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Testing of Vacuum Insulation Panels for Liquefied Hydrogen Storage Tanks

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For the future use of liquefied hydrogen (LH2) as a green energy carrier, new concepts for storage tanks and in particular their insulation are necessary. The methodology applied in current LH2 tanks has some disadvantages while manufacturing and operation of large tanks that may be required in the future. While liquefied natural gas tanks exist in the necessary capacities, they are incompatible with LH2 due to its significantly lower storage temperature. In this paper, the possibility of using vacuum insulation panels (VIPs) as an alternative to the conventional double walled, powder filled vacuum insulation is presented. The two systems are introduced and compared on a conceptual level with a focus on the loss of vacuum failure mode. Furthermore, a test rig that enables the testing and quantification of thermal properties of VIP based insulations in ordinary and loss of vacuum conditions is presented. The test rig is a boil-off calorimeter using liquefied nitrogen and features a square cold surface with a side length of 3 m. An overview over the planned testing and its goals is given.

* 1. Introduction

Hydrogen is envisioned as a future green energy carrier. For its large-scale transport and storage, liquefied hydrogen (LH2) at -253 °C could be suitable. Compared to other forms of hydrogen or hydrogen derivatives, LH2 is not toxic and offers a better supply chain efficiency. (IEA 2024) LH2 tanks could be built where needed, which makes them attractive for import and export, seasonal energy storage and industrial use. The aimed capacities for stationary and mobile LH2 tanks are in line with tanks for liquefied natural gas (LNG), which is also stored at cryogenic temperatures (-161 °C). Unlike LNG facilities that offer storage capacities of up to 200,000 m³ (IEA, 2022), Currently, the largest LH2 tanks are at the Kennedy Space Center in the USA (Fesmire, 2021) and on the HyTouch LH2 terminal in Kobe, Japan (Urabe, 2022), with a usable volume of 4700 m³ and 2250 m³ respectively.

Cryogenic storage tanks require excellent thermal insulation to avoid heating and evaporation of its payload. Below a temperature of -183 °C, it is considered critical that the insulation system does not contain air. The oxygen in air liquefies at this temperature, which poses a significant safety risk since its contact with flammable materials can lead to explosions (Peschka, 1992). At temperatures below -196 °C, the nitrogen in the air condenses, which can change the thermal conductivity in the insulation system and additional heat transfer from the latent heat of evaporation of the condensing nitrogen. which raises further questions to the static and transient properties of the thermal insulation. To avoid these issues, double walled tanks with vacuum and a filler material are typically used in LH2 storage tanks (Peschka, 1992). In contrast, large LNG-Tanks, which are standardized in e.g. EN 14620 or API 625 do not need vacuum in their insulation, due to their storage temperature and the lower performance requirements. Therefore, techniques and experiences gathered in the LNG industry cannot directly be transferred to large stationary or mobile LH2 tanks. (IEA, 2022)

The double-walled tank design found in current LH2 tanks offers poor failure resistance since a loss of vacuum significantly decreases insulation performance for the whole tank. This scenario is considered in the sizing of safety valves (according to relevant standards such as ISO 21013-3) which should prevent over pressurization of the tank. When applied to large-scale storage the large amount of LH2 evaporating still poses significant risks for the availability and reliability of critical infrastructure with financial and societal consequences.

This study contains an analysis of potential safety issues which was done in the framework of the NICOLHy project. NICOLHy researches a novel insulation concept based on Vacuum Insulation Panels (VIP) that enables the cost- and energy efficient storage of large quantities of LH2. The targeted tank sizes for the application of this technology are between 40.000 m³ and 200.000m³. Aside from a potential reduction in cost, this concept of using VIPs for LH2 storage tanks limits the insulation degradation in case of a loss of vacuum in single elements.

While this offers risk reduction, the new design concept also contains new safety concerns, which are presented in this study. The focus is on evaluating potential faults in the insulation system and developing the necessary test plan. The testing results can then be utilized as inputs for a larger scope failure mode effects analysis (FMEA).

