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## A hydrogen fuelled LH2 tanker ship design

Abdullah NFNR Alkhaledi, Suresh Sampath and Pericles Pilidis

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### ABSTRACT

This study provides a detailed philosophical view and evaluation of a viable design for a large liquid hydrogen tanker fuelled by liquid hydrogen. Established methods for determining tank sizing, ship stability, and ship characteristics were used to evaluate the preliminary design and performance of the liquefied hydrogen tanker named 'JAMILA', designed specifically to transport liquid hydrogen. JAMILA is designed around four large liquid hydrogen tanks with a total capacity of  $\sim 280,000 \text{ m}^3$  and uses the boil-off gas for propulsion for the loaded leg of the journey. The ship is 370 m long, 75 m wide, and draws 10.012 m at full load. It has a fully loaded displacement tonnage of 232,000 tonnes to carry 20,000 tonnes of hydrogen. Its propulsion system contains a combined-cycle gas turbine of approximately 50 MW. The volume of the hydrogen cargo pressurised to 0.5 MPa primarily determines the size and displacement of the ship.

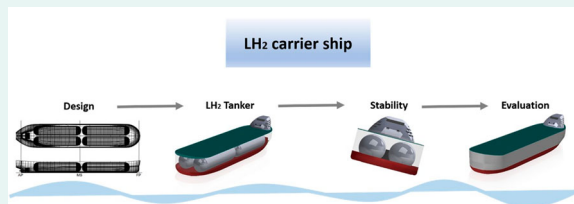
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Liquefied hydrogen; LH<sub>2</sub> tanker; ship design; liquid hydrogen tank



### Nomenclature

| Symbol                     | Meaning                                                                  | Symbol                               | Meaning                                               |
|----------------------------|--------------------------------------------------------------------------|--------------------------------------|-------------------------------------------------------|
| $B$                        | Extreme ship breadth                                                     | $LOA$                                | Length overall                                        |
| $B_v$                      | Volumetric thermal expansion coefficient                                 | $LW$                                 | Length of waterline                                   |
| $BM_{T,L}$                 | Transverse, longitudinal metacentric radius of the ship                  | $LWT$                                | Lightweight                                           |
| $C_B$                      | Block coefficient                                                        | $M_{\text{boil off}}$                | Mass of hydrogen boil off                             |
| $C_m$                      | Midship section area coefficient                                         | $M_{\text{insulation}}$              | Mass tank of insulation                               |
| $C_p$                      | Prismatic coefficient                                                    | $M_{LH_2}$                           | Mass of liquefied hydrogen                            |
| $C_{wp}$                   | Waterplane area coefficient                                              | $M_{\text{liner}}$                   | Mass of tank liner                                    |
| $D$                        | Ship depth                                                               | $\sum_{\text{moment}}$               | Total moment about the keel                           |
| $DWT$                      | Deadweight                                                               | $M_t$                                | Mass of the hydrogen tank before being isolated       |
| $FOS$                      | Factor of safety                                                         | $M_{\text{total LH}_2 \text{ tank}}$ | Total mass of the hydrogen tank after being isolated  |
| $G$                        | Gravitational acceleration                                               | $MTc^1$                              | Moment required to change trim by 1 cm                |
| $GM$                       | Metacentric height                                                       | $N_{UD}$                             | Nusselt number                                        |
| $GM_{T,L}$                 | Transverse, longitudinal metacentric height                              | $P_{LH_2}$                           | Pressure inside the tank                              |
| $GZ$                       | Righting arm                                                             | $PR$                                 | Prandtl number                                        |
| $H$                        | Convection coefficient for air surrounding the tank                      | $Q_{\text{convection}}$              | Heat convection                                       |
| $h_{fg}$                   | Latent heat of vaporisation of liquid hydrogen                           | $Q_{\text{in to the tank}}$          | Tank heat input                                       |
| $I_T$                      | Transverse moment of inertia                                             | $Q_{\text{out of the tank}}$         | Tank heat output                                      |
| $K$                        | Insulation thermal conductivity                                          | $Q_{\text{radiation}}$               | Heat radiation                                        |
| $K_g$                      | Air thermal conductivity                                                 | $r$                                  | Internal tank radius                                  |
| $KB$                       | Vertical centre of buoyancy                                              | $R_{ad}$                             | Rayleigh number                                       |
| $KG$                       | Vertical centre of gravity                                               | $R_1$                                | Inner insulation radius                               |
| $KM_{T,L}$                 | Transverse, longitudinal height of the metacentre above the keel line    | $R_2$                                | Outer insulation radius                               |
| $L$                        | Tank cylinder section length                                             | $T_{in}$                             | Temperature inside the tank                           |
| $L_{\text{total}}, L_{et}$ | Tank total hemisphere and cylinder sections internal and external length | $T$                                  | Ship draft                                            |
| $LBP$                      | Length between forward and aft perpendicular                             | $t_{\text{insulation}}$              | Insulation thickness                                  |
| $LCB$                      | Longitudinal centre of gravity                                           | $T_{LH_2}$                           | Internal tank temperature                             |
| $LCF$                      | Longitudinal centre of floating                                          | $T_{\text{surface}}$                 | Insulation surface temperature                        |
| $LH_2$                     | Liquefied hydrogen                                                       | $t_w$                                | Wall thickness for the cylindrical tank               |
| $LHV$                      | Lower heating value                                                      | $T_{\infty}$                         | Temperature transitions from the external temperature |
| $LNG$                      | Liquefied natural gas                                                    | $TPc$                                | Tonnes per centimetre immersion                       |
|                            |                                                                          | $V_i$                                | Excess volume                                         |
|                            |                                                                          | $V_t$                                | Total tank volume                                     |
|                            |                                                                          | $VCG$                                | Vertical centre of gravity                            |
|                            |                                                                          | $\Delta_{\text{total}}$              | Ship total displacement                               |
|                            |                                                                          | $\epsilon$                           | Emissivity of the insulation surface                  |

