An approach to ventilation on hydrogen powered ships

Thomas-André Dahl
Oscar Hexeberg Staveli
Grunde Sakariassen

Bachelor's thesis in Energy technology
Bergen, Norway 2019

Høgskulen på Vestlandet

Ventilation on hydrogen powered ships

Thomas-André Dahl
Oscar Hexeberg Staveli
Grunde Sakariassen

Department of Mechanical- and Marine Engineering
Western Norway University of Applied Sciences
NO-5063 Bergen, Norway

IMM 2019-M72

Høgskulen på Vestlandet
Fakultet for Ingeniør- og Naturvitskap
Institutt for maskin- og marinfag
Inndalsveien 28
NO-5063 Bergen, Norge

Cover and backside images © Norbert Lümmen

Norsk tittel:	En tilnærming til ventilasjon på hydrogendrevne skip
Author(s), student number:	Thomas-André Dahl, h182411 Oscar Hexeberg Staveli, h182415 Grunde Sakariassen, h182412
Study program:	Energy technology
Date:	May 2019
Report number:	IMM 2019-M72
Supervisor at HHVL:	Norbert Lümmen
Assigned by:	TeknoTherm HVAC
Contact person:	Sigbjørn Tyssen
Antall filer levert digitalt:	4

Preface

This study was written by Thomas-André Dahl, Oscar Hexeberg Staveli and Grunde Sakariassen as the final thesis in Energy technology at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS). The topic question was issued by TeknoTherm HVAC.

The purpose of this thesis is to provide a tool for TeknoTherm to achieve an understanding of the systems from hydrogen storage to ventilation of engine rooms on board hydrogen ships and the safety issues associated with it. It will hopefully assist in creating a foundation for a program designed to calculate pressure loss and utilizable excess energy.

We want to give a special thanks to Sigbjørn Tyssen for excellent guidance and availability. He and his team at TeknoTherm made us feel welcome from the very beginning. We would also like to acknowledge Veronica C. Andersen Haugan, Bjørn Holo and Kristina Juelsgaard for advice and directing us to the right path. Last, but not least, we would like to express our gratitude to Dr. Norbert Lümmen for his inspiring passion and interest in the subject. He has been of great importance in our endeavors.

Abstract

The last years it has been a race to build the first hydrogen powered ferry, following the increasing focus on CO_2 and greenhouse emissions. This study investigates how a heating ventilation and air conditioning (HVAC) system must be adapted to accomodate for hydrogen being present in the air. A further objective is to identify ways to recovery waste heat for useful purposes on board in order to improve the overall energy efficiency.

Hydrogen powered ships are designed somewhat differently from those powered by diesel or natural gas. Tanks are chosen depending on what state the hydrogen is in, affecting further systems including pipeline, use of evaporators, valves and pumps. Liquid hydrogen requires a low temperature, and must be heated to correct temperature, while hydrogen under high pressure must lower the pressure. The fuel cell will then produce electricity and heat. This energy is later utilized for the HVAC system, and power the electric motors.

In the hydrogen power chain, available excess energy is found in the heating of liquid hydrogen. Additionally, the fuel cell requires cooling during operation, producing heat for the HVAC system. The water created in the fuel cells holds some energy, but it is available in a scale that is too small to be used in an absorption chiller.

Laws and regulations for hydrogen powered ships are still being developed. There are however documents of safe handling and use of hydrogen, as well as desired design to reduce risk. Fuel cells are placed in rooms where corners may be rounded, and the ceiling angled to achieve an even spread of hydrogen gas in case of a leak. In the ventilation channels, volume flow must be high enough to keep hydrogen gas from accumulating into concentrations that are large enough for explosions. All electrical equipment must be certified for safe use in an explosive mix of air and hydrogen, and materials carefully chosen to avoid sparks and friction that can ignite the mixture.

Sammendrag

Det har i de siste årene vært et kappløp for å produsere den første hydrogendrevne fergen, som følge av et økt fokus på CO_2-utslipp og en grønnere hverdag. Denne studien er gjennomført for å se hvordan et ventilasjonsanlegg på et slikt skip må tilpasses, og om det finnes tilgjengelig overskuddsenergi om bord for å forbedre energieffektiviteten.

Disse skipene vil utformes noe annerledes enn tilsvarende versjoner drevet på enten diesel eller naturgass. Tankene er valgt basert på ønsket tilstand av hydrogenet, som påvirker videre valg av rørsystem, fordampere, ventiler og pumper. Flytende hydrogen holder en lav temperatur, og må varmes opp for å kunne brukes i brenselcellene, mens hydrogen under høyt trykk trenger ventiler for å oppnå ønsket trykk. Brenselcellene omformer deretter hydrogenet til vann, og produserer elektrisitet og varme i prosessen. Denne energien tas i bruk for å produsere varme til ventilasjonsanlegget, og drive motorer i båten.

I et slikt system finner man mulig tilgjengelig overskuddsenergi i oppvarming av flytende hydrogen i form av energigjenvinning. I tillegg har brenselcellene behov for kjøling under drift, noe som produserer tilgjengelig varme for bruk i ventilasjonsanlegget. Vannet som dannes i brenselcelle-reaksjonen inneholder også energi, men det er tilgjengelig i for liten skala til å kunne utnyttes i maskiner som for eksempel en absorpsjonskjøler.

Et regelverk for design og sikkerhet på hydrogendrevne skip er enda ikke fastslått, men det finnes dokumenter på trygg håndtering og ønskelig design for å redusere farene ved bruk av hydrogen. Brenselcellerommet plasseres gjerne på samme sted som motorrom i dieselbåter, men kan ha runde hjørner og vinklet tak for å oppnå en jevnere spredning av hydrogengass ved en eventuell lekkasje. I ventilasjonsanlegget er det viktig at volumstrømmen er høy nok til at hydrogengass ikke ansamles og utgjøre en eksplosjonsfare. Alle elektriske komponenter må være sertifisert til bruk i en eksplosiv blanding av hydrogen og luft, i tillegg til at materialene blir nøye utvalgt for å unngå gnister og friksjon som kan antenne gassen.

Table of contents

Abbreviations

Proton Exchange Membrane Fuel Cell/ Polymer Electrolyte Membrane fuel cell	PEMFC
High Temperature Proton Exchange Membrane Fuel Cell	HT-PEMFC
Hot Water	HW
Coefficient Of Performance	COP
Heat, Ventilation and Air Conditioning	HVAC
Liquid Organic Hydrogen Carriers	LOHC
Metal Organic Frameworks	MOF
Liquid Hydrogen	LH_2
Carbon Monoxide	CO
Non Disclosure Agreement	NDA
Lithium Bromide	LiBr
Norwegian Directorate for Civil Protection	DSB

1. Introduction

Due to growing awareness among the public on the issues surrounding global warming [1], and tighter legislation on CO_2 emissions [2], there is an increasing focus on how to build more energy efficient and environmentally friendly ships. Hydrogen power is a proven technology, and hydrogen have already been used on smaller boats [3], as well as for supplementary electrical production on large ships [4, 5].

Studies have been conducted regarding hydrogen in a wide variety of fields. An example is Gexcon, a consulting company for safety and risk management, who performed a study to research hydrogen deflagration in small compartments, showing the importance of controlling risk assessment in case of ignition. Another study researched how blowing air at hydrogen accumulation might reduce and increase risk of ignition, depending on airflow, concentrations and obstacles.

