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Hydrogen Re-liquefaction Process for Boil-off Gas Handling on a Large-scale Liquid Hydrogen Carrier

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ABSTRACT

With the recent focus on hydrogen, seaborne shipping is considered an option for the large-scale transport of liquid hydrogen (LH_2). For efficient shipping, boil-off gas (BOG) from the cargo tanks needs to be optimally utilized. This work suggests a BOG handling system (BHS) producing fuel for an LH_2 carrier and liquefying excess BOG in a hydrogen Claude cycle. The process offers a simple configuration that does not require a refrigerant makeup facility. The simulation results of the BHS also show relatively low specific power consumption (5.7 to 2.6 kWh/kgLH_2) with a good utilisation of cold energy in BOG. The sensitivity analysis with the BOG to fuel (BtF) ratio shows that a higher BtF gives a simpler configuration and a smaller size liquefier, saving capital costs. However, the optimal capacity of the BHS needs to be determined based on the techno-economic performance of the entire system of the LH_2 carrier.

Keywords: Hydrogen, Liquefaction, Liquid hydrogen carrier, Transport, Boil-off gas, Claude cycle

1. INTRODUCTION

Hydrogen is considered one of the key energy carriers to replace fossil fuels in order to decarbonize our society (Berstad et al., 2022). Thus, the demand is expected to grow rapidly to meet the zero-emission target by 2050 (IEA, 2022). However, one of the major challenges for the transition to a hydrogen economy is the lack of H_2 infrastructure. In particular, ship transport of liquid hydrogen (LH_2) is an important option for long distances and at scale due to the higher energy density per volume than in a compressed gas phase. Hence, developing LH_2 carriers will make hydrogen transport economically feasible for mass transport, targeting energy-importing countries (IEA, 2019). Part of the liquid hydrogen in the storage tank on a ship will evaporate during a voyage due to heat ingress, reducing the valuable cargo delivered. To make long-haul LH_2 shipping efficient, it is essential to utilize the boil-off gas (BOG) from the cargo tank in an optimal way. On LH_2 carriers, part of the BOG can be used as fuel for the propulsion system while any excess can be re-liquefied to recover the valuable cargo.

There have so far been few studies on the BOG handling system (BHS) for LH_2 carriers. Lee et al. (2019) introduced a BHS with a helium reverse Brayton cycle. The helium-based refrigeration, however, will give a refrigerant makeup issue onboard the LH_2 carriers, which is challenging in a maritime environment. In addition, this work considers a hybrid propulsion system utilizing both LNG and BOG as fuels, increasing the carbon intensity of the hydrogen for end-use. The helium gas expander process is also studied for LH_2 carriers using BOG as fuel for ship operation via fuel cells (Choi et al., 2021). Considering changes in the propulsion power during a voyage, Choi et al. (2021) also estimated the impact of different BOG-to-fuel ratios (BtF) on the performance of the BHS. It is however worth noting that the refrigeration system shows a high level of process complexity even without BOG compression, resulting in high capital costs and potential operational issues.

This work suggests a BHS for a BOG-fuelled LH_2 carrier, aiming for a simple process configuration with high energy efficiency. The BHS uses the hydrogen Claude cycle such that the BOG can be used to make up the

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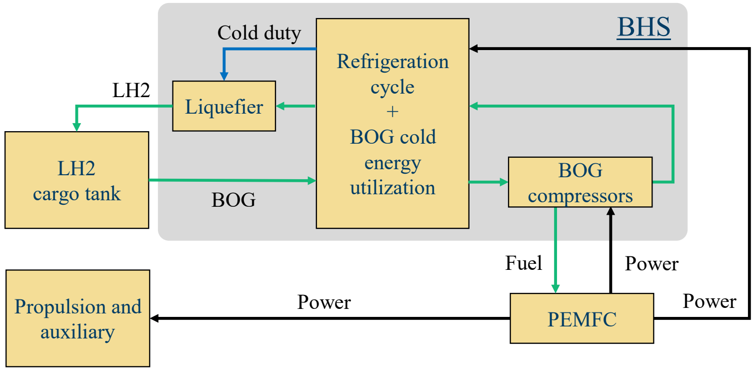

Figure 1: Overall system block diagram of an LH2 carrier with a BOG handling system (BHS).

refrigerant on the vessel. For process intensification of the BHS, different approaches to utilizing the cold BOG from the tank are discussed while considering the compression of the BOG. The characteristics of the BOG handling process are also analysed, assuming the fuel demand can vary with tank insulation, tank size, and ship sailing profiles applied to the LH_2 carrier. For a comparative evaluation, mathematical optimization is conducted to minimize the power consumption at different BtF ratios throughout this work.