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|                       |                                             |
|-----------------------|---------------------------------------------|
| $\rho_{\text{insu}}$  | Density of the rigid open-cell polyurethane |
| $\rho_{\text{LH}_2}$  | LH <sub>2</sub> density                     |
| $\rho_{\text{liner}}$ | Aluminium alloy liner (Al-Mg 5086) density  |
| $\rho_t$              | Aluminium density (4.4% Cu)                 |
| $\sigma$              | Stefan–Boltzmann constant                   |
| $\sigma_y$            | Yield strength of aluminium (4.4% Cu)       |

## 1. Introduction

Intensive global efforts are currently focused on decarbonisation to achieve the EU 2050 net-zero emissions target (European Commission 2019). The utilisation of hydrogen has a high potential to be a viable option for decarbonisation in different sectors such as transportation, energy, manufacturing, and the residential and commercial sectors (Körner et al. 2015). There is enormous interest in the generation and utilisation of hydrogen future technologies; for instance, the EU has specified that half the essential energy demand is fulfilled by hydrogen, i.e. 3100–6000 TWh/year of hydrogen, is assessed to be required by 2050 (European Commission 2019; van Wijk and Wouters 2019). Additionally, in 2025, the commissioning of the largest green hydrogen project by Neom is expected to save globally 3 million tons of CO<sub>2</sub> emissions each year by creating 650 tons of hydrogen each day, and henceforth, utilising an environmentally friendly power to achieve a sustainable hydrogen economy (Scita et al. 2020).

In this regard, the key issues that necessitate examination are hydrogen storage, transportation, and safety to enable the usability of hydrogen on a global scale. The use of hydrogen as an energy fuel is considered particularly useful in the context of electricity generation involving a significant mismatch between supply and demand. Besides, creating hydrogen from sustainable resources will be a remarkable alternative, wherein it will be possible to store power in the hydrogen structure of the resource from which it shall originate and revert it to utilisation when required. The employment of clean energy sources such as wind, solar, and nuclear energy to the seawater electrolysis process for hydrogen production indicates that coastal countries between the tropics appear promising sources of green hydrogen production. This will require the transportation of this green hydrogen to other places of high demand. As mentioned, the Neom project will generate approximately 5,20,000 tons of liquefied hydrogen per day. This large quantity of liquefied hydrogen is expected to be exported to other countries via seaborne using liquefied hydrogen carrier ships, requiring an expected back and forth journey of 20 days. In terms of weight, liquefied hydrogen is approximately 800 times denser than gaseous hydrogen at atmospheric pressure (Escher and Ohta 1979; Scita et al. 2020). In this case, there is a need to construct more than 500 large-scale liquefied hydrogen carrier ships, each with an approximate capacity of 20,000 tons of liquefied hydrogen, within a decade, to operate this promising project. Therefore, there is a need to design large liquefied hydrogen tanker ships to support global hydrogen projects in the future.

