only cool it down to 40°C (if possible). This is slightly simplified, as in reality the cooling system can start as soon as the filling process commences. The overall heat transfer coefficient (U) between high pressure gases and seawater is typically in the range of 30 – 300 W/m^{2}K (Coulson & Richardson, 2005). An average value of 160 W/m^{2}K is considered as a starting point for the model. This is already conservative, as according to Saari (2022), the overall heat transfer coefficient between high pressure gases at 25 bar or more and low viscosity liquid (e.g. water) can be as low as 150 W/m^{2}K. However, a worst-case scenario with 30 W/m^{2}K is also considered in this study, to test the robustness of the results. The energy balance over the vessel with active cooling can then be written as equation (iii) below:

$$u_{cyl}(t) = \frac{m_{cyl,0} * u_{cyl,0} + h_2 * \dot{m}_{in} * t - Q_{cooling}(t)}{m_{cyl}(t)} \qquad (iii)$$

where $Q_{cooling}(t)$ is the cooling power provided by the seawater at time t, which can be calculated using the following sets of equations based on the design method adopted. The methods are also briefly discussed below.

3.2.4 LMTD method

Due to the non-linearity of temperature change across a heat exchanger, the LMTD method utilizes a logarithmic temperature difference (ΔT_{lm}) between the hot and the cold fluid, which in our case are hydrogen and seawater, respectively. A correction factor (F_t) is applied to calculate the "true" mean temperature difference (ΔT_{mean}), in order to account for the mixture of different flows (co-current, counter-current and cross flow) in shell and tube heat exchangers. For a single-shell and two-pass U-tube configuration, as the one we have considered, the correction factor and the cooling power $Q_{cooling}(t)$ can be calculated using the following expressions.

$$Q_{cooling}(t) = U * n_{tubes} * A_{tube} * \Delta T_{mean}(t) \tag{iv}$$

$$\Delta T_{mean}(t) = F_t(t) * \Delta T_{lm}(t) \tag{v}$$

$$\Delta T_{lm}(t) = \frac{(T_{cyl}(t) - T_{seawater,out}) - (T_{H2,target} - T_{seawater,in})}{ln\frac{(T_{cyl}(t) - T_{seawater,out})}{(T_{H2,target} - T_{seawater,in})}} \tag{vi}$$

$$F_t(t) = \frac{\sqrt{(R(t)^2 + 1)}\ \ln\left[\frac{1 - S(t)}{1 - R(t)S(t)}\right]}{(R(t) - 1)\ \ln\left[\frac{2 - S(t)[R(t) + 1 - \sqrt{R(t)^2 + 1}]}{2 - S(t)[R(t) + 1 + \sqrt{R(t)^2 + 1}]}\right]} \tag{vii}$$

$$R(t) = \frac{T_{cyl}(t) - T_{H2,target}}{T_{seawater,out} - T_{seawater,in}} \tag{viii}$$

$$S(t) = \frac{T_{seawater,out} - T_{seawater,in}}{T_{cyl}(t) - T_{seawater,in}} \tag{ix}$$

$Q_{cooling}(t)$	is the cooling power provided by the tubes in kJ at time t

U	is the overall heat transfer coefficient in W/m² K
n_{tubes}	is the number of tubes considered
A_{tube}	is the heat transfer area of one tube in m²
$\Delta T_{mean}(t)$	Is the true mean temperature difference between the fluids in K at time t
$F_t(t)$	Is the correction factor for the logarithmic mean temperature difference at time t
$\Delta T_{lm}(t)$	Is the logarithmic mean temperature difference between the fluids in K at time t
$T_{seawater,out}$	Is the exit temperature of seawater in K
$T_{seawater,in}$	Is the inlet temperature of seawater in K
$T_{H2,target}$	Is the target temperature of hydrogen in the vessel after cooling in K
$R(t)$	Is the dimensionless temperature ratio between the shell-side and tube-side at time t
$S(t)$	Is the dimensionless temperature ratio and a measure of temperature efficiency of the exchanger at time t

3.2.5 ε-NTU method

The LMTD method requires complete specification of the heat exchanger system and, therefore, necessitates the assumption of seawater exit temperature and hydrogen target temperature in our case, followed by an iterative solution to identify the required heat transfer area based on the design temperatures. The ε-NTU method, on the other hand, does not require these temperature assumptions. It requires the individual fluid heat capacity flows $(\dot{m}\, C_p)$ to be specified, instead. These are easily obtained from the CoolProp database, for every timestep t during the filling process. The fluid with the larger heat capacity flow is denoted as $(\dot{m}\, C_p)_{max}$, while the smaller one is denoted as $(\dot{m}\, C_p)_{min}$. The heat transfer across the heat exchanger is limited by the latter. The ε-NTU method proceeds with determining the effectiveness (ε) of the heat exchanger, which can be calculated for a heat exchanger with one shell and even tube passes (2,4,6 etc.) as follows.

$$Q_{cooling}(t) = \varepsilon * (\dot{m}\, C_p)_{min} * (T_{cyl}(t) - T_{seawater,in}) \quad \text{(x)}$$

$$NTU = \frac{U\, A_{tube}\, n_{tubes}}{(\dot{m}\, C_p)_{min}} \quad \text{(xi)}$$

$$C_r = \frac{(\dot{m}\, C_p)_{min}}{(\dot{m}\, C_p)_{max}} \quad \text{(xii)}$$

$$\varepsilon = 2\left\{1 + C_r + \sqrt{1 + C_r^2}\, \frac{1 + e^{-\frac{NTU}{Np}\sqrt{(1+C_r^2)}}}{1 - e^{-\frac{NTU}{Np}\sqrt{(1+C_r^2)}}}\right\}^{-1} \quad \text{(xiii)}$$