* 1. Comparison of conventional approach to VIP-based insulation

In this section, the currently established technology for large-scale LH2 tanks is compared to the VIP based concept. Figure 1 offers an overview of the different concepts.



b)

a)

Figure 1: Comparison of conventional double-walled vacuum insulation (a) and the VIP approach (b)

* + 1. Double-walled vacuum insulation

Conventional LH2 tanks feature an inner wall that contains the LH2, which is typically constructed from austenitic steel which is suitable for low temperature applications. A second wall is built around this inner wall, often from carbon steel since this reduces fabrication costs (Krenn et al., 2016). The space between the inner and outer wall is filled with a porous powder (often expanded perlite or glass bubbles) and a vacuum is created. The vacuum minimizes convective and conductive heat transfer, while the powder reduces radiative heat transfer at the expense of adding a lesser amount of conductive heat transfer through the low thermal conductivity powder. Today the most common shape for LH2 tanks is spherical, which minimizes the surface to volume ratio and thereby minimizes heat leakage.

The inner wall must be designed to support the internal pressure from the LH2 against the vacuum in the insulation layer, while the outer wall has to withstand the atmospheric pressure against the vacuum.

Large tanks require extensive specialist work on site, as the outer wall needs to be constructed around the inner and requires vacuum tight welding and leak testing. The construction of the 4700 m³ LH2 tank was expected to take 2.5 years (Fesmire 2021). A single defect on the inner or outer wall can lead to the failure of the vacuum in the entire insulation system, which is essential for the tank. Lodhi and Mires (1989) describe an incident where air solidifying in the vacuum layer led to a thermal bridge between the outer wall and the inner tank, which caused overpressure in the tank and subsequent explosion. Based on an incident at Stennis Space Center, where a slow leakage of air into the vacuum insulation occurred, Krenn et al. (2016) describe the difficulties of removing solidified air from the vacuum insulation layer. In this incident, the leakage was detected but the operation of the tank continued with precautions, leading to large amounts of frozen air forming on the inner wall. After the hydrogen was drained from the tank, attempts to remove the frozen air by vacuum pumping failed. The dripping liquid air caused embrittlement and rupture of the outer wall.

* + 1. NICOLHy VIP concept

VIPs are constructed from a porous core material, which is surrounded by a gas-tight envelope. Inside the envelope, a vacuum is created, which creates an insulation with the same principle as in the previously described double-walled system. Since the envelope has a higher thermal conductivity than the core, consequently at the edge of a VIP a thermal bridge is created, which increases the effective thermal conductivity of the insulation system (Tenpierik and Cauberg, 2007). To reduce the effects of these thermal bridges, the use of multiple staggered layers of VIPs is proposed as well as varying the size of the VIPs.

The layers of VIPs surround an inner tank, which is proposed to be prismatic or cylindrical, depending on the application. Especially for large transport shipping-tanks, this is a more space efficient concept which enables to increse the overall payload than using spherical tanks. The increasing surface to volume ratio is acceptable, as it is significantly lower due to the scaling than in the dimensions of today's tanks.

This concept creates the possibility of building single walled tanks systems. The single wall contains the fluid and is insulated by VIPs, it only needs to provide support for the internal pressure against atmospheric pressure. Each VIP individually handles the pressure differential due to the vacuum by the combination of the core material and the gas-tight membrane. The core material needs to withstand the compressive stresses, which will be amplified through thermal contraction and expansion of the envelope when the insulation changes temperature with varying LH2 fill levels.

To prevent the condensation of air between the VIPs, the insulation layer is sealed from the enviroment with an outer wall. The space between the tank wall and the outer wall can then be flooded with a gas with a normal boiling point at or below the storage temperature of LH2 (Hydrogen or Helium), or CO2 which would sublime and form a frozen layer near the inner tank wall. To minimize air ingress, this gas could be kept at slightly higher pressure than the surrounding atmospheric pressure from a pressurized source. While this still requires a degree of gas- tightness of the outer wall, an adequate leakage rate for this system is much easier to achieve than for a vacuum insulation system.