Some of the most prominent existing projects are Norled's hydrogen ferry, HySeas 3, and Water-Go-Round. The fomer is said to launch the first commercial hydrogen ferry into operation in 2021 [6], experiments and testing is being undergone while developing [4, 7-11]. HySafe [4, 7-11]. Water-Go-Round will be the first American fuel cell vessel and is developed to demonstrate that hydrogen fuel cell power trains are well suited for a broad range of maritime applications. HySeas III is the final development stage of a programme to deliver what the team hopes will be the world's first sea-going vehicle and passenger ferry that will employ carbon-free hydrogen as energy source.

Energy Observer from France operates with several technologies in cooperation to power the ship. This boat is powered through electricity generated by wind turbines and solar panels. When the batteries are fully charged, excess energy is used to perform electrolysis and generate hydrogen from seawater, in addition to compressing and storing it. If the wind slows down and there is no sunlight, hydrogen will provide electricity using fuel cells. The goal is to test the system in extreme conditions to show its reliability and possibilities [12].

This study will give a deeper insight into potentially usable excess energy in the hydrogen powertrain and how to safely and efficiently ventilate hydrogen ships. It will also include a general overview of the hydrogen powertrain, as well as regard probable and current laws and regulations, in addition to best practices concerning hydrogen-powered vessels.

2. Method

Information used in this study is collected from literature. Previous studies have been read and analysed. Peer-reviewed scientific documents have been the main priority.

Further information has been provided through correspondence and meetings with TeknoTherm, Norwegian Maritime Authority, Ballard, European Marine Energy Centre (EMEC), Gexcon, Norled and other experts.

Calculations are based on numbers from scientific studies, experts and assumptions.

One part of the study is based upon technical specifications, and a mutual oral agreement was made not to spread this information.

2.1 Theoretical approach

The main report uses one formula to illustrate how much hot water is produced per amount of hydrogen.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{energy} \tag{1}$$

$$\text{Weight} - \text{ratio: } 2{,}016\ H_2 \text{ yields } 18{,}016\ H_2O \tag{2}$$

$$1\ \text{kg}\ H_2 \rightarrow 8{,}937\ \text{kg}\ H_2O \tag{3}$$

H_2 is hydrogen gas, O_2 is oxygen gas, and H_2O is water produced. The weight ratio between hydrogen gas and water is based on the atom weight, as 1 molecule of hydrogen gas produces 1 molecule of water. This gives an estimate of 9 kg water per kg of hydrogen gas.

The study includes a spread sheet with calculations for a hydrogen power chain. This spread sheet is documented separately through appendix 1, delivered alongside the report. The documentation includes assumptions, formulas and explanation as to how the spread sheet is designed to be used.

2.2 Sources of error

As mentioned, the study is written based on literature, conversations with experts and calculations. Common sources of error include human errors, and errors in sources. Throughout the study, it has been necessary to approach calculations with assumptions, usually based on correspondence with said experts, scientific studies and already aquired knowledge.

In order to avoid mistakes, numbers and assumptions have been collected from multiple sources when available, and calculations have been thoroughly checked. Regardless, if this study is to be applied in professional context, formulas should be validated for correct use.

3. System

3.1 Hydrogen system description

Figure 1 illustrates an overview of a possible setup for the hydrogen power chain. Hydrogen is usually stored cryogenically or with high pressure in specialized tanks (1). Hydrogen is transported to the fuel cell in a pipeline (2), designed depending on the choice of storage. The fuel cells require a stream of air (3) for the hydrogen-oxygen reaction. These fuel cell stacks (4) generate electricity to use as power for the electric motors on the ship. Surplus energy from the coolant and hot water (HW) (5) produced by the fuel cells are handled for use in the HVAC system. The fuel cells produce electricity that will be managed and put into batteries and motors (6), in addition to other electrical equipment, lights etc. Electric motors (7) use electricity to generate kinetic energy for the propeller.

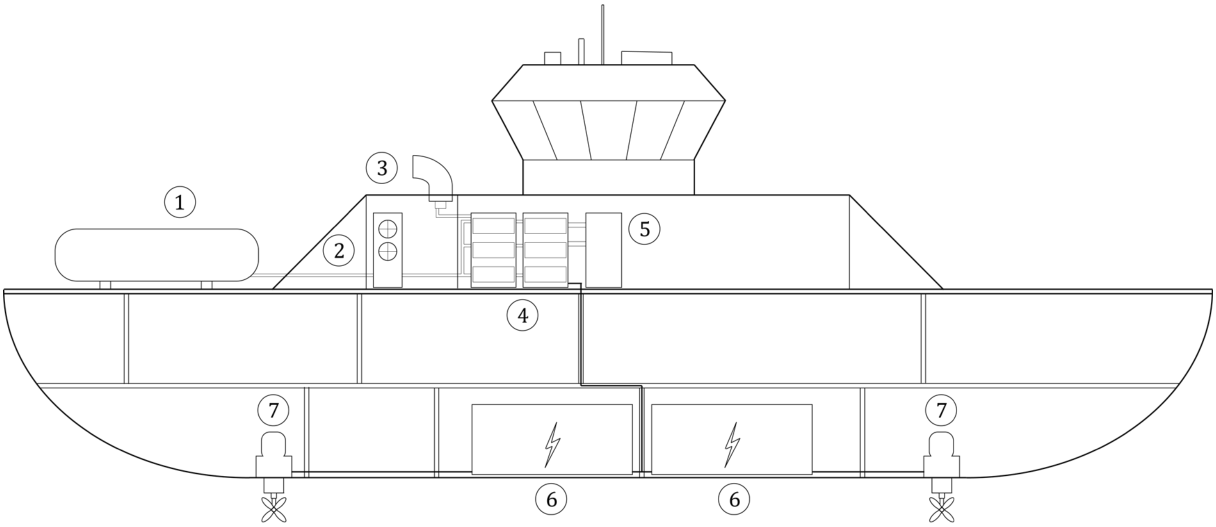

Figure 1 – Hydrogen drive chain overview

3.2 Hydrogen storage

Storage of hydrogen is one of the most important elements of the system, but efficient storage is difficult from a technoeconomic view. It is paramount to use methods with high gravimetric and volumetric energy densities to compete with existing options on the market. Therefore, new concepts and technologies have been and is being developed to make hydrogen a competitive option. Usually hydrogen storage is divided into two parts: stationary and mobile storage. This part of the study will only handle mobile storage on ships. Currently there are four options for realistic storage methods: high pressure gas storage, cryogenic liquid storage, low temperature-high pressure storage and storage of hydrogen gas in metal hydride. [13]

High pressure, compressed, storage is the most widely developed form of hydrogen gas storage, with the most common being high pressure steel cylinders operating at up to 200 bar. Technology also exists that store hydrogen at a pressure of up to 800 bar, which allows for far greater density, up to 36 kg/m^3 [14]. The high-pressure storage method is available at low production volumes commercially and has been subject to extensive testing and demonstration in prototype fuel cell vehicles [15].

Cryogenic storage operates below 20,25 K and 3-6 bar [16], at which point the hydrogen gas will undergo a phase transition into a liquid. Liquid hydrogen reaches a density of around 70 kg/m^3, about double that of compressed storage [14]. The prominent challenge of this type of storage is the amounts of energy required to to both liquify it and keep it in the liquid state. Around 40% of the energy is lost in the liquefication process compared to 10% for compressed storage [9]. Cryogenic tanks have an extra protection layer, a vacuum jacket which is an outer shell that provides vacuum conditions between the layers. Also, hydrogen has a relatively low adiabatic expansion energy at such low temperatures [12]. As a result, there will not be a severe explosion unless the gas is ignited. Valves and pressure relief devices not rated for the low temperature are at risk of damage or malfunctioning in case of a leak, but the chance of this happening is essentially non-existent [14].