$Q_{cooling}(t)$	is the cooling power provided by the tubes in kJ at time t
U	is the overall heat transfer coefficient in $W/m^2 K$
n_{tubes}	is the number of tubes considered
A_{tube}	is the heat transfer area of one tube in m^2
ε	Is the effectiveness of the heat exchanger
$(\dot{m}\, C_p)_{min}$	Is the smaller heat capacity rates of the two fluids in J/K.s
NTU	Is the dimensionless parameter exhibiting the number of transfer units across the exchanger
$(\dot{m}\, C_p)_{max}$	Is the larger heat capacity rates of the two fluid in J/K.s
$T_{seawater,in}$	Is the inlet temperature of seawater in K
C_r	Is the ratio of the heat capacities of the two fluids
N_p	Is the number of tube passes

3.3 Results

Based on the system in Figure 3 (buffer filling without cooling) and different storage pressures at the port, the temperature of the gas in the on-board storage vessels evolves as shown in Figure 7, during the refuelling process. The impact of port storage pressure is almost negligible on the temperature evolution, as the post-refuelling temperatures of 128.3°C and 130.9°C are obtained from port storages at 300 bar and 350 bar, respectively. The slightly lower temperature from the former can be attributed to the reduced impact of the JT coefficient, due to a lower pressure difference. Regardless of the storage pressure, the temperature is found to be significantly above safety limits, which is breached even before 10% of the filling process is completed. As predicted earlier, the temperature rise is much faster during the initial stage of the process due to the JT effect, when the pressure in the on-board vessel is low. Its impact diminishes as the pressure in the vessel increases, but the heat of compression, albeit slower, continues to cause a rise in temperature.

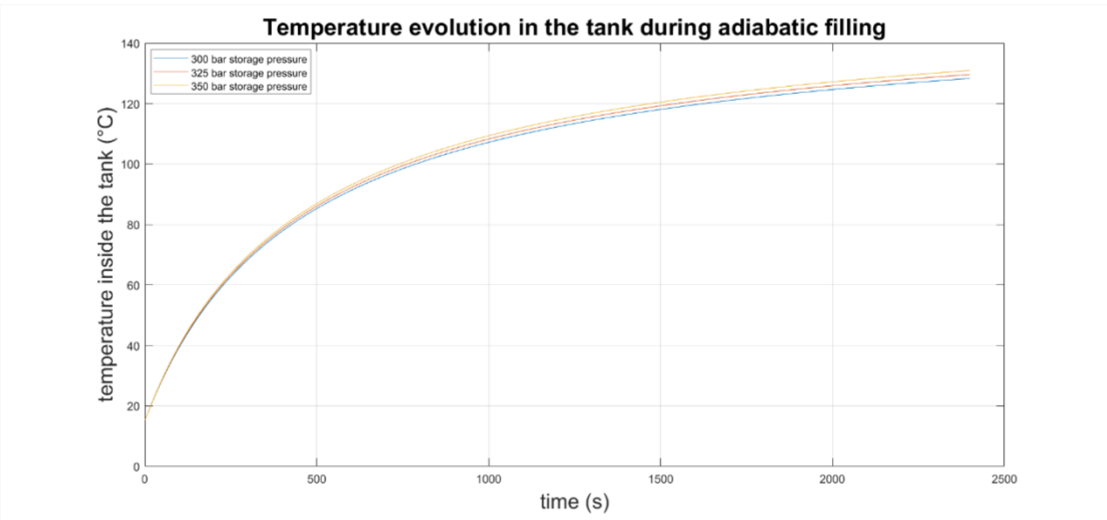

Figure 7: The temperature evolution in the on-board hydrogen storage tank, with respect to different port storage pressures.

If cascade filling is adopted instead, the impact of JT effect is somewhat reduced and, consequently, the temperature rise in the on-board storage vessel is lower than what is obtained from buffer filling. However, the issue of overheating of the gas cannot solely be solved by switching to cascade filling, as only about 7.5°C of temperature reduction is achieved through it (see Figure 8 below). Based on the assumed pressure levels for the cascade filling, it was also seen that about 21.6% of filling takes place from the low-pressure storage, followed by 61.6% from the medium pressure and only 16.6% from high pressure storage. As majority of the filling takes place from low or medium pressure, the cascade filling can allow for energy savings in the form of reduced electricity for compression. This has to be investigated further, while also taking into account other aspects, e.g. utilization factor of the refuelling system and additional costs due to increased system complexity. Nevertheless, for our case, implementation of a cooling system remains necessary, regardless of the refuelling strategy adopted.