There are limited previous studies with a similar background that can be found in the literature. In 1998, a group of Japanese companies published a preliminary study on large-scale transportation of liquid hydrogen, including a preliminary conceptual design of a liquid hydrogen tanker with a prismatic and spherical four-tank system having a total capacity of 200,000 m<sup>3</sup> and total cargo weight of 14,000 tons of liquefied hydrogen (Abe et al. 1998). Also, a design of an LNG carrier ship with different wedged tanks was introduced (Zhang 2015).

There is considerable potential for carbon-free hydrogen production using solar energy in regions with a marine coast which benefit from extensive sunshine, for example, North Africa and the Arabian Gulf. This will raise the demand to transport hydrogen

**Table 1.** LNG ship parameters and dimensions (Noble 2009; Pratt et al. 2009).

| LNG ship model parameters | Specification and values | Units          |
|---------------------------|--------------------------|----------------|
| Model name and ship name  | Q-max ship (MOZAH)       | –              |
| Vessel type               | LNG Tanker               | –              |
| Summer deadweight (DWT)   | 130,102                  | t              |
| Length overall (LOA)      | 345                      | m              |
| Beam                      | 53.8                     | m              |
| Depth                     | 27                       | m              |
| Loaded draft              | 12                       | m              |
| Ship speed                | 19.5                     | knots          |
| LNG carrying capacity     | 266,000                  | m <sup>3</sup> |
| Year of construction      | 2008                     | –              |

**Table 2.** Physical properties of hydrogen (Colozza and Kohout 2002; Bourne 2012).

| Property                                 | Hydrogen | Unit                                 |
|------------------------------------------|----------|--------------------------------------|
| Density (gaseous)                        | 0.089    | kg/m <sup>3</sup> (@ 0 °C, 1 bar)    |
| Density (liquid)                         | 70.79    | kg/m <sup>3</sup> (@ –253 °C, 1 bar) |
| Boiling point                            | –253     | °C (@ 1 bar)                         |
| Energy per unit of mass (LHV)            | 120.1    | MJ/kg                                |
| Energy density (ambient conditions, LHV) | 0.01     | MJ/L                                 |
| Specific energy (liquefied, LHV)         | 8.4      | MJ/L                                 |
| Flame velocity                           | 346      | cm/s                                 |
| Ignition range                           | 4–77     | % in air by volume                   |
| Autoignition temperature                 | 585      | °C                                   |
| Ignition energy                          | 0.02     | MJ                                   |

Note: LHV = lower heating value.

from the production sites to the consumption sites. However, other consumption centres will have a significant demand for hydrogen trade. In this regard, an effective method to transport hydrogen will be by the sea. Until recently, the integrated study of liquified hydrogen tanker ship design and stability analysis have not been considered. This leads to the following question: what would a hydrogen tanker look like?

The objective of this study is to provide a preliminary answer to this design question. Using state-of-the-art design and analysis methods, the authors offer a practical view of the design of such a ship. This study does not include economic and costs analyses which will be carried out in a future study using the TERA assessment method specifically for different marine applications, which was introduced for comparable studies (Tsoudis 2008; Nalianda 2012; Talluri et al. 2016).

## 2. Overall design philosophy and major specifications

The philosophical starting point for this evaluation was an existing LNG tanker design, also known as the Mozah (RINA 2007; Noble