Cryo-compressed storage is a promising method due to storage and safety level. The cryo-compressed hydrogen does not liquefy and is a super critical cryogenic gas. For this application the hydrogen is cooled to about 40 K and compressed to 250-350 bar [17], and a density of around 80 kg/m^3 is obtainable. It also allows for efficient refuelling, and is a safe alternative because it, like cryogenic storage, has a vacuum jacket. However, it is not yet as widely developed and tested as the previous storage methods, making it a relatively expensive and unavailable option [18].

Material-based hydrogen storage is divided into two parts: chemical and physical sorption. In chemical sorption the molecules are split into atoms and stored in the chemical structure of the material, with hydrides being the most famous materials used. In physical sorption the hydrogen is stored in porous materials that allows for a high surface area and low binding energy, resulting in faster kinetics in charge/discharge processes. Also, the materials are at a low cost and is a method with potentially high storage capacity and reliability. The most promising methods are Liquid Organic Hydrogen Carriers (LOHC) for chemical sorption and porous carbon materials and Metal Organic Frameworks (MOF) for physical sorption. Unfortunately, these technologies are not far enough in development to necessarily provide capacity, charge/discharge speed, and reasonable price to yet be able to compete in today's market [18].

It is fair to consider compressed and cryogenic storage as the most suitable methods for hydrogen storage with current technology. Choosing cryogenic storage means an evaporator and insulated pipes are required for the system to function. Insulating double-walled vacuum pipes are most common when transferring the liquid hydrogen to the evaporator to keep the hydrogen below boiling point (20,25 K). It will also minimize hydrogen loss through vaporization and liquid air formation in the pipes with ensuing oxygen enrichment [19, 20]. Pipes will be further reviewed in section 3.3. An evaporator is required before the fuel cells to transform the liquid hydrogen to gas, which means a heat exchanger must be connected before the evaporator if the low temperature liquid is to be utilized as an energy source. Heating and phase changing the hydrogen is an energy-costly process, which must be taken into consideration when deciding which storage method to use. Single-walled pipes are advised from the evaporator to the fuel cells.

3.3 Pipes and valves

When designing the pipeline for a hydrogen drive chain, it is important to keep the properties of hydrogen gas in mind. As mentioned, there are differences between high pressure storage and cryogenic storage, leading to difference in choice of materials, valves and joints. Hydrogen embrittlement is a common concern, in addition to metal properties at low temperatures.

3.3.1 Choice of material

Liquid hydrogen is remarklably cold and requires materials that can withstand these temperatures. Materials that are subject to low-temperature embrittlement should be avoided at cryogenic temperatures [21]. Liquid hydrogen is heated and vaporized before use in fuel cells. Connections in front and after the evaporator must assure no leakage, as pipes for hydrogen gas are usually not designed for cryogenic temperatures [21]. The pipeline should also be properly insulated with materials that are non-combustible or have self-extinguishing fire rating [21]. The most commonly used insulated pipes for hydrogen transportation today are double-walled vacuum jacketed pipes.

High pressure hydrogen requires a choice of material that can withstand hydrogen embrittlement and high pressure [22]. Typical materials used in these conditions are austenitic stainless steels, aluminium alloys, copper and copper alloys [22]. When designing pipelines for offshore applications, the corrosive environment should also be taken into consideration. According to DNV-GL, traditional austenitic stainless steels like 316 and 316L are generally not suitable for maritime use, although they are among the more corrosion resistant steel alloys. Stainless steel that contain more molybdenum, chromium or nitrogen are usually better fit as they are resistant to localized corrosion. Copper have better resistanse to corrosion but should not be used above temperatures of 473-573 K [23].

3.3.2 Valves

In pipelines where liquid hydrogen is flowing, all valves must be functional at the operating conditions. Valves can have parts of different materials than the valve body, which can cause problems. If the valve traps liquid hydrogen and heats it up enough, the hydrogen will cause high pressure. This leads to globe valves to be the most popular choice in these conditions [24]. Another suggestion is drilling a hole in a ball valve so the liquid hydrogen can escape into the high-pressure side if heated [24].

Similar to liquid applications, valves for use in high pressure can be made of different materials than the body [25]. These parts should be made of the same, suitable material as the body. The popular choice for high pressure hydrogen valves is the ball valve, as it rarely leaks and is usually fire-resistant [25].

3.3.3 Joints

One should avoid joints if possible, especially when handling liquid hydrogen due to both hydrogen exposure and embrittlement at low temperatures. Joints are selected based on, but not limited to, tightness and ability to withstand thermal cycles and mechanical energies. Furthermore, joints should generally not be placed in areas where leaks are unacceptable [26].

3.4 Fuel cell systems

The two dominating and most promising types of hydrogen fuel cell systems used for the shipping industry are Proton Exchange Membrane fuel cell (PEMFC) and High Temperature Proton

Exchange Membrane fuel cell (HT-PEMFC). This is due to their versatility and wide range of use for different applications [27].

3.4.1 PEMFC

Proton Exchange Membrane fuel cell, also known as Polymer Electrolyte Membrane fuel cell (both PEMFC), operates on a relatively low temperature, usually between 353-373 K. Also, the electrical output can be adjusted in case of dynamic power requirements [28]. PEMFC currently has an efficiency of around 50%, with most of its waste energy going to heat [29, 30].

The PEMFC polymer membrane is water-based and acidic. The membrane functions as its electrolyte with platinum-based electrodes. Due to the PEMFC low heat and its use of precious electrodes, its operation is dependent on pure hydrogen [28].

PEMFC converts hydrogen and oxygen to water and electricity. Hydrogen atoms enters the fuel cell at the anode where the hydrogen atoms are stripped for its electrons. The proton then goes through a PEM and arrives at the cathode, while the electrons travels through an external circuit. Hydrogen reacts with oxygen from the air at the cathode which produces water and releases energy. The energy released is in the form of electricity and heat. PEMFC can be used in combination with both liquid hydrogen (LH_2) and high-pressure hydrogen. This process produces around 9 kg of water for every kilogram of hydrogen consumed as shown in eq. (1)-(3).

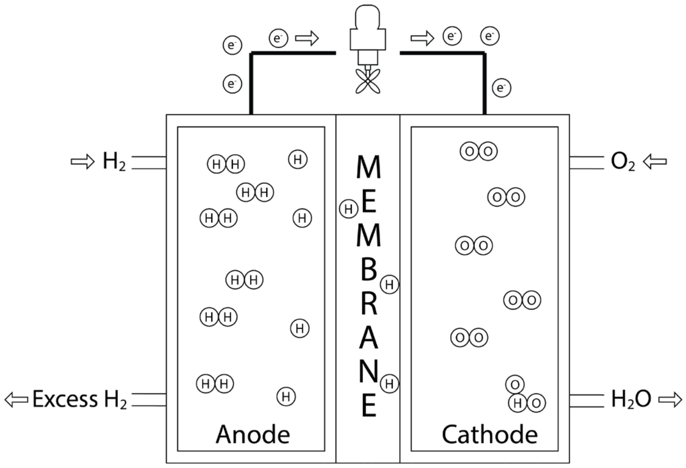

Figure 2 – Proton exchange membrane fuel cell

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O + \text{energy} \tag{1}$$

$$\text{Weight} - \text{ratio: } 2{,}016\ H_2 \text{ yields } 18{,}016\ H_2O \tag{2}$$

$$1\ \text{kg}\ H_2 \rightarrow 8{,}937\ \text{kg}\ H_2O \tag{3}$$

3.4.2 HT-PEMFC

There are several advantages of the HT-PEMFC compared to the regular PEMFC. Most importantly, the HT-PEMFC works at significantly higher temperatures, around 373-473 K [31]. The high operating temperatures provide some important advantages compared to other fuel cell systems.