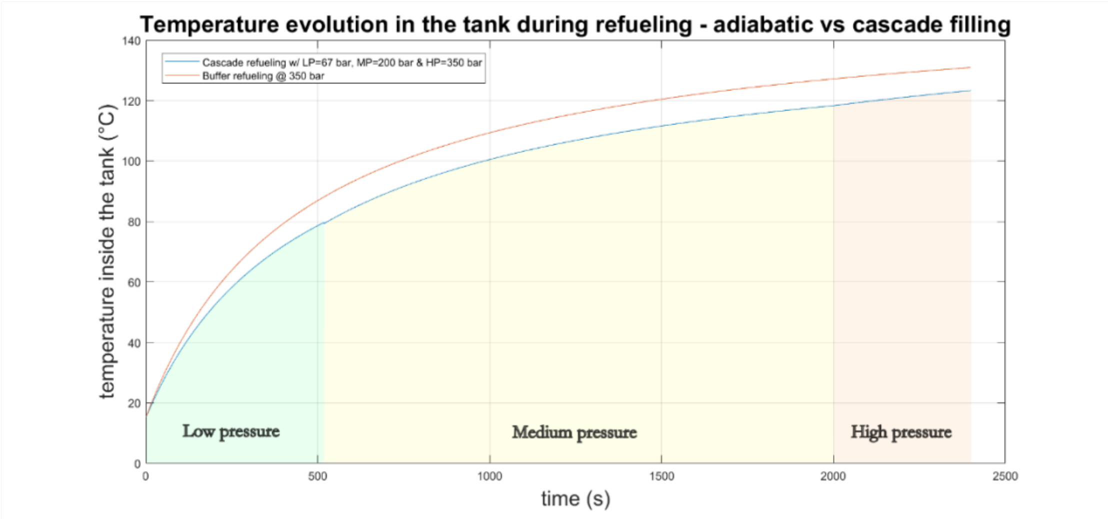

Figure 8: The impact of buffer filling vs cascade filling on the temperature evolution in on-board hydrogen storage tank. The buffer filling takes place from port storage @ 350 bar and the cascade filling takes place from low pressure, medium pressure and high-pressure port storages @ 67 bar, 200 bar and 350 bar, respectively.

When active cooling via tubes is implemented, it is found that the temperature conditions could be met without having to significantly modify the on-board vessels. For an average overall heat transfer coefficient of 160 W/m^{2}K, the cooling is possible with only six such u-tubes, regardless of the design method adopted. According to the ε-NTU design method, the final temperature after refuelling is found to be 59.3°C, as shown in Figure 9. The LMTD method yields even better results, as temperature is restricted to 46.4°C; however, for such a model, where final temperature has to be determined, the ε-NTU method may be considered more suitable.

Nevertheless, employing six cooling tubes will account for only 1.1% of the total vessel volume, slightly reducing the volume which hydrogen can occupy; however, its impact on the pressure and the temperature of the gas was found to be negligible. When reduced volume was taken into account, the final gas pressure increased by only about 1.2% (or 2 bar) for both the methods but remained below the 250 bar target pressure. Also, it should be noted that around 1.5 cubic meter per second of seawater will be required to enable such a cooling system for the complete on-board storage.

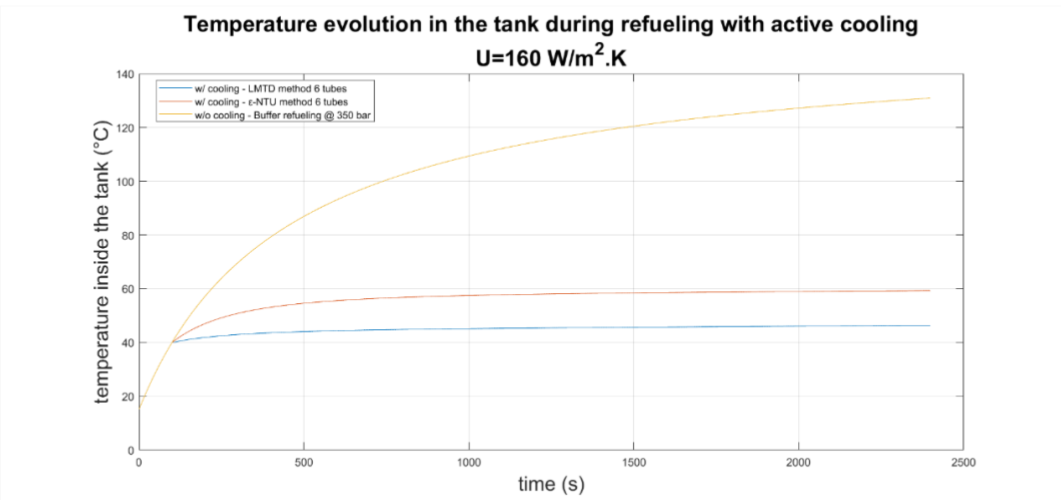

Figure 9: The temperature evolution in on-board storage vessels during the refuelling process, with 6-tube active cooling and an overall heat transfer coefficient of 160 W/m².K.

When a worst-case scenario, with an overall heat transfer coefficient of 30 W/m^2K, is considered instead, it is still possible to satisfy temperature restrictions, although with more cooling tubes. In such an extreme case, it will require 31 cooling tubes that occupy 5.7% of the total vessel volume. Post-filling temperatures of 60°C and 47.6°C are achieved, as shown in Figure 10, from the ε-NTU and LMTD methods, respectively. The rise in pressure, due to reduced volume, is slightly higher (12 bar) in this case; however, post filling pressures of 212 bar and 204 bar, are still under the target pressure limit, for the ε-NTU and LMTD methods, respectively. One drawback for such a system could a significantly higher requirement for cooling water flow, as 7.8 cubic meter per second would be needed for the whole on-board storage.

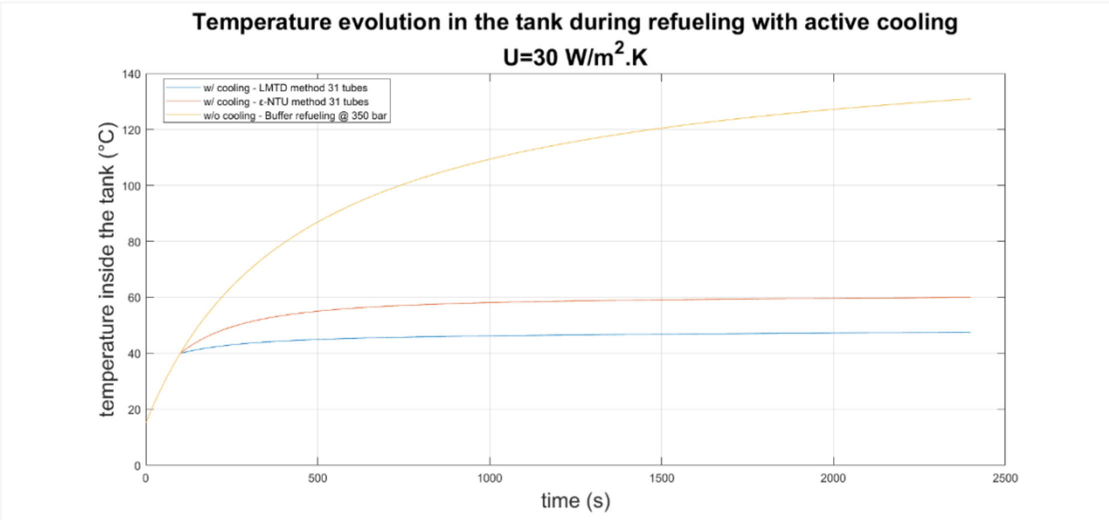

Figure 10: The temperature evolution in on-board storage vessels during the refuelling process, with 6-tube active cooling and an overall heat transfer coefficient of 30 W/m2.K.