2. Boil-off gas handling systems on LH_2 carriers

A large-scale LH_2 carrier is assumed to be operated by proton exchange membrane fuel cells (PEMFC) (Yum et al., 2022) in this study. BOG from the cargo tank is used as fuel for the PEMFC while the excess amount of hydrogen gas is fully reliquefied via a refrigeration cycle as presented in Fig. 1. This study focuses on the BOG handling system where the fuel gas is compressed, and hydrogen is re-liquefied with electricity inputs from the PEMFC. Details on the fuel cell system are not discussed. Since the development of LH_2 carriers is in an early stage, there are several uncertainties such as the tank insulation design, the sailing profile of the vessel, and the efficiency of the PEMFC. These factors have significant impacts on the BOG balance on the vessel and the performance of the BHS. Therefore, this work considers a wide range of the BOG-to-fuel ratio in order to represent the operating conditions the BHS may encounter.

Fig. 2 presents the BHS suggested, which uses the H_2 Claude cycle with feed gas (BOG) compression. BOG from the cargo tank is first divided into two streams via Tee-1 to optimally distribute the cold energy between the precooling of the refrigerant (H_2) and the precooling of the compressed BOG. This stream splitter will give operational flexibility to the system, maintaining a high energy performance at a wide range of BtF ratios. After delivering the cold energy, the two BOG streams are merged and compressed to produce low-pressure fuel. If there is an excess amount of the BOG, it is further pressurized and precooled before being sent to the liquefaction system. The high-pressure precooled BOG is then liquefied through the heat exchangers (MHE-3 and 4) and throttled to meet the storage pressure. The flash gas generated during the throttling is recycled and mixed with the BOG from the cargo tank while the liquid hydrogen is delivered to the cargo tank.

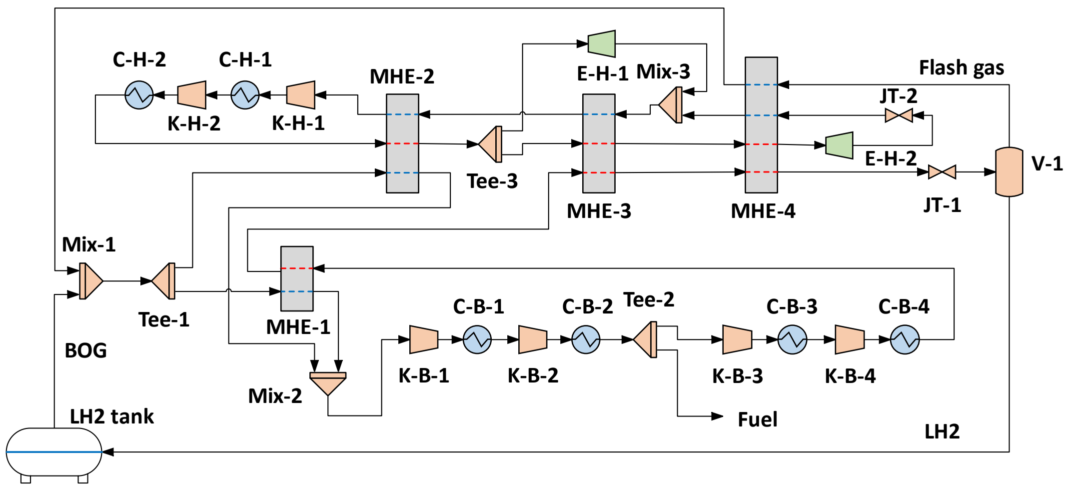

Figure 2: Process flow diagram of a BOG handling system (BHS) for LH2 carriers using the H_2 Claude cycle.