First of all, the high temperature provides a much higher carbon monoxide (CO) tolerance (around 3%) which is 1000 times more than the PEMFC can normally tolerate, meaning less gas cleanup is needed. In addition, the HT-PEMFC does not need a humidifier, air compressors or oversized radiators, and the architecture of the system is simpler with fewer components [32]. It also uses a mineral acid-based electrolyte [28].

Lastly, the waste heat is at a higher temperature than PEMFC, thereby it has potential for utilization in HVAC-systems. Most of it leaves through the cooling circuit or exhaust pipe, which means it is easily utilizable by installing an air-to-air or air-to-liquid heat exchanger. This excess heat can be further used for HW generation, absorption cooling, steam generation or simply heating [33].

Serenergy AS have created a HT-PEMFC with an electrical efficiency of up to 57%, and with more than 90% of its waste-heat leaving in a contained usable directional stream. This makes most of the excess heat easy and cheap to recover [32, 33].

Disadvantages of the HT-PEMFC include warmup time (which means an additional power source is needed, in addition to the fuel cell having longer reaction time), limited selection of materials (much more expensive), and generally lower current density and faster material degradation, which are important factors when deciding what kind of fuel cell is the most suitable for the desired use. [31, 32]

PEMFC and HT-PEMFC have advantages and disadvantages, and it is hard to declare a clear superior system as they have very different benefits. The main differences between the two variants will be shown in Table 1.

Table *1 – Comparison of PEMFC and HT-PEMFC*

Fuel cell	**PEMFC**	**HT-PEMFC**
Operating temperature	353-373 K	Up to 473 K
Electrolyte	Water based	Mineral acid based
Pt loading	0,2-0,8 mg/cm^2	1,0-2,0 mg/cm^2
CO tolerance	<50 parts per million	1 – 5% by volume
Other impurance tolerance	Lower	Higher
Power density	Higher	Lower

3.5 Surplus energy and utilization

In order to increase overall energy efficiency, utilizable waste heat/energy should be identified. The hydrogen power train can provide energy for the HVAC system in some of the processes. If the ship is powered by liquid hydrogen, this must be heated before use, and the fuel cells require cooling during operation. In this study, an attempt has been made to show the available energy at certain conditions, based on calculations.

3.5.1 Heating liquid hydrogen

Liquid hydrogen is stored at below 20,25 K as stated in section 3.2. In order to use it in the fuel cell, it is heated to a temperature of about 273 K [16]. This is done in a similar process as in LNG where the LNG is stored at 113 – 118 K and then heated before entering the engine [34]. It is possible to extract some of this cold temperature using cold recovery. The process is not yet used extensively, but it shows promise for use on LNG ships, and could thereby show promise for hydrogen use.

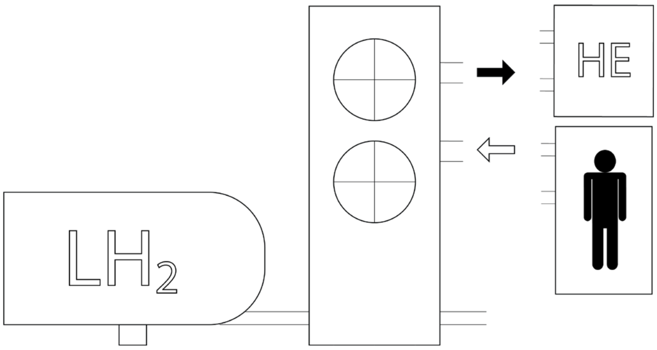

Figure 3 – Energy for heating liquid hydrogen can be collected from outlet air or other heat sources

Based on calculations performed in this study, given a mass flow of 28,8 kg/h LH_2 at 20,25 K that is to be elevated to 273,15 K, it is possible to extract approximately 29 kW of cooling power. Based on numbers from a technical specification, protected by a non disclosure agreement (NDA), dimensioned cooling power for a ferry might be around 175 kW [35]. The cold recovery is therefore able to cover a part of the required cooling.

3.5.2 Fuel cell coolant

The fuel cells require cooling during operation. Ballard Power Systems, Inc. deliver modules intended for maritime use, with a separate cooling system provided. This coolant is made from 50/50 pure ethylene glycol and deionized water, with inlet at 333 K and outlet at 343 K [36].

Heat produced by the fuel cell is transferred to the coolant, which is then designed to be able for use in HVAC systems. Given the same conditions as in section 3.5.1, the coolant can provide 486 kW of heating power. This energy can provide heating for inlet air, cabins separately or public areas.

3.5.3 HW produced by fuel cells

This water is produced from the fuel cell is assumed to be roughly 5 K below fuel cell operating temperature, resulting in HW utilizable for the HVAC system. Calculations performed in this study shows that the total water available from the HW is approximately 257 kg/h at 348,15 K, using the same conditions as in section 3.5.1.

This water can be utilized in the HVAC system for general heating, or in an absorption cooler if conditions are correct. This is discussed in section 3.5.4.

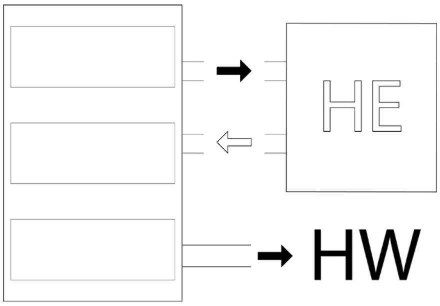

Figure 4 – Fuel cells require cooling during operation, and produce hot water that can be utilized in HVAC systems

3.5.4 Absorption cooler

The absorber contains a mixture of water and ammonium or water and lithium bromide, the latter being the more common refrigerant as it is safer to use and less toxic. Therefore, this part of the study will focus on how the lithium bromide (LiBr) absorption chillers work.