4 Safety and regulations

The objective from a safety and regulation perspective is delimited to the port and covers the storage of up to 50 tons of hydrogen and the three 16 tonnes bunkering sessions of the ferry per day.

The following chapter presents a summary of regulations and guidelines relevant to maritime hydrogen filling stations – presented in Table 1. The regulations contains both absolute requirements and recommendations, they stem from the Swedish government agency, the Swedish Civil Contingencies Agency (MSB), and European Council. These regulations demand certain levels of safety, hence there exist guidelines on how to construct systems fulfilling such requirements. The International Organization for Standardization (ISO) has published several standards on safe handling of hydrogen, which can be used as guidelines to meet part of the requirements in the regulations. MSB has also published guidelines on safety expectations on operations utilizing flammable gases.

4.1 The National hydrogen strategy

A Swedish national hydrogen strategy was presented in November 2021 but is still to be approved (Energimyndigheten, 2021). The proposition includes standards, regulations and permit processes which must be updated in line with the upcoming hydrogen infrastructure. With the launch of the EU's Fit for 55 legislative package, several regulations and directives are being revised to accelerate the implementation of a hydrogen infrastructure. The regulation FuelEU maritime, stating that vessels larger than 5000 gross tonnes arriving at EU ports must lower the greenhouse emission intensity by 6% in 2030 and 75% in 2050 compared to the levels in 2020 (European Council, 2022a). The alternative fuels infrastructure regulation is another beneficial regulation in the Fit for 55 package, which strives to implement an infrastructure for fuelling ships with alternative fuels, such as hydrogen (European Council, 2022b). Both these regulations, among several other, works in favor of the implementation of a hydrogen network. Below in this this chapter, acts and regulations relevant when developing a hydrogen bunkering station will be presented.

4.2 Hydrogen operations - Acts, Regulations and Codes – table summary

Below in Table 1 a summary of regulations and guidelines relevant to hydrogen filling stations for maritime use is presented. For each of them the relevance to maritime hydrogen filling is briefly described. Further below in Table 2, the impact of those regulations and guidelines i different areas and functions related to the handling of hydrogen in the port is presented.

Definitions:

- **Acts** are laws that are passed by the legislative assembly.
- A **directive** is a broader term that includes acts and other types of legal rules and regulations. For example, 2 says that legislation can be divided into regulations, which are binding legislative acts, and directives, which set out goals that EU countries must achieve.
- A **standard** is a set of technical definitions, specifications and guidelines whereas a **code** is a model that is established after years of use and can be adopted into law.

- An **ordinance** is a specific rule or regulation enacted by a local governing body, such as a city council or county board. It is designed to address local concerns, like zoning or noise control, reflecting the immediate needs of a community.

Table 1: Relevant regulations

	Acts	Directive/Regulations	Codes/standards	Comments/ relevance
1	The Act on natural gas			No – It is probably not the intent of the act, since hydrogen proposes some additional challenges compared to natural gas.
2			The environmental code (1998:808)	Yes - Environmental impact assessment mentioned in the environmental code Ch. 6. 11§.
3	The planning & building Act (2010:900)			Yes - For Gotland in particular, permission according to the environmental code Ch. 4. 2§ will be needed since Gotland is classified as an area of special consideration.
4	Act of certain pipelines (1978:160)			No - There is an exception regarding pipelines solely dedicated for use within a port or industrial area, hence no concession is needed.
5	The environmental review ordinance (2013:251) Ch. 20.			If hydrogen would be classified as a natural gas and if the storage contains more than 50 million normal cubic meters of gas per calender year, it would be necessary to apply for permit obligation B and the facility must be examined by the county administrative board.
6	The act of flammable and explosive goods (2010:1011)	Regulation on flammable and explosive goods (2010:1075)		Yes - To get a permit for the handling of explosive goods, the operations need approval from both the police authority, municipal or governmental authorities, and the authority for social protection and preparedness or local municipality.
7		The regulation on explosive environments when handling flammable gases and liquids (SRVFS 2004:7)		Yes - This regulation states what preventive measures should be taken and which investigations and assessments to consider when dealing with explosive atmospheres.
8		MSBFS 2013:3 the regulation on permission for dealing with flammable gases and fluids		Yes - This regulation states that if the volume of gas managed exceeds certain predetermined limits, the operations need permission from the local municipality to start