Manufacturing of the VIPs can be performed in a factory enviroment, which offers good opportunities for automatization, parallelization and quality assurance. The finished VIPs can be transported to the construction site and assembled to form the insulation system.

* + 1. Comparison

Both concepts utilize the same mechanism to limit heat transfer, which relies on a vacuum to reduce convective heat transfer. While the vacuum in conventional double-walled tanks spans across the whole tank, it is separated into individual compartments by the VIPs, offering redundancy. If a VIP fails, the tanks thermal insulation performance slightly decreases, but there is no total loss of the payload and the tank can continue to be operated.

The ability to manufacture all gas-tight connections for the VIPs in a factory could significantly speed up the manufacturing process compared to the conventional double-walled vacuum insulations, where several welding procedures are carried out on site.

While the double-walled evacuated powder system is state of the art and deals with known design methods, the VIP approach requires the development of new methods to calculate the thermal performance.

* 1. Testing

VIPs are established technology for building thermal insulation systems and vaccine transport, but the transferability of data and experience gathered in this context to the application on LH2 tanks is limited. VIPs used in the building industry typically use a metallized polymeric foil as gas-tight envelope (Tenpierik and Cauberg, 2007). Due to durability and low temperature compatibility requirements, stainless steel foil will be used for NICOLHy VIPs, which has a significantly higher thermal conductivity, which will amplify the influence of thermal bridges. Double layer configurations of VIPs have been investigated by Grynning et al. (2010), as well as Ghazi Wakili et al. (2010) for applications in buildings. In NICOLHy more than 2 layers will be regarded and the performance will be tested in relation to cryogenic conditions. For comparing the thermal performance of insulation materials, the effective thermal conductivity $k\_{e}$ calculated by Eq(1) is typically used.

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| $$k\_{e}=\frac{\dot{Q}t}{AΔT}.$$ |  | (1) |

Here, $A$ is the surface area covered by the insulation, $ΔT$is the temperature differencebetween the warm and cold side of the insulation, $t$ is the insulation thickness and $\dot{Q}$ is the heat flow through the insulation. This is based on Fourier’s law for an anisotropic material and is a severe simplification of the actual mechanisms of heat transfer found in insulation systems. More specifically, the heat transferred $\dot{Q}$ can be calculated regarding theradiative $\dot{Q}\_{rad}$, conductive $\dot{Q}\_{cond}$, and convective $\dot{Q}\_{conv}$ components of heat transfer by Eq(2).

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| $$ \dot{Q}=\dot{Q}\_{rad}+\dot{Q}\_{cond}+\dot{Q}\_{conv},$$ |  | (2) |

Between two parallel and aligned surfaces of area $A$ and with the emissivity coefficients $ϵ\_{1}$ and $ϵ\_{2}$, and regarding the Stefan-Boltzmann-constant $σ$ the heat transfer by radiation can be calculated by Eq(3).

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| $$ \dot{Q}\_{rad}=\frac{A}{\frac{1}{ϵ\_{1}}+\frac{1}{ϵ\_{2}}-1} σ(T\_{1}^{4}-T\_{2}^{4})$$ |  | (3) |

Conductive heat transfer depends on the thermal conductivity of the material, which is a function of its temperature. For the 304 stainless steel proposed for the envelope it is with 15 W/(m K) at 20°C approximately 7-times higher than the 2.2 W/(m K) at -253°C (Ekin, 2006). Convective heat transfer is a complex phenomenon, that depends on the exact geometry, type and pressure of ambient gas, boundary temperatures and more.

* + 1. Boil-off calorimeter

Due to the strong dependence of heat transfer on temperatures and geometry described above, values of $k\_{e}$ can only be applied during the design of an insulation system if they were measured in relevant conditions. This in combination with the differences between the NICOLHy VIP system and those currently used in the building industry that were pointed out earlier, lead to the development of a specialized test rig.