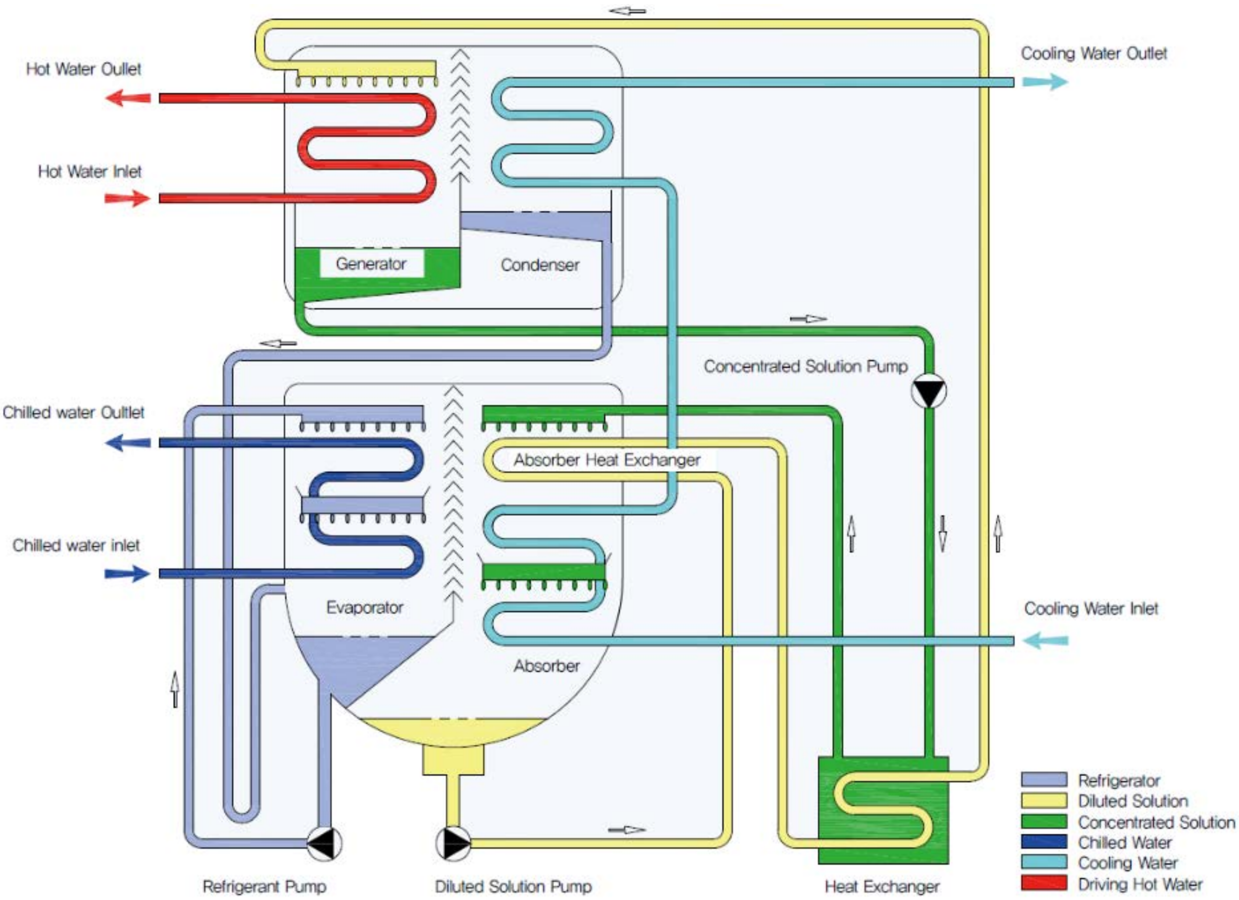

Figure 5 – Absorption cooler overview [37].

This "weak" or diluted solution (40% water and 60% LiBr) is pumped through a heat exchanger and poured into a generator, where the solution is heated by an external HW/steam source. The heat forces the water to evaporate into the condenser, separating the water and LiBr because of the heavier LiBr molecules. Therefore, liquid LiBr will be accumulated in the generator and transferred from the generator back through the heat exchanger as a heat source and sprayed over the absorber to be re-used in the water-LiBr solution [37, 38].

Meanwhile, the water vapour is condensed into a liquid. Pipes connected to a cooling tower runs through the condenser, removes the heat from the vapour, and liquefies the water as it hits the pipe surface [38].

A collection tray in the condenser will gather the now liquid water and transfer it to the evaporator. The water volume flow rate is controlled by the pipe orifice. The pressure in the evaporator is close to vacuum condition, around 0,84 kPa, causing the water to flash drop to about 277 K [37, 38].

The chilled water carries all the unwanted heat for the vessel or building in a pipe and enters the evaporator at about 285 K. The condenser water is then sprayed over the pipe surface to release all unwanted thermal energy. Because of the low pressure, the water will instantly evaporate when it encounters the surface of the pipes [37, 38].

Water that is not evaporated by the pipes gather in a collection tray and is transported back to repeat the cycle until all excess water has evaporated. This process cools the water in the pipes to around 280 K, and the pipes run back to again gather unwanted heat from the building/vessel [37, 38].

The water vapor is now released from the evaporator, and the strong attraction between LiBr and water forces them to mix. Contact between these fluids release some heat. To prevent heating of the mixture the cooling tower pipes pass through the absorber to cool down the solution. In addition, the cooling tower pipes condense the residual water particles so all the vapour that has not yet mixed with the solution by attraction now will. Now the absorption chiller is back at its starting point and ready to repeat the cycle [37, 38].

A design limitation for the use of absorption coolers in ships is size. Space is paramount in ship design. It is therefore crucial to make sure that the system is properly dimensioned. In order to keep the size of the absorption cooler small enough, the HW must be around 353-363 K. The HW from the fuel cell is around 348 K as shown in section 3.5.3, and therefore needs to be heated in order to be usable in the absorption cooler, lowering overall efficiency [39].

4. Maritime HVAC

Ventilation at sea is very similar to the practice on land, with some adaptations. Passengers generally require better air quality in order to reduce the amount of seasick people. This leads to the HVAC system generally providing more air changes per hour than is normal for buildings on land. These air changes carry enough fresh air into the cabins and public rooms.

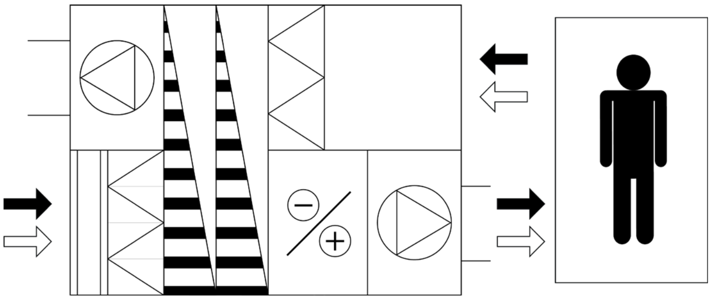

Figure 6 – Typical air handling unit, including mist eliminator, filters, double rotary heat exchangers and cooling/heating battery.

A maritime HVAC system is a combination of many solutions for several purposes. The system at sea is usually dimensioned with a wider range of temperature operation than on land. This requires the system to be able to handle both cold and warm climate, which can cause issues regarding size. In order to reach the outer dimensioned limits, it might be a necessity to install more and larger components.

Most of the energy for HVAC systems must be brought along, making energy efficiency highly important. Where it is possible, energy should be circulated through heat exchangers either as heat sources or heat sinks. In addition, ships need to have enough power in the HVAC system to provide a high standard of comfort for passengers and crew.

4.1 Where does the energy come from?

In addition to energy brought along in the form of electricity and fuel, other sources can be utilized. Indirectly, waste heat can be recovered to be converted into either electricity or space heating through heat exchangers, power pumps or radiators. Furthermore, exhaust air from cabins and public areas are used in heat exchangers to recycle energy. Sea water can provide cooling in hot climates, for example when solar irradiance heats the ship. Additional sources include but are not limited to electricity from wind turbines and solar panels, absorption chillers, and heat from batteries and technical rooms. As mentioned in section 1, Energy Observer is one of the projects that use several technologies to cover the total energy demand.

4.2 System

First, air is brought in through mist eliminators and filters to avoid mist, dust and unwanted items entering the HVAC system. The mist eliminator slings air from side to side so the heavier water drops are caught by hooks and removed from the air before it enters the filters.

After the filtration, inlet air is run through the rotary heat exchanger which heats the air up by using heat from exhaust air. These heat exchangers can reach up to more than 85% effectivity and provide great energy efficiency. This is simply because the temperature of the air must be raised just a few degrees by the heating coil. It is also possible to use the heat exchanger to cool inlet air, leading to less energy required from a cooling coil to achieve the wanted temperature.

The air flow is then controlled into the rooms where air is required, with possible alterations depending on the type of room, time of day and amount of people in them. For example, cabin rooms with more people can require more air changes to counter CO_2 levels in the room, the wheelhouse might need air blown at windows to counter dew, and technical rooms enough air changes to keep desired air quality and temperature.