9	1999:381, Measures to prevent and limit consequences of serious chemical accidents	(MSBFS 2015:8). a regulation from MSB on measures to prevent and limit consequences of serious chemical accidents		Yes - It includes guidelines on internal and municipal emergency plans in case of an accident. Included is also requirements on the supervision of the technical, organizational, and operating systems.
10		The handling of flammable gases and aerosols regulation (MSBFS 2020:1)		Yes - This includes general requirements for the handling of flammable gases and specific requirements for gas tanks and hose lines. Due the scale of operations the Gotland fuelling station will most likely need to consider MSBFS 2013:3 and 2020:1.
11	Measures to prevent and limit consequences of serious chemical accidents - act 1999:381	To prevent and limit consequences of serious chemical accidents (MSBFS 2015:8)		Until now MSB has not issued any regulations specific for hydrogen. There is however work being done towards creating a coherent methodology for risk analysis and risk reduction for hydrogen facilities (MSB, 2021). – Status?
12		2014/68/EU on the market of pressure equipment	In ISO 15916:2022 basic considerations for the safety of hydrogen systems is presented to give an understanding of the safety issues connected to the upcoming hydrogen applications	Yes - There must be certain distance between the hydrogen storage and populated areas or potential hazardous industrial areas. The standard gives directions on where electrical components should be placed and how they should be treated in relation to hydrogen safety.
13		Arbetsmiljöverkets regulation regarding tests with over- and underpressure(AFS 2006:8) and AFS 2017:3 on guidelines when working with pressurized devices		Yes - These regulation gives guidelines on how tests should be managed when looking for leakage or testing the strength of pipelines and vessels.
14			ISO 19880-1:2020 Hydrogen	Yes - This ISO standard covers the minimum safety and appropriateness for design,

			refuelling stations	installation, commissioning, operation, inspection, and maintenance requirements for hydrogen refuelling stations.
15			EIGA Doc 15/21 (Gaseous Hydrogen Installations)	Guideline recommendations only
16			DNV Hand book for hydrogen-fuelled vessels	Mostly focused on road vehicles, but there is work being done and ISO 19885-5 concerning the standardization of activities to develop a fuelling protocol for maritime hydrogen, is on its way.
17			ISO/TS 18683:2015 Bureau Veritas Guidance Note NI 618 DT R00 E	Yes – as a reference. The safety manual on LNG bunkering procedures for the Port of Helsinki. Should be used for SIMOPS (simultaneous operations) risk assessment
18			DNVGL-RP-G 105	Yes . Includes ISO/TS 16901 for the risk assessment of ship-to-shore interface scenarios. The appendix of DNVGL-RP-G105 includes how to address SIMOPS in a risk assessment
19			The ISO 26142:2022 standard on hydrogen detection	Yes. sets out the performance requirement s and test methods for hydrogen detection in stationary applications.

There are in principle four hydrogen installations in the port;

- (zone 0) a pipeline to get the hydrogen in to the port,
- (zone 1) a compressor will increase the pressure and pump the hydrogen into
- (zone 2) a buffer storage in the port.
- Finally, (zone 3) the filling will move the hydrogen from the port to the ferry. This report considers only regulations for Zone 1-3, hence, regulations on-board the ship is not considered in this work.

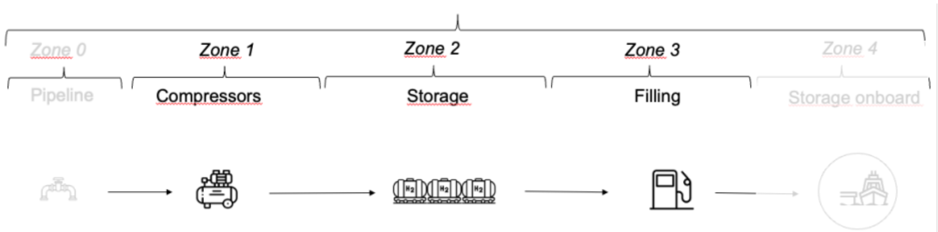

Figure 11: Zones considered from a regulatory perspective

Below Table 2 shows whether the regulations and guidelines presented in Table 1 will impact the different zones described above or not.

Table 2

Act, directive, code/standard – reference number	Zone 1 compressors	Zone 2 storage	Zone 3 fuelling
1			
2		POTENTIALLY	
3		YES	
4			
5		POTENTIALLY	
6		YES	YES
7	YES	YES	YES
8	YES	YES	YES
9	YES	YES	YES
10	YES	YES	YES
11	YES	YES	YES
12		YES	
13	YES	YES	YES
14			YES
15	YES	POTENTIALLY	POTENTIALLY
16			POTENTIALLY
17			POTENTIALLY
18			POTENTIALLY
19	YES	POTENTIALLY	YES

4.3 Regulations regarding hydrogen operations, in more detail

Below, relevant regulations and their impact on the hydrogen operations are briefly described.

4.3.1 Bunkering station regulation

Since there are as of now, only a few acts specifically describing larger hydrogen systems, *The Act on Natural Gases* (2005:403) can be examined to give some indicators of future hydrogen regulation. The natural gas act states that gases that can be used in natural gas systems are included in the act. Since hydrogen can be used in natural gas systems if mixed with natural gas (up to 30% hydrogen (U.S. Department Of Energy, 2021)), it might already be covered by the natural gas act. This is probably not the intent of the act, since hydrogen proposes some additional challenges than natural gas. According to the natural gas act, a storage facility for natural gas is not allowed to be built without a permission from authorities. The requirements for a permission range from suitability from a general point of view to meet requirements in the environmental code. In addition to the requirements stated in the Natural gas act, several other aspects of *The environmental code* (1998:808) must be considered before building hydrogen storage. Among these is the environmental impact assessment mentioned in the environmental code Ch. 6. 11§. The facilities themselves must also have a permission according to *The planning and building act* (2010:900). For Gotland in particular, permission according to the environmental code Ch. 4. 2§ will be needed since Gotland is classified as an area of special consideration.

Depending on the layout of the port, there might be a need for pipeline systems in the port, e.g., between the storage and refuelling dock. The natural gas act mentions requirements on transmission pipelines, but since the pipelines are dedicated to internal use this part of the natural gas act is not valid. In the Act on certain pipelines (1978:160) it is stated that a concession might be needed for pipelines transporting gases used as fuel. However, there is an exception regarding pipelines solely dedicated for use within a port or industrial area, hence no concession is needed.