To measure the heat flow $\dot{Q}$, boil-off calorimetry was chosen. This is a technique, where the cold side condition is created with a cryogenic fluid stored in a test tank at ambient pressure. Any heat transferred into the test tank leads to a portion of the fluid vaporizing (boil-off). The mass flow rate $\dot{m}$ of the boil-off is measured and the heat flow into the test tank can be calculated by Eq(4), using the specific latent heat of vaporization and the specific volume in gaseous $ν\_{g}$ and liquid $ν\_{l}$ state for the cryogenic fluid.

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| $ \dot{Q}=\dot{m}Δh\_{vap}\left(\frac{ν\_{g}}{ν\_{g}-ν\_{l}}\right)$. |  | (4) |

Except for one surface, the test tank is surrounded by a guard tank, which contains the same cryogenic fluid as the test tank. The insulation system to be tested is installed on the test surface. Since the guard tank and test tank are held at the same temperature, there are no heat flows in between them, thereby ensuring that the heat flow calculated from the test tanks boil-off represents the heat flow through the insulation. This makes the apparatus an absolute boil-off calorimeter according to ASTM C 1774. A schematic of the test rig is shown in Figure 2.

Figure 2: Schematic representation of the test rig design

Liquefied Nitrogen (LN2) is used as the cryogenic fluid, which is stored at -196 °C. While this is significantly warmer than LH2, testing with LN2 provides several advantages: Its high volumetric latent heat of vaporization of 160.6 J/ml reduces the necessary storage volume for the same testing time, compared to LH2 with 31.54 J/ml (Ekin, 2006). Since nitrogen is an inert gas, it also requires less safety precautions, and it can also be obtained at lower cost.

To ensure that the LN2 in the guard tank does not evaporate too quickly, it requires good thermal insulation. This is provided by a perlite filled vacuum insulation layer, as is state of the art for cryogenic tanks. Since the tanks contract during cooldown, a flexible membrane between the test surface and the outer wall is used. Copper tubes attached to the test surface ensure a good thermal conduction between the LN2 and test surface across a wide range of fill levels. To create a controlled temperature on the warm side of the tested insulation, a heat exchanger can be mounted on the top of the insulation which is supported by a pump with water from a large reservoir.

The test rig has a square test surface with a side length of 1.5 m, and the guard tank extends the cold surface to a square of 1.9 m. The test and guard tank have a usable capacity of approximately 0.35 m³ and 0.45 m³ respectively. This is a larger scale than previous test rigs (e.g. Kamiya, 2000), which is dictated by the need to test at relevant conditions for very large cryogenic tanks. For safety, the maximum allowable overpressure in the tank is set at 0.5 bar. This is ensured with safety valves on the test tank, where the flow of boil-off needs to be constrained through a small tube for the mass flow meter. The guard tank features an open vent to the atmosphere. The boil-off lines and components of both tanks were designed to provide appropriate capacity for the expected mass flow in a complete loss of insulation with redundant lines outside of the test rig.

* + 1. Proposed tests

First and foremost, the test rig allows the measurement of thermal performance of an insulation system. Testing will be performed with a variety of VIP configurations to gain an understanding of the influence of parameters such as: Number of layers, size of panels, core material, envelope thickness, on the effective thermal conductivity $k\_{e}$. In addition to the measurement of $k\_{e}$, temperature probes at strategically placed points in or between the VIPs can provide insight into the thermal behavior of the system.

Thermal performance tests will consist of 4 phases:

First the insulation system is installed on the test surface, alongside any necessary measuring equipment within the insulation layers, and the heat exchanger. Then the test rig is cooled and filled, during this phase an estimated 0.3 m³ of LN2 will be evaporated to cool down the test rig, in addition to the 0.8 m³ necessary to fill the tanks. In the third phase, the system is left to cool the insulation system until steady state is reached. This process may take multiple days. As the steady state is approached, the measurement of the mass flow rate from the test tank is started to determine the thermal conductivity of the insulation.