**Table 3.** Primary LH<sub>2</sub> tank design parameters.

| LH <sub>2</sub> tank input parameters                                            | Parameter value | units             |
|----------------------------------------------------------------------------------|-----------------|-------------------|
| Mass of LH <sub>2</sub> ( $M_{\text{LH}_2}$ )                                    | 5,000           | t                 |
| Pressure inside the tank ( $P_{\text{LH}_2}$ )                                   | 0.5             | MPa               |
| Temperature inside the tank ( $T_{\text{in}}$ )                                  | 20              | k                 |
| LH <sub>2</sub> density ( $\rho_{\text{LH}_2}$ )                                 | 71              | kg/m <sup>3</sup> |
| Excess volume ( $V_i$ )                                                          | 0.252           | %                 |
| Tank cylinder section length ( $L$ )                                             | 111.6           | m                 |
| Total internal length of hemisphere and cylinder sections ( $L_{\text{total}}$ ) | 138             | m                 |
| Total external length of hemisphere and cylinder sections ( $L_{\text{et}}$ )    | 141.36          | m                 |
| Yield strength of aluminium (4.4% Cu) ( $\sigma_y$ )                             | 410             | MPa               |
| Design factor of safety (FOS)                                                    | 54              | –                 |
| Aluminium density (4.4% Cu) ( $\rho_t$ )                                         | 2,800           | kg/m <sup>3</sup> |

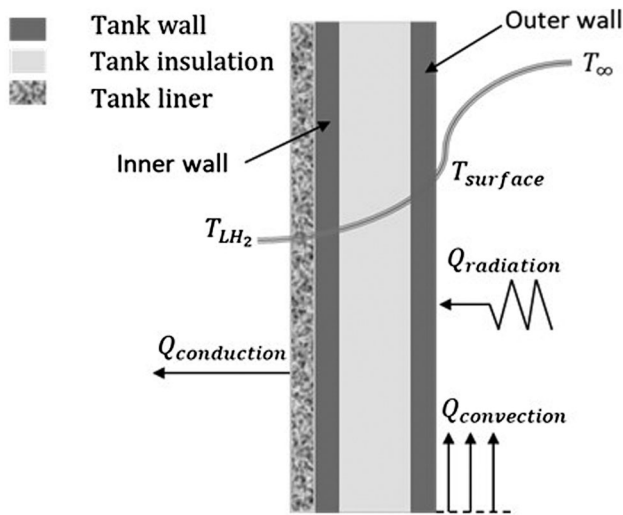


Figure 1. Heat transfer for liquefied hydrogen tank layers.

2009; Pratt et al. 2009). Table 1 shows the characteristics of this ship. Liquefied hydrogen properties are shown in Table 2. Liquefied hydrogen can be obtained by cooling hydrogen to  $-253\text{ }^{\circ}\text{C}$ ; this will give it a density of  $70.79\text{ kg/m}^3$ , much higher than  $0.089\text{ kg/m}^3$  at  $0\text{ }^{\circ}\text{C}$  also higher than  $38\text{ kg/m}^3$  when stored at 70 MPa. (Colozza and Kohout 2002). So, the use of liquid hydrogen requires a much smaller volume and storage at a much lower pressure. Therefore, to reduce the physical size of the ship the authors opted to design the ship to carry liquid hydrogen because the volume and pressure requirements are much smaller than those associated with the compressed hydrogen gas. This choice promises a smaller ship and a much lighter tank. There are several reasons for selecting four tanks, such as maintaining the ship balance during the journey, preparing piping factors and positions, and preserving the stability in the event of damage. The large amount of liquefied hydrogen will produce 20 tonnes of hydrogen boil-off per day during the journey, considering 1.68 m as the thickness of the insulation tanks. The main engine of the ship will be supplied with liquefied hydrogen cargo boil-off in the same way as in the LNG ships. The boil-off amount will save 29% of the liquefied hydrogen fuel consumption of the ship in the fully loaded condition, where the total fuel consumption of the ship is 68.9 tonnes per day of hydrogen, and the power generation is assumed to be 50 MW using a combined gas and steam turbine propulsion system, based on the designed power of an LNG

tanker ship. The tank is designed to fit inside the hull, which contains four tanks of liquefied hydrogen. The large volume of liquefied hydrogen when compared with that of LNG results in a ship of very large dimensions with respect to the weight of the cargo it carries. Furthermore, the light weight of the cargo results in a design with an unusually shallow draft for the size of the ship. The ship's propulsion and steering are delivered by two podded azimuthal systems. Finally, the ship stability and hydrostatic values were calculated and validated by using the IMO Intact Stability Code (ISC) (IMO 2008).