The organization MultHyFuels aim is to develop a common strategy for the implementation of hydrogen refuelling stations (HRS) in a multi-fuel context (MultHyFuel, 2021). The report Deliverable 1.2 (D1.2), about permitting requirements and risk assessment methodologies for HRS in the EU, presents several relevant European legislations for HRS such as 2014/94/EU on the deployment of alternative fuel infrastructure, and 2014/68/EU on the harmonization of laws of the member states relating to pressure equipment. It also includes how quantitative risk assessments are performed and risk assessment regulations/methodologies for HRS. The regulations/methodologies are primarily derived from ISO 19880:2020 and how different countries apply this standard. Furthermore, D1.2 also includes guidelines for safety distances, maintenance, and mitigation measures (Fonseca, 2021).

MultHyFuels Deliverable 3.1 (D3.1) on state of the art technology for HRS presents safety features usually included in a HRS. It also includes how they should be placed and the purpose they fulfill (Houssin, et al., 2021). The report D3.2 included a statistical analysis of HRS which highlighted gas and fire detectors, shut-off valves, emergency shutdown devices, and firewalls as safety barriers (Quesnel, Nouvelot, & Ouadghir, 2021).

Since the hydrogen facilities do not release any toxic waste or emissions, they might not need a permit for environmentally hazardous activities according to the Swedish environmental code. The reason for a permit could be the risk of explosion which could be classified as a detriment to human health and in such case the facility would need a permission according to the environmental code. If the facility at some point would contain more than 5 000 tonnes of hydrogen, it is required to notify the supervisory authority according to *The environmental review ordinance* (2013:251) Ch. 20. If hydrogen were to be classified as a natural gas then if the storage contains more than 50 million normal cubic meters of gas per calender year, it would need to apply for permit obligation B and the facility must be examined by the county administrative board.

Since hydrogen is a flammable gas, operations must meet the requirements in *The act of flammable and explosive goods* (2010:1011). The act sets requirements on attentiveness, investigations on safety in case of an accident, competence, facilities, storage and more. The regulation on flammable and explosive goods (2010:1075) sets additional requirements for the management of flammable and explosive goods. These include the prohibition of fire and other ignition sources in areas with flammable and explosive goods. The person handling the goods needs to be at least 18 years old, and those who conduct activities subject to a permit need to collaborate with the supervisory authority regarding the minimization of risks. To get a permit for the handling of explosive goods the operations need approval from both the police authority, municipal or governmental authorities, and the authority for social protection and preparedness or local municipality.

4.3.2 MSB regulations

MSB (the Swedish Civil Contingencies Agency) is responsible for preparing the society for major accidents, crises, and consequences of war. MSB has written several guidelines and regulations to protect people's health and safety, the society's functionality and core values such as democracy, legal certainty, and human rights (MSB, n.d.). Some of these guidelines and regulations concerning the safe management of gases can be applied on hydrogen. Since hydrogen is classified as a flammable gas, MSBFS 2010:4, it needs to follow certain regulations. Among these is the regulation on explosive environments when handling flammable gases and liquids (SRVFS 2004:7). This regulation states what preventive measures should be taken and which investigations and assessments to consider when dealing with explosive atmospheres.

Another regulation connected to hydrogen being a flammable gas is MSBFS 2013:3 the regulation on permission for dealing with flammable gases and fluids. This regulation states that if the volume of gas managed exceeds certain predetermined limits, the operations need permission from the local municipality to start. However, an exception is if the fuel is being used in a vehicle's fuel system. This is also true for the handling of flammable gases and aerosols regulation (MSBFS 2020:1) which includes general requirements for the handling of flammable gases and specific requirements for gas tanks and hose lines. Due the scale of operations the Gotland fuelling station will most likely need to consider MSBFS 2013:3 and 2020:1.

In connection with act 1999:381, *Measures to prevent and limit consequences of serious chemical accidents*, there is a regulation from MSB on measures to prevent and limit consequences of serious chemical accidents (MSBFS 2015:8). It includes guidelines on internal and municipal emergency plans in case of an accident. Included are also requirements on the supervision of the technical, organizational, and operating systems.

Until now MSB has not issued any regulations specific for hydrogen. There is however work being done towards creating a coherent methodology for risk analysis and risk reduction for hydrogen facilities (MSB, 2021).

4.3.3 Safe handling of hydrogen systems ISO/TR 15916:2022

In ISO 15916:2022 basic considerations for the safety of hydrogen systems are presented to give an understanding of the safety issues connected to the upcoming hydrogen applications. The standard includes a risk analysis of factors that could go wrong based on previous accidents. This risk analysis is based on Ordin (1974), although a lot has changed since the publishing of the book some information may still be useful. Results from the risk analysis showed that 51% of hydrogen related accidents were due to mishaps in operational procedures and 36% due to design and planning. Both of these errors are in part due to human error; hence the goal should be to minimize the possibility of human errors and have a system that can remain safe in the event of human error.

Gaseous hydrogen storage with high pressure can lead to severe hazards even without ignition. Hence the flow rate, both intentional and unintentional, needs to be monitored and any area or container containing hydrogen should be equipped with a pressure-relief device in case of overpressure. Safety standards and directives for pressurized vessels can be found, such as directive 2014/68/EU on the market of pressure equipment, AFS 2017:3 on guidelines for how to work with pressurized devices, and AFS 2016:1 on regulations for pressurized devices.

In ISO 15916:2022 precautions concerning localization of a hydrogen facility are described. There must be a certain distance between the hydrogen storage and populated areas or potentially hazardous industrial areas. It is recommended to keep the storage outdoor, and the necessary safety distance increases with the quantity of hydrogen stored. Inside the facility, safety control equipment such as warning systems, flow control, and other safety features should be installed to detect and prevent hydrogen leakage. In case of leakage, it is important that no ignition sources, e.g., static discharges from electric equipment, are present. The standard gives directions on where electrical components should be placed and how they should be treated in relation to hydrogen safety.