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In the liquefier, hydrogen refrigerant is compressed via a multi-stage hydrogen compressor and precooled by BOG from the cargo tank. A part of the cold refrigerant is sent to the first gas expander (E-H-1) to supply the cold duty of the intermediate temperature region. The rest of the refrigerant is further cooled and depressurized via E-H-2 and JT-2 to produce a low-temperature refrigerant that can liquefy the high pressure gas before the final throttling. The outlet pressure level of the two gas expanders is set to be identical to simplify the process. It is worth noting that each gas expander can be a series of two expander stages if the enthalpy change is large (≫ 140 kJ/kg). The first gas expander (E-H-1) and the Joule-Thomson valve (JT-2) in this system can be skipped depending on the BtF ratio, which will reduce the process complexity and capital costs of the BHS.

3. Design basis and optimization

Aiming for large-scale transport, the size of the LH_2 carrier is assumed to be in the same range as current LNG carriers at around 170 000 m^3. The cargo is stored as a saturated liquid at 1.1 bara with 0.2 vol%/d of boil-off rate (BOR), generating 23 t/d of BOG. Since the design of the insulation for a large-scale LH_2 tank is still under development, a conservative value of the BOR is selected considering existing LH_2 containment systems (<0.2 vol%/d) (Fesmire, 2017, KHI, 2016) and modern LNG carriers (0.1 vol%/d) (IGU, 2022). In this work, the boil-off gas (BOG) is regarded as pure para-hydrogen due to the marginal fraction of ortho-hydrogen in the liquid cargo. The BOG temperatures at the tank top and the inlet of the BHS are set to be 30 K and 35 K higher than the LH_2 storage temperature due to heat ingress. The BHS is designed to produce LH_2 under the same conditions as the liquid cargo. Other simulation assumptions are presented in Tab. 1.

The boil-off gas handling system is simulated in Aspen HYSYS with different BtF ratios and optimized to minimize the specific power consumption (SPC) by using the sequential quadratic programming (SQP) algorithms via Matlab. All the decision variables such as the BOG boost pressure level, the refrigerant pressure levels, the heat exchanger outlet temperatures, and the split ratios of the stream splitters are varied during the optimization. As introduced in Tab. 1, the maximum pressure ratio of hydrogen compressors and minimum temperature differences of cryogenic multi-stream heat exchangers are constrained.

Table 1. Simulation assumptions applied to the BOG handling system.

PEMFC		BOG temperature at BHS	-217.6 °C
PEMFC efficiency	50 %	BOG pressure at BHS	1.1 bara
Fuel type	H_2	Reliquefied LH_2 temperature	-252.6 °C
Fuel temperature	20 °C	Reliquefied LH_2 pressure	1.1 bara
Fuel pressure	5 bara	Rotating machinery	
LH_2 and BOG		Compressor stage isentropic efficiency	80 %
LH_2 tank volume	162 000 m^3	Compressor stage pressure ratio	max. 3
LH_2 tank utility rate	90 %	Gas expander isentropic efficiency	80 %
LH_2 storage temperature	-252.6 °C	Heat exchanger	
LH_2 storage pressure	1.1 bara	Pinch ΔT above -162 °C	3 °C
Boil-off rate (BOR)	0.2 vol%/d	Pinch ΔT below -162 °C (gas/gas)	1 °C
BOG composition	para H_2	Pinch ΔT below -162 °C (liquid/gas)	0.2 °C
BOG temperature at tank top	-222.6 °C	Cooling water temperature	35 °C
BOG pressure at tank top	1.1 bara	Water cooler outlet temperature	45 °C
BOG flow rate	22.5 t/d	Relative pressure drops	2% of inlet

4. Results

The optimization results in Fig. 3 (left) indicate that the total power consumption of the BHS is reduced with the BOG-to-fuel (BtF) ratio. In particular, the liquefaction part dominates the total power consumption while the fuel compression part remains minor. Although the power demand for fuel compression is increased with the BtF ratio, a decrease in the liquefier duty with the reduced amount of BOG to be liquefied leads to a net decrease in the total power usage of the BHS. The lower level of power consumption in the BHS will be favourable to minimizing the fuel consumption and the operating cost of the LH_2 carrier.