The results can then be used to validate numerical or analytical models for the thermal performance of VIP based insulation systems, which will be a crucial tool to extrapolate the test results to a large scale LH2 tank. The effect of different ambient gases around the VIPs on thermal conductivity can be tested only partially due to the use of LN2, which is not sufficiently cold to test the influence of air condensation. However, the influence of a layer of frozen gas in the insulation system can be tested by sealing the VIP stack from the environment and flooding the space with CO2 gas.

Aside from the thermal performance, the mechanical and thermo-mechanical behavior of the VIPs is an important point of research as it determines the lifespan of the insulation system. Single panels can be tested for their stress-strain relationship by introducing them to mechanical or thermal loads. For this, 3-point bending tests and exposure to cryogenic temperatures will be performed and the deformation measured. The behavior of the VIP core material under thermal and thermo-mechanical stress will be tested with a test setup described in Eberwein et al. (2024).

Gaining an understanding of the strains that will be seen by VIPs inside an insulation system may be more difficult. With varying fill levels of a LH2 tank, the temperature at the tank wall changes, which induces thermal strain within the tank wall and the insulation system. These are combined with purely mechanical strain from gravitation and mounting systems, which will likely result in a complex behavior. Measuring the deformation of the VIPs within an insulation system on the test rig will provide a first insight into the strains that they need to be designed for.

Additionally, testing will include conditions that arise from failures or accidents. To prove the enhanced redundancy of the VIP system compared to the conventional double walled vacuum insulation, the effect of a loss of vacuum in a single or multiple VIPs on thermal performance can be tested by opening the envelope to the atmosphere. To simulate an air leak, the freezing of CO2 may be performed as a transient test, where first the sealed insulation system starts with nitrogen as an ambient gas and is cooled to steady state conditions. Then CO2 can be introduced with a defined flow rate and the effects on temperature distribution and heat flow are measured.

* 1. Conclusions

A new approach to thermally insulate LH2 tanks based on VIPs was introduced and compared to the currently used double-walled design, with a focus on the loss of vacuum failure mode. In this aspect the VIP concept offers redundancy, while a loss of vacuum in the state-of-the-art system causes degradation of the whole insulation system. Additionally, tanks with the VIP system may be manufactured faster with a higher degree of automation.

As the performance of the VIP system is yet unknown, a test rig that will allow the measurement of the systems effective thermal conductivity $k\_{e}$ was designed. This test rig is an absolute boil-off calorimeter with a square cooled surface with a side length of 1.9 m which is cooled with LN2.

This test rig will be used to characterize the thermal performance of VIP based and other insulations in cryogenic conditions by measuring $k\_{e} $for different configurations and conditions. Further testing will include the measurement of temperatures throughout the insulation layers which can be used to validate numerical and analytical models necessary to design a VIP based insulation system.

For testing the redundancy of the system, teste with damaged or leaking VIPs can be done and $k\_{e}$ measurements performed. Here one or multiple failures can be regarded. The influence of an air leak into the normally purged space between the VIPs can also be tested with CO2 gas, which will freeze between them.

Nomenclature

$\dot{Q}$ – heat flow, W

$\dot{Q}\_{rad}$ – heat flow by radiation, W

$\dot{Q}\_{cond}$ – heat flow by conduction, W

$\dot{Q}\_{conv}$ – heat flow by convection, W

$A$ – surface area, m

$\dot{m}$ – mass flow rate, kg/s

$ΔT$ – Temperature difference, K

$T$ –Temperature, K

$Δh\_{vap}$ – latent heat of vaporization, J/kg

$ν\_{g}$– specific volume of gas, m³/kg

$ν\_{l}$– specific volume of gas, m³/kg

$σ$ – Stefan-Boltzmann constant, W/(m²·K4)

$ϵ$ – emmisivity, -

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