Finally, the standard includes recommended practices for organizations stating that policies and procedures must address issues such as safety responsibility, hazards and risk management, applicable standards and regulations that apply to the organizations operations. Such regulations on operations can include Arbetsmiljöverkets regulation regarding tests with over- and underpressure (AFS 2006:8) and AFS 2017:3 on guidelines when working with pressurized devices. These regulation gives guidelines on how tests should be managed when looking for leakage or testing the strength of pipelines and vessels.

4.3.4 ISO 19880-1:2020 Hydrogen refuelling stations

This ISO standard covers the minimum safety and appropriateness for design, installation, commissioning, operation, inspection, and maintenance requirements for hydrogen refuelling stations. The standard is developed for light-duty road vehicles but can act as a baseline for other types of refuelling stations such as marine applications. It provides guidelines for risk assessments, safety distances, and mitigation measures to improve system safety. Mitigation measures include safety measures to mitigate the risk of fuelling the vehicle to unsafe conditions and mitigations to reduce the formation of flammable mixtures in enclosed systems or under a canopy.

To avoid those such formations, the installation should include emergency shut-off systems, pressure relief devices, well-ventilated environments (ventilation and relief equipment should be piped to a safe area), the protection of electrical and mechanical apparatus located close to potential leak points. The physical room should be designed to minimize high points where hydrogen can accumulate.

If, anyway, a formation of flammable mixtures would occur it is important to mitigate the possibility of an ignition. This is done by minimizing the presence of potential ignition sources and introducing hazardous areas, in where all equipment that could cause any form of ignition should comply with the safety recommendations for use in hazardous areas.

If, despite all precautions, an accident was to occur there need to be mitigations of escalation and/or impact of the fire or explosion. This can be achieved using fire/flame detection systems, over-pressure protection and emergency release of gas from the storage vessels under fire conditions. In case of hydrogen being released from the storage vessel, it should be vented to a safe location away from the hazard.

If an external event such as a fire would occur, there must be preparations to mitigate the effect on the fuelling station. The site should be designed to allow for a good overview of the fuelling station from the operating building and the hydrogen delivery installation. There must be easy accessibility to the installation for firefighters, including evacuation routes. Access roads and exits must be arranged to allow clear visibility and to minimize collision risks. The fuelling station should also be separated from vegetation, debris, and other flammable materials. Fire barriers can be used to increase safety, these barriers should in such a case be made of appropriate fire-resistant material.

In case of overpressure, the barriers should be installed so they will not cause any additional risks. The site should also be readily equipped with firefighting equipment and there should be an emergency escape plan with plenty of available exits from the facility in case of danger. Some of these requirements such as evacuation routes, accessibility for fire fighters, and available exits could be challenging for maritime refuelling stations depending on the port layout.

Safety distances can vary depending on the context, in ISO 19880-1:2020 several different types of safety distances and their interpretation are presented. The safety distances are not to protect from catastrophic events, the other mitigations and requirements are supposed to protect from that. For standard equipment and application, safety distances can be calculated quantitatively from a generic design or get prescribed by national regulations. For unique cases, the safety distance can be calculated by quantitative risk assessments. If the safety distance was to be considered too large, additional mitigations or prevention measures should be implemented.

4.3.5 EIGA Doc 15/21, Gaseous Hydrogen Installations

European Industrial Gases Association (EIGA) works with safety and technical matters related to the gas industry to achieve the highest level of safety and environmental care. Much like previous ISO standards EIGAs guide on gaseous hydrogen installations mentions general design features such as the location of the hydrogen fuelling station, layout, how the associated building should be designed, pipelines and discharge devices, material, pressure vessels, connections, instruments, and control and safety systems. The guide also includes hazardous zones, maintenance and handling of compressors, purification, electric equipment, fire protection, personnel training, and maintenance and repair procedures (EIGA, 2021).

4.3.6 DNV Handbook for hydrogen-fuelled vessels

DNVs handbook on hydrogen-fuelled vessels is primarily focused on regulatory frameworks and risk assessments for the vessel itself. It does however include some chapters related to the bunkering of compressed hydrogen gas. In the handbook, it is stated that there is no current regulation or standard that covers the safety issues related to large volumes of bunkering hydrogen. But there is work being done and ISO 19885-5 concerning the standardization of activities to develop a fuelling protocol for maritime hydrogen is on its way. For now, the primary guideline is for hydrogen fuelling stations dedicated to land vehicles and previous experiences of bunkering natural gas. As stated in the handbook one of the major safety concerns is that the heat generated while bunkering can soften the pressure vessels and lead to catastrophic failure. Controlling the flow rate and heat is thus of high concern during the bunkering of hydrogen vessels, which was analyzed in chapter 2. Another concern is if the ship would move further away from the bunkering station than the refuelling hose allows. Hence a break-away coupling should be installed that seals both ends of the system preventing further release of hydrogen (DNV, 2021).

For further functional requirements and regulations for the bunkering station, manifold, and system see The International Code of Safety for Ships using gases or other low-flashpoint fuels (IGF Code) (Breinholt, 2015).