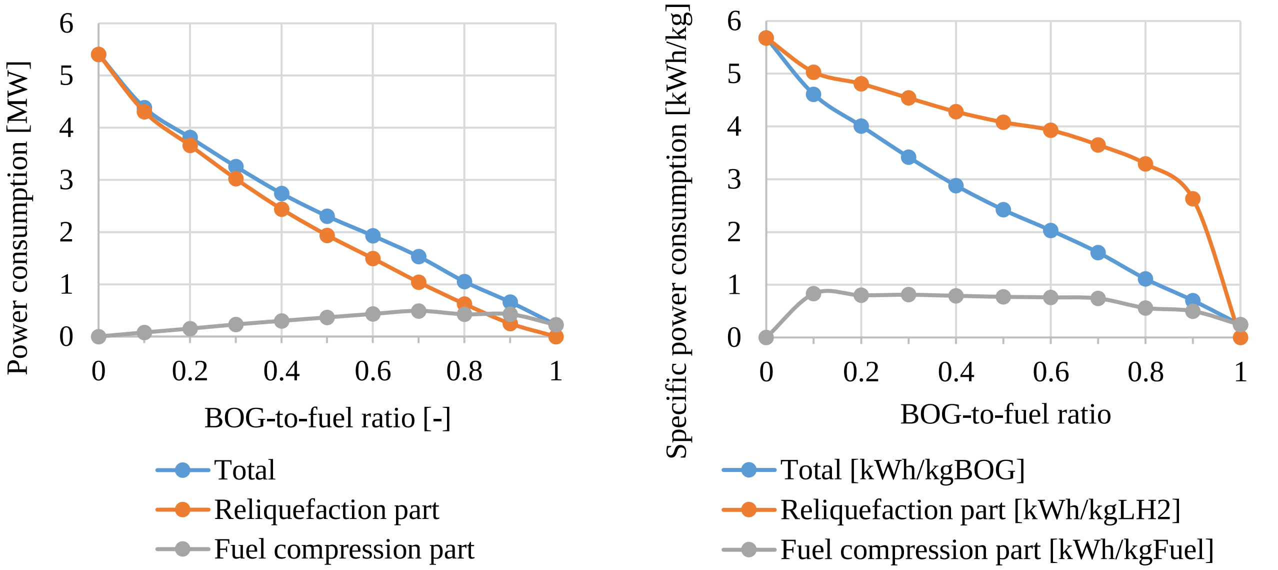

Figure 3: Power consumption (left) and specific power consumption (right) of the BOG handling system (BHS) for LH2 carriers.

Fig. 3 (right) also presents that the liquefier has a considerably higher specific power demand than the fuel compression process where a multi-stage compressor is simply applied. Hence, the specific power consumption of the BHS is primarily influenced by the liquefaction process. The SPC of the reliquefaction unit is gradually decreased with a higher BOG-to-fuel ratio since a smaller amount of BOG needs to be liquefied while the same amount of BOG cold energy is available. The utilization of the BOG cold energy allows the liquefier to achieve an SPC ranging from 5.7 to 2.6 kWh/kgLH$_2$, which is lower than previously reported values with helium refrigeration (Choi et al., 2021).

As presented in Fig. 4 (left), a large fraction of BOG from the cargo tank is initially routed to the liquefaction unit to deliver the cold energy for the precooling of the refrigerant. If less amount of BOG is liquefied (higher BtF ratio), the fraction of the BOG cold energy utilized to precool the compressed BOG is increased. However, the majority of the BOG cold energy (>50 %) is still used for refrigerant precooling in the entire range of the BtF ratio to minimize total energy consumption of the BHS. The utilization of the BOG cold energy also influences the process configuration. Fig. 4 (right) indicates that the refrigerant is not delivered to the first gas expander (E-H-1) when the BtF ratio is over 0.4, thus simplifying the process configuration. When a small amount of BOG is sent to the liquefier to be reliquefied (high BtF ratios), the cooling of the feed gas provided by the BOG cold energy is large enough, making the first gas expander have a marginal role in the refrigeration cycle.