### 3. Design of LH<sub>2</sub> cargo tanks

The primary purpose of the ship is to carry hydrogen, a very light but voluminous cargo. Its properties are listed in Table 2. A preliminary analysis indicated that a ship with approximately the similar size as that of the Mozah (see Table 1) could carry about 20000 tonnes of hydrogen if it is stored in four cylindrical tanks with two hemispherical ends. Although using four tanks is a suitable choice, it is not the only solution. The IMO Intact IGC Code for Hydrogen (IMO 2016) was used as a guideline. Table 3 shows the main characteristics of the tanks, which were determined considering preliminary mechanical sizing, thermal considerations, and liner application.

#### 3.1. Mechanical sizing

The mechanical design of the tank wall is critical to address the liquefied hydrogen pressure load. It is assumed that the insulation and liner do not offer any construction strength. The tank volume is calculated, including the additional volume needed for boil off, resulting in a bigger and heavier tank than would be required for other fuel types. The volume of a LH<sub>2</sub> tank to store the required mass of hydrogen is calculated using the following equation (Colozza and Kohout 2002; Goldberg 2017):

$$V_t = \frac{M_{LH_2}}{\rho_{LH_2}} (1 + V_i). \quad (1)$$

Mechanically, in order to achieve the total volume requirements of liquefied hydrogen, the tank design should consider the inner radius ( $r$ ) in the case of a cylindrical tank with hemispherical end caps. The tank volume ( $V_t$ ) is a function of the length of the cylinder section ( $L$ ) and inner radius of the tank ( $r$ ), which can be

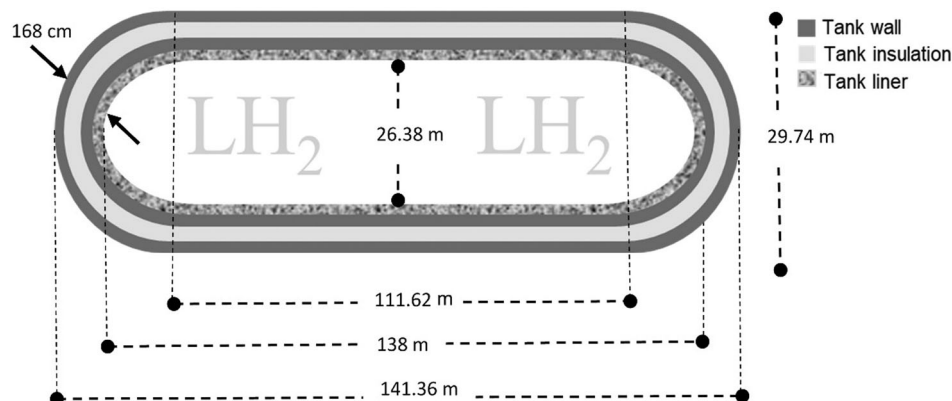


Figure 2. Cross-section of LH<sub>2</sub> tank design (not to scale). The 168-cm-thick wall includes 100 cm of rigid open-cell polyurethane foam insulation, 43.4 cm of aluminium, and 24.6 cm of aluminium alloy liner (Al-Mg 5086).

Table 4. Output results of the liquefied hydrogen tank design model.

| LH <sub>2</sub> tank output parameters                                         | Parameter value | units          |
|--------------------------------------------------------------------------------|-----------------|----------------|
| Required volume of LH <sub>2</sub> tank ( <i>V<sub>t</sub></i> )               | 70,600          | m <sup>3</sup> |
| Tank inner radius ( <i>r</i> )                                                 | 13.19           | m              |
| Tank wall thickness ( <i>t<sub>w</sub></i> )                                   | 0.434           | m              |
| Tank weight with wall only ( <i>M<sub>t</sub></i> )                            | 14,226          | t              |
| Boil-off rate                                                                  | 0.1             | %              |
| Inner insulation radius ( <i>R<sub>1</sub></i> )                               | 13.624          | m              |
| Outer insulation radius ( <i>R<sub>2</sub></i> )                               | 14.624          | m              |
| Mass of insulation polyurethane foam ( <i>M<sub>insulation</sub></i> )         | 14.5            | t              |
| Mass of tank liner ( <i>M<sub>liner</sub></i> )                                | 7,715           | t              |
| Total weight of the LH <sub>2</sub> tank ( <i>M<sub>total LH2 tank</sub></i> ) | 21,955          | t              |

determined by utilising the following equation:

$$V_t = \frac{4\pi r^3}{3} + \pi r^2 L.$$

(2)