4.3.7 SIMOPS and bunkering

Simultaneous operations (SIMOPS) while bunkering is an important aspect to make bunkering of hydrogen viable. For the ferry to keep its tight schedule, bunkering must be possible while passengers are boarding the ferry. A review by Fan, Enshaei, & Jayasinghe (2021) evaluated several regulations, standards, and rules concerning LNG bunkering and SIMOPS. The review found several documents stating general requirements, risk assessment requirements, and how to conduct the risk assessment. Among these were ISO/TS 18683:2015, the safety manual on LNG bunkering procedures for the Port of Helsinki, Bureau Veritas Guidance Note NI 618 DT R00 E, and DNVGL-RP-G105. What all documents had in common was that a risk assessment should be conducted and that they all used ISO/TS 18683:2015 as a guideline for the assessment. DNVGL-RP-G105 also included ISO/TS 16901 for the risk assessment of ship-to-shore interface scenarios. The appendix of DNVGL-RP-G105 includes how to address SIMOPS in a risk assessment. Key criteria included conducting a quantitative risk assessment for bunkering operations with SIMOPS, that SIMOPS may be allowed if it does not increase the risk by a significant amount, and that mitigating measures should reduce risks to an as low as reasonably practical level. This is in agreement with SGMFs guide on gas as a marine fuel where they mention that SIMPOS while bunkering LNG can be allowed if the port authority and safety regulator agree that it is safe (SGMF, 2017).

4.3.8 ISO 26142:2022

A common theme of the regulations and safety standards is that hydrogen detection is of great importance. In case of a hydrogen leakage, it should be detected and vented before an explosive atmosphere can be formed. The ISO 26142:2022 standard on hydrogen detection apparatus sets out the performance requirements and test methods for hydrogen detection in stationary applications. The standard is primarily aimed towards hydrogen refuelling stations for vehicles where safety is of high priority but can also be applied in other use cases. In the standard general requirements for the construction, labelling and marking, instruction manual, and the vibration is mentioned. For the general requirements of construction; alarm systems, indicators, and software were some of the more highlighted topics. The alarm system should detect hydrogen fractions of less than 1% and include a latching alarm. All alarms should be tamperproof and have at least one backup in case of failure. Detection apparatus should indicate under or over-range measurements and have a clear colour scheme to indicate its status.

If the detection apparatus is software controlled, a manual override should be available in case of software malfunction. The software version should be identified, and it should not be possible to change parameter settings for unauthorized users nor should it be possible, for anyone, to alter program code. Self-testing routines should be performed by the apparatus at regular intervals of 24h or less. Other testing guidelines for the hydrogen detection apparatus include the number of samples, sequence of tests, preparations, equipment, conditions, and methods of testing.

5 Discussion

The refuelling of hydrogen to the ship is a crucial part of the hydrogen supply system and poses certain challenges, both from a technical as from a regulatory point of view. In a large-scale ferry system, such as the Gotland ferries, the hydrogen volumes needed to refuel will be large, up to 16 tonnes, which is challenge. Furthermore, there is a need to refuel those volumes in very short time, in our Gotland ferry case it must be done in about 45 minutes. Using a thermodynamic simulation model, we have shown that filling 16 tonnes of hydrogen in 45 minutes will breach the allowed temperature limits. Some kind of cooling process must be added to avoid the temperature problems. When filling hydrogen to trucks at 700 bar pressure in the cylinder, the gas is pre-cooled to -40°C to avoid the temperature problem. However, there is a huge difference in volumes, a truck is refuelled with up to 50 kg hydrogen, the ferry shall have 16 tonnes.

From the above we can conclude that if composite cylinders are to be used for the on-board hydrogen storage, some kind of cooling system is necessary. Using a pre-cooling system would consume a significant amount of electricity and would increase the needed investments.

As an alternative to pre-cooling, we present a new concept called active cooling, where a heat exchanger is placed in the onboard cylinder instead (see Figures 11 and 12). Using seawater with a temperature of 10°C as cooling media will, according to our simulation, keep the temperature below the upper limit.

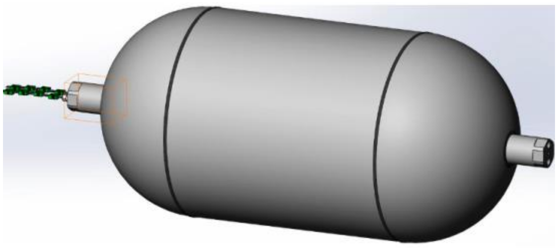

Figure 11. The hydrogen test cylinder

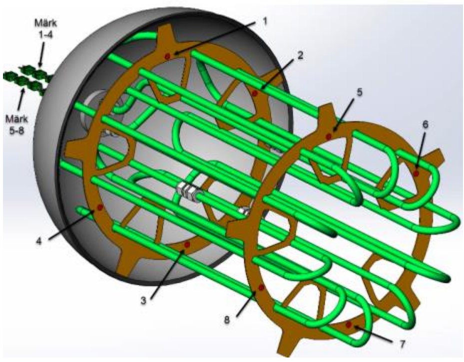

Figure 12. The heat exchanger inside the cylinder

There are several possible benefits with the above-described system with active cooling. The energy needed for cooling will be significant lower and there is no need for any installations in the port for a pre-cooling system. A drawback is that each ship that shall refuel hydrogen must be equipped with this active cooling.

To evaluate the concept of active cooling of hydrogen cylinders, a research project has been initiated where a cylinder with active cooling will be manufactured. The cylinder is a down-scaled version of the hydrogen cylinder planned to be installed in the future Gotland ferry. The temperature will be monitored both inside the cylinder and on the outside of the metal-liner.

The laboratory tests aim to evaluate whether the concept of active cooling is working or not, as well as to evaluate the accuracy of the simulation model. If it can be showed that the proposed new concept works, a further evaluation can start to obtain whether the concept can be up-scaled and if it is a practicable solution both from a technical as well as an economical point of view.

The laboratory tests will be carried out in cooperation with Research Institutes of Sweden (RISE) during quarter 3 in 2024.

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Lighthouse gathers leading maritime stakeholders through a Triple-Helix collaboration comprising industry, society, academies and institutes to promote research, development and innovation within the maritime sector with the following vision:

Lighthouse – for a competitive, sustainable and safe maritime sector with a good working environment

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