5. Safety measures

Extra precautions must be made when designing hydrogen-powered ships. This part of the study will shed light on the most important safety factors and dangerous elements. The most prominent challenge is the lack of extensive testing. This means there are few concrete rules to relate to, considering that the majority of the research is conducted while developing new ships. Therefore, it is in many cases necessary to look to LNG ships for solutions because of its similarities. This, in addition to testing, experience and sense combined will provide safe handling of hydrogen.

This study will address the most important challenges. Two critical issues are leakage, and detection in normal operating conditions and after, safe ventilation by avoiding accumulation of hydrogen. The challenges of handling ventilation on hydrogen-powered ships include but are not limited to concentrations and spread, engine room design, choice of materials, fire prevention, and staff training.

5.1 Concentration and ignition

Concentration and ignition are important factors for fire safety in hydrogen-powered ships. But before examining how these factors work a greater understanding of hydrogen and its properties are essential. To ignite a hydrogen fire two things are necessary: a mixture of hydrogen and air with proper proportions and sufficient energy to bring the mixture to its ignition point. Table 2 provides a comparison between the most common fuels used in LNG and hydrogen to highlight the crucial characteristics of each fuel. The most important question to answer is when flammable fuel-air mixtures occur. Hydrogen has a wide range between lower flammable limit (LFL) and upper flammable limit (UFL), respectively 4%-8% (4% in turbulent air, 8% in still air) and 75%, with the optimal combustion condition at 29% [40]. Any mixture of hydrogen in oxygen between these limits could possibly lead to ignition. In unconfined or open areas, the upper limit usually is of less importance, while in confined or enclosed areas high concentrations are of great danger. This is because in areas not containing enough ignition energy to spark immediate ignition the hydrogen gas can accumulate and cause a detonation. This is a possibility in the fuel cell room and ventilation shafts. Handling of these areas will be reviewed in section 5.2.1 - 5.2.3 of the study [41].

Secondly, when applying this knowledge, it is important to understand what sources can spark ignition. The 0,02 mJ ignition energy of hydrogen shown in Table 2 is based on stoichiometric conditions, meaning the total mass of the reactants equals the total mass of the products [42], which is unrealistic in every practical scenario. Thus, it is fair to assume the ignition energy required will be higher. For example, the discharge from an electrostatic charge on a person can be as high as 30 mJ [43], 1500 times higher than any of the minimum ignition energy value for hydrogen from Table 2. If the hydrogen is not handled properly it can ignite from the electrostatic charge from a human, the discharge from a valve or even a burst disk.

Table *2 – Flammability, detonability and ignition energy for some fuels [41]*

Fuel	**Hydrogen**	**Methane**	**Propane**	**Gasoline**
Flammability limits				
Lower (% fuel by volume)	4.0	5.3	2.1	1.0
Upper (% fuel by volume)	75.0	15.0	10.4	7.8
Detonability limits				
Lower (% fuel by volume)	18.3	6.3	3.4	1.1
Upper (% fuel by volume)	59.0	13.5	-	3.3
Ignition energy (mJ)	0.02	0.29	0.31	0.24

Lastly, in the event of a leak, will the hydrogen-air mixture meet an ignition source of sufficient strength? This question is vastly situational depending on the size of the volume containing a flammable mixture and how close the hydrogen-air mixture is to the minimum ignition energy. These are affected by the rate of dispersion, the amount of fuel released, and obstacles disrupting the flow. Hydrogen has a wide flammability range, meaning in enclosed or partially enclosed rooms the likeliness of ignition may be higher than for the other gases mentioned. This can be especially dangerous if leaks occur in the fuel cell room without proper ventilation.

5.2 Laws, regulations and best practices

Hydrogen ships will follow regulations similar to those for natural gas [16]. Changes made to regulations will then be based on the difference in how hydrogen and natural gas behaves.

5.2.1 Room design

Design of the fuel cell room may be regulated due to the impact this can have for general safety. This study points at topics that may be affected by these regulations.

The ventilation inlet should be located at floor level, and the outlet either close to the ceiling or in the ceiling. This is because hydrogen accumulates in the ceiling due to its properties. The inlet air flow must be enough to fulfill required air changes per hour without causing turbulence in the air that could prove hazardous.

Studies have been performed to test how inclinations in the ceiling can provide a more controlled spread of hydrogen concentrations in the room. One study suggests an apex angle of 120° is the optimal in order to achieve the most favorable dispersion [44]. This is illustrated in Figure 7. In addition to having angles in the ceiling, rounding the corners of the room might prevent hydrogen pockets from emanating in said areas.

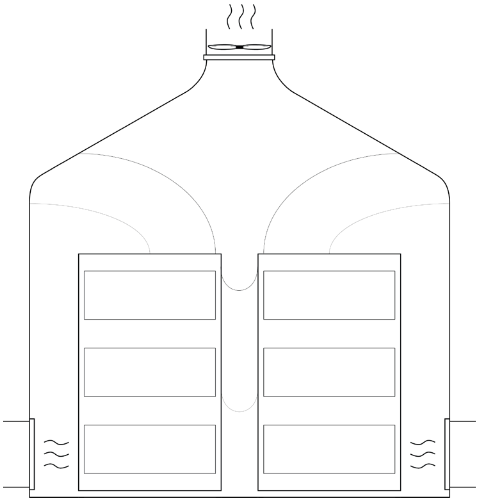

Figure 7 – Fuel cell rooms may have inclined roof and rounded corners.

Furthermore, Norwegian fire regulations for ships powered by natural gas state that engine rooms must only contain the objects they require to be functional [45]. This is to avoid unnecessary obstacles, which can provide turbulence and increased risk of explosion. Hydrogen with even lower ignition energies than LNG should avoid this risk. Hence, the regulation is likely to apply for hydrogen powered ships.

5.2.2 Pipes, fans and equipment

As stated in section 5.1, hydrogen gas requires very little energy to ignite. Equipment should be made of non-sparking materials [46]. This will also apply to the fans in the ventilation ducts where hydrogen passes through. These fans should additionally be close to frictionless. Electrical equipment in all rooms where hydrogen may be present must be certified to use in an explosive mix of air and hydrogen [46].

Sensors should be placed in such a way that concentrations that are too high will be noticed as soon as possible. Fuel cell stacks are usually provided with own sensors for hydrogen [36]. Furthermore, sensors can be positioned close to both ventilation outlets and pipe connections.

5.2.3 Ventilation

In addition to placement of ventilation inlet and outlet, the air ventilated out should never be circulated back into the ventilation system. The exhaust point must be higher than other points on the ship as hydrogen will drift upwards and can potentially accumulate in unwanted areas [46].

Ventilation outlet channels should always have enough volume flow to keep the hydrogen concentration below LFL in the outlet pipes [46]. If the speed is lower, hydrogen can accumulate in the channels, making sparks and friction hazardous.

Ventilation of this room should not be turned off during an emergency shutdown as hydrogen must be ventilated out [46]. However, if there is a fire in the fuel room, ventilation must be shut off and hydrogen supply cut off. This is to cut off additional fuel, similar to shutting fire doors and fire dampers in order to starve the fire.

5.2.4 Documents and tools

There are existing documents for safe use of hydrogen, although the regulations for ships are not completed. The IGF-code from International Maritime Organization provides regulations for ships using gases or other low-flashpoint fuels, making it relevant for hydrogen use [47]. Another document is the guide to Safety of Hydrogen and Hydrogen Systems by American Institute of Aeronautics and Astronautics (AIAA), which discusses hydrogen for areospace applications [48].