The authors considered that the liquefied hydrogen pressure is 0.5 MPa at the temperature of −252.76 °C to carry the hydrogen in the liquid form (Benner et al. 2004; Petrucci et al. 2007; Bottini 2008). The wall thickness (*t<sub>w</sub>*) for a cylindrical tank with

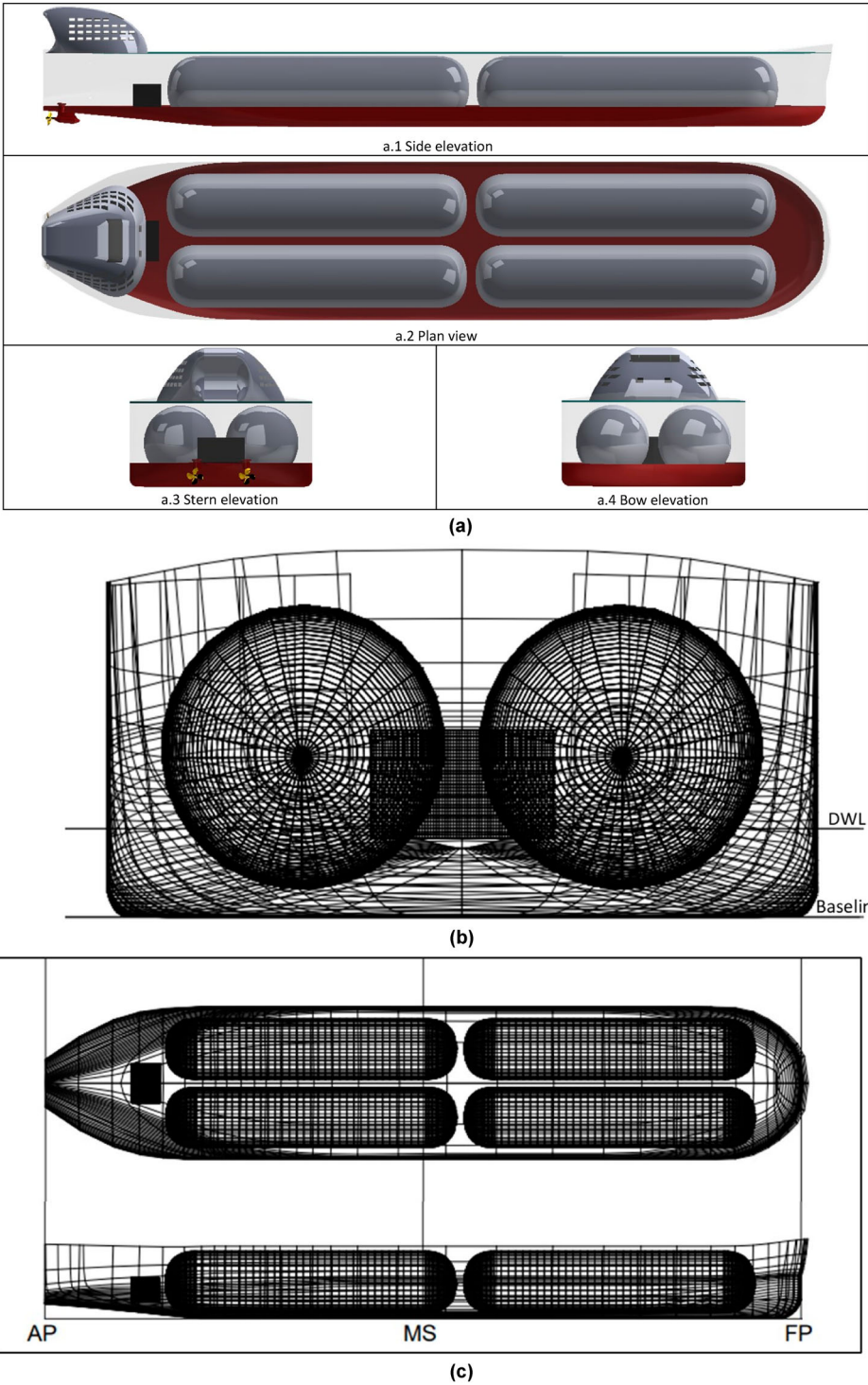


Figure 3. (a) JAMILA LH<sub>2</sub> tanker ship (3D model); (b) perspective and water line; (c) profile ship