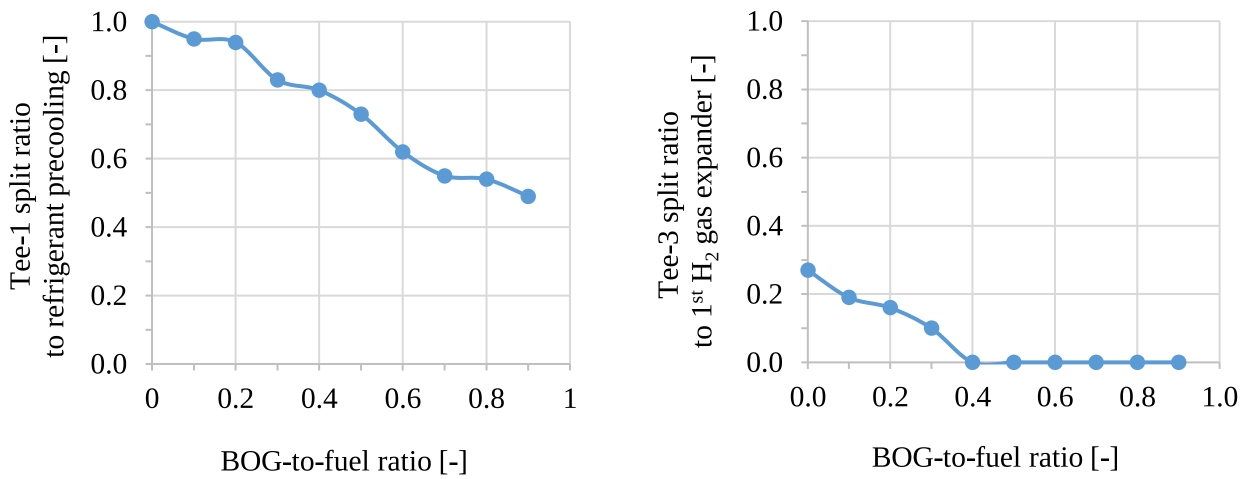

Figure 4: Split ratio of the splitter for BOG cold energy distribution (left) and the 1st refrigerant gas expander (right).

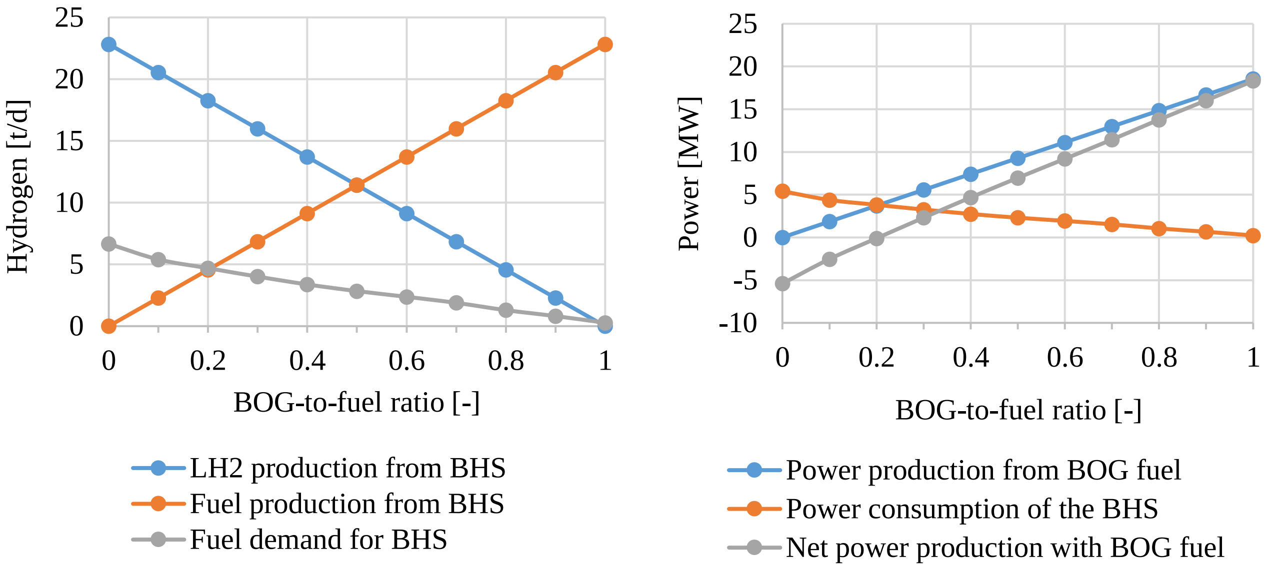

Figure 5: Hydrogen (left) and power balance (right) on an LH2 carrier.

It is also encouraged to use a relatively high BtF ratio when considering the hydrogen and power balance of the vessel. Fig. 5 (left) presents that the BOG fuel is not sufficient to meet the power demand of the BHS if the BtF ratio is below 0.2. Thus, the additional liquid cargo needs to be evaporated to meet the fuel demand for the operation of the BHS. However, using the LH_2 cargo as fuel while reliquefying the BOG is thermodynamically inefficient. Therefore, BOG from the storage tank needs to be prioritized for fuel, and only the excess amount is required to be liquefied.

The LH_2 carrier even demands a BtF ratio higher than 0.2 in order to generate the propulsion power as seen in Fig. 5 (right). The maximum propulsion power produced with the entire BOG from the cargo tank is around 18 MW at the BtF ratio of 1. If the vessel requires constantly high propulsion power, installation of the liquefaction unit will not be a cost-effective solution to handle the BOG as most of the gas will be consumed as fuel. This also implies that the BOR of the tank can be targeted to produce BOG that is sufficient to meet the power requirement of an LH_2 carrier, which will minimize the excess amount of BOG. Such hydrogen balancing will help avoiding an overdesigned containment system and a large-size liquefier on the vessel, resulting in a lower cost of LH_2 shipping. For the targeted size of the vessel in this work, the maximum capacity of the liquefaction unit reaches 23 t/d, which is almost the same capacity as the largest current onshore hydrogen liquefaction facilities (Ghafri et al., 2022). Thus, a high BtF ratio will be favourable for an LH_2 carrier, allowing the deployment of a compact liquefaction unit onboard.

Although the small capacity of the liquefier at a high BtF ratio gives potential savings in capital costs, the amount of the reliquefied hydrogen and the cargo delivered are reduced, which will result in a significant economic loss at a high LH_2 price. A high BtF ratio also means the ship will sail at a high speed where the energy efficiency of the vessel will be low, utilizing the valuable BOG in a less efficient way. Thus, a cost-effective size of the liquefaction unit needs to be selected considering the vessel design and the hydrogen market price (Yum et al., 2022).

5. CONCLUSIONS

This work suggests a boil-off gas handling system (BHS) for a large-scale LH_2 carrier to produce fuel gas and reliquefy the excess amount of BOG. The liquefaction process based on the hydrogen Claude cycle shows a reasonable specific power demand obtainable with a simple process configuration. The use of hydrogen as a refrigerant also enables the BHS to conduct refrigerant makeup by BOG. Thus, the liquefier will be suitable to be deployed on LH_2 carriers where the space is limited, and a separate make-up refrigerant can be challenging. The sensitivity analysis with the BtF ratio presents that the process complexity and the size of the liquefier can be minimized at a high BtF ratio. However, even though a high BtF ratio means a smaller reliquefaction capacity, it is causing a reduction in the cargo delivered. Thus, a techno-economic analysis of the BHS system considering the design and the economic performance of the LH_2 carrier is required to identify the economic viability and the optimal capacity of the liquefaction unit.

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NOMENCLATURE

BHS	Boil-off gas handling system	BOG	Boil-off gas
BtF	Boil-off gas to fuel	d	Day
LH_2	Liquid hydrogen	LNG	Liquefied natural gas
PEMFC	Proton exchange membrane fuel cell	SPC	Specific power consumption
SQP	Sequential quadratic programming	vol	Volume
t	Ton		

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