Furthermore, H2tools.org has launched a project called lessons learned, enabling people to share accidents, experience and other important information regarding hydrogen usage [49]. This includes a search bar and tags for easy navigation and reading. Another available tool is the HyRAM software, designed by Sandia National Laboratories [50]. This toolkit is created to produce hydrogen risk assessment models and predict and quantify accident scenarios.

There will be a better understand of handling hydrogen in maritime applications in the following years as a result of the current and upcoming hydrogen ship projects. The project for the hydrogen ferry that is to be operated by Norled is made in collaboration with the Norwegian Maritime Authority and the Norwegian Directorate for Civil Protection (DSB) [9]. These government agencies are both responsible for general safety and ensuring safe operation for everyone involved [51, 52]. Norwegian Maritime Authority are working on regulations for maritime hydrogen applications [16].

As hydrogen is a new fuel, it is important to train staff to ensure safety. For staff, it is paramount to learn how turbulence and concentrations affect the risk, in addition to the low ignition energies of hydrogen. DSB is one of the agencies that can provide either counceling and training or direct to experts for these situations.

6. Suggestions and further reading

This study has depicted a hydrogen drive chain with larger components like tanks and fuel cell room on the upper decks of the ship. This is loosely based on illustrations from the SF-BREEZE hydrogen ferry project but is not necessarily the best placement for them [53]. It is common practice to place large and heavy objects closer to the bottom of ships to achieve better stability and to free up space for passengers and commerce. However, hydrogen has a reputation of being dangerous and is connected to major accidents like the Hindenburg accident. Therefore, convincing the public that a practical placement below deck is safe could prove challenging.

In laboratories, fume hoods are used to safely ventilate gases and fumes directly out of the building to maintain a safe environment. As stated in section 5.2.3, outlet air from fuel cell rooms should be ventilated separately and never be connected back into the ventilation ducts. Perhaps it is a possible to utilize a solution like the fume hood target specific areas with higher probability of leakage, as fuel cell stack connections and pipe joints. However, as obstacles must be kept to a minimum, this solution must be carefully designed and tested.

In addition to ensure no projectiles can be created from an eventual explosion, it could be possible to control the combustion in a chosen direction by designing walls and roof with different strength. As an example, if the room is positioned in the upper part of the ship and the roof is made of materials that are designed to blow out, a controlled explosion could be directed straight up with lower risk of excessive material or personal damage.

There will be a better understand of handling hydrogen in maritime applications in the following years as a result of the current and upcoming hydrogen ship projects. The project for the hydrogen ferry that is to be operated by Norled is made in collaboration with the Norwegian Maritime Authority and the Norwegian Directorate for Civil Protection (DSB) [9]. These government agencies are both responsible for general safety and ensuring safe operation for everyone involved [51, 52]. Norwegian Maritime Authority are working on regulations for maritime hydrogen applications [16].

The authors suggest that a CFD-simulation should be performed for a fuel cell room with inclined roof and round corners in order to see dispersion of hydrogen and compare it to a normal cubic shaped room. In addition, attention should be directed towards the ongoing hydrogen ferry projects, especially Norled's hydrogen ferry in collaboration with DNV-GL, a leading authority in maritime specifications and regulations.

7. Conclusion

The hydrogen drive chain must be adapted depending on the choice of storage. Liquid hydrogen is stored at below 20,25 K and 3 – 6 bar, while high pressure storage is around room temperature and 250 bar. Hydrogen power fuel cells that generate electricity and heat by utilizing the exothermic reaction between hydrogen and oxygen.

Surplus energy can be found in heating liquid hydrogen for use in fuel cells, fuel cell coolant, and fuel cell exhaust water. The amount of energy available is mainly based on the amount of hydrogen mass flow. An example calculates available energy to be around 29 kW cooling and 486 kW heating, with 28,8 kg/h of LH_2 being heated from 20,25 K to 273,15 K, powering three fuel cells at 200 kW.

It is possible to utilize excess energy in multiple ways, one being an absorption cooler. This machine produces cooling power with a good COP if HW is available "free of charge".

Safety is a great concern when handling hydrogen and should be top priority. Concentrations between 4% - 75% hydrogen in air is explosive and requires as little as 0,02 mJ for ignition. In comparison, discharge from electrostatic charge on a person can hold 10 – 30 mJ. Risk of explosion is greatly increased with turbulence, making obstacles and airflow a point of concern.

Laws and regulations will be based upon LNG-standards, adjusted to the behaviour of hydrogen. Materials must be able to withstand exposure to hydrogen due to hydrogen embrittlement, extreme temperatures and pressure. Fans in ventilation ducts where hydrogen passes through must be non-sparking and close to frictionless. All electrical equipment must be certified for use in an explosive mix of hydrogen and air.

8. Bibliography

[1] R.J. Orsato. Competitive Environmental Strategies: When Does it Pay to Be Green? California Management Review. Vol 48 (2006) pp. 127-43.
[2] V. Blich. Roser politikerne for innstilling om nullutslipp i 2026. Available at: https://www.skipsrevyen.no/article/roser-politikerne-for-innstilling-om-nullutslipp-i-2026/, accessed online: 22.01.2019.
[3] T. Stensvold. Kappløp om å bygge verdens første hydrogenferge. Available at: https://www.tu.no/artikler/kapplop-om-a-bygge-verdens-forste-hydrogenferge/367699, accessed online: 22.01.2019.
[4] Golden Gate Zero Emission Marine. Water-Go-Round-Project Technology. Available at: https://watergoround.com/technology/, accessed online: 16.01.2019.
[5] T. Stensvold. Viking Lady blir sjøens Prius. Available at: https://www.tu.no/artikler/viking-lady-blir-sjoens-prius/237821, accessed online: 22.01.2019.
[6] M. Launes. Norled to develop the world's first hydrogen ferry. Available at: https://maritimecleantech.no/2018/11/30/norled-to-develop-the-worlds-first-hydrogen-ferry/, accessed online: 01.05.2019.
[7] HySeasIII. HySeasIII. Available at: https://www.hyseas3.eu/, accessed online: 22.01.2019.
[8] J.W. Morgan. HySeas III: World-first Renewables-Powered Hydrogen Ferry. Available at: https://mcphy.com/en/press-releases/hyseas-iii-world-first-renewables-powered-hydrogen-ferry/, accessed online: 22.01.2019.
[9] T. Stensvold. Norled bygger verdens første hydrogen-ferge. Available at: https://www.tu.no/artikler/norled-bygger-verdens-forste-hydrogen-ferge/452526, accessed online: 22.01.2019.
[10] Big Hit. HYSEAS III – the World’s First Hydrogen Powered Sea-Going Car Ferry – Destination Orkney. Available at: https://www.bighit.eu/news/2018/6/18/hyseas-iii-the-worlds-first-hydrogen-powered-sea-going-car-ferry-destination-orkney, accessed online: 22.01.2019.
[11] E. Holbrook. The First Commercial Fuel-Cell Ferry in the World Will Launch in 2019. Available at: https://www.energymanagertoday.com/the-first-commercial-fuel-cell-ferry-in-the-world-will-launch-in-2019-0177598/, accessed online: 22.01.2019.
[12] Energy Observer 2019. Energy Observer. Available at: http://www.energy-observer.org/en/, accessed online: 12.05.2019.
[13] L. Baetcke, M. Kaltschmitt. Chapter 5 - Hydrogen Storage for Mobile Application: Technologies and Their Assessment. in: C. Azzaro-Pantel, (Ed.). Hydrogen Supply Chains. Academic Press, 2018. pp. 167-206.
[14] S.S. Makridis. Hydrogen storage and compression. Vol 1 (2016) p. 28.
[15] Office of Energy Efficiency & Renewable Energy. Physical Hydrogen Storage. Available at: https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage, accessed online: 24.04.2019.
[16] V.C. Andersen (Sjøfartsdirektoratet), Personal Communication. 2019, VCH@sdir.no.
[17] R.K. Ahluwalia, J.K. Peng, T.Q. Hua. 5 - Cryo-compressed hydrogen storage. in: R.B. Gupta, A. Basile, T.N. Veziroğlu, (Eds.), Compendium of Hydrogen Energy. Woodhead Publishing, 2016. pp. 119-45.
[18] R. Moradi, K.M. Groth. Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. International Journal of Hydrogen Energy. Vol 44 (2019) pp. 12254-69.
[19] S. Kikukawa, H. Mitsuhashi, A. Miyake. Risk assessment for liquid hydrogen fueling stations. International Journal of Hydrogen Energy. Vol 34 (2009) pp. 1135-41.
[20] I. Air Products and Chemicals. Liquid hydrogen. Available at: https://www.airproducts.com/~/media/Files/PDF/company/safetygram-9.pdf, accessed online: 24.04.2019.
[21] H2 tools. Material Selection LH2. Available at: https://h2tools.org/bestpractices/material-selection-0, accessed online: 01.05.2019.

[22] H2 tools. Material Selection HP. Available at: https://h2tools.org/bestpractices/material-selection, accessed online: 01.05.2019.
[23] DNV-GL. Piping systems. Available at: https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2010-01/ts406.pdf, accessed online: 21.05.2019.
[24] H2 tools. Valves for Cryogenic Liquid Service. Available at: https://h2tools.org/bestpractices/valves-cryogenic-liquid-service, accessed online: 01.05.2019.
[25] H2 tools. Valves for Compressed Gas Service. Available at: https://h2tools.org/bestpractices/valves-compressed-gas-service, accessed online: 01.05.2019.
[26] H2 tools. Fitting and Joints LH2. Available at: https://h2tools.org/bestpractices/fittings-and-joints-0, accessed online: 01.05.2019.
[27] D. Dr Carter, M. Ryan, J. Wing. The Fuel Cell Industry Review 2012. (2012) pp. 40-1.
[28] FuelCellToday. PEMFC. Available at: http://www.fuelcelltoday.com/technologies/pemfc, accessed online: 24.04.2019.
[29] A.E. Gonnet, S. Robles, L. Moro. Performance study of a PEM fuel cell. International Journal of Hydrogen Energy. Vol 37 (2012) pp. 14757-60.
[30] Wikipedia: The free encyclopedia. Proton-exchange membrane fuel cell. Available at: https://en.wikipedia.org/wiki/Proton-exchange_membrane_fuel_cell, accessed online: 06.05.2019.
[31] A. Fesseler, T. Kistenfeger, J. Dr. Scholta. Low Temperature PEM vs. High Temperature PEM Fuel Cells. Available at: https://www.zsw-bw.de/fileadmin/user_upload/PDFs/Vorlesungen/est3/WS_2017/Seminar-Notes/LTPEM_vs_HTPEM.PDF, accessed online: 05.02.2019.
[32] Serenergy. HT PEM BASICS. Available at: https://serenergy.com/forside-test/technology/ht-pem-basics/, accessed online: 05.02.2019.
[33] Serenergy. HT PEM MODULES. Available at: https://serenergy.com/forside-test/technology/ht-pem-modules/, accessed online: 05.02.2019.
[34] V. La Rocca. Cold recovery during regasification of LNG part one: Cold utilization far from the regasification facility. Energy. Vol 35 (2010) pp. 2049-58.
[35] B. Holo (Teknotherm HVAC), Personal Communication. 2019, bjorn.holo@teknotherm.no.
[36] Ballard Power Systems. Fuel Cell Power Module for Heavy Duty Motive Applications. Available at: http://ballard.com/docs/default-source/motive-modules-documents/fcvelocity_hd_family_of_products_low_res.pdf, accessed online: 22.01.2019.
[37] G. Energy. How Does An Absorption Chiller Work? Available at: http://goldman.com.au/energy/company-news/how-does-an-absorption-chiller-work/,
[38] P. Evans. Absorption Chiller, How It Works. Available at: https://theengineeringmindset.com/absorption-chiller-works/,
[39] W. Salmi, J. Vanttola, M. Elg, M. Kuosa, R. Lahdelma. Using waste heat of ship as energy source for an absorption refrigeration system. Applied Thermal Engineering. Vol 115 (2017) pp. 501-16.
[40] H2 tools. Impact of Hydrogen Properties on Facility Design. Available at: https://h2tools.org/bestpractices/impact-hydrogen-properties-facility-design, accessed online: 27.04.2019.
[41] J.T. Ringland. Safety issues for hydrogen-powered vehicles. United States. 01.03.2019. Retrieved from https://www.osti.gov/servlets/purl/10136126, accessed online: 24.04.2019.
[42] Wikipedia: The free encyclopedia. Stoichiometry. Available at: https://en.wikipedia.org/wiki/Stoichiometry, accessed online: 22.01.2019.
[43] P. Bhattacharjee. Electrostatic discharge hazards and control measures. 2015 4th International Conference on Reliability, Infocom Technologies and Optimization (ICRITO) (Trends and Future Directions). Vol 1 (2015) pp. 1-3.
[44] Y. Hajji, M. Bouteraa, A.E.L. Cafsi, A. Belghith, P. Bournot, F. Kallel. Dispersion and behavior of hydrogen during a leak in a prismatic cavity. International Journal of Hydrogen Energy. Vol 39 (2014) pp. 6111-9.
[45] Forskrift om brannsikring på skip. I 2014 hefte 12. Nærings- og fiskeridepartementet.
[46] H2 tools. Ventilation. Available at: https://h2tools.org/bestpractices/ventilation, accessed online: 27.04.2019.

[47] International Maritime Organization (IMO). International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code). Available at: http://www.imo.org/en/OurWork/Safety/SafetyTopics/Pages/IGF-Code.aspx, accessed online: 30.04.2019.
[48] American Institute of Aeronautics and Astronautics. Guide to Safety of Hydrogen and Hydrogen Systems (ANSI/AIAA G-095A-2017). (2019).
[49] H2 tools. Lessons learned. Available at: https://h2tools.org/lessons, accessed online: 30.04.2019.
[50] National Technology and Engineering Solutions of Sandia, LLC. Hydrogen Risk Assessment Model (HyRAM). Available at: https://energy.sandia.gov/transportation-energy/hydrogen/quantitative-risk-assessment/hydrogen-risk-assessment-model-hyram/, accessed online: 30.04.2019.
[51] Wikipedia: The free encyclopedia. Norwegian Maritime Authority. Available at: https://en.wikipedia.org/wiki/Norwegian_Maritime_Authority, accessed online: 21.05.2019.
[52] Wikipedia: The free encyclopedia. Norwegian Directorate for Civil Protection. Available at: https://en.wikipedia.org/wiki/Norwegian_Directorate_for_Civil_Protection, accessed online: 21.05.2019.
[53] J.W. Pratt, L.E. Klebanoff. Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry. Sandia National Laboratories, United States of America. Report no. Unlimited release, 2016. Retrieved from https://energy.sandia.gov/transportation-energy/hydrogen/market-transformation/maritime-fuel-cells/sf-breeze/, accessed online: 21.05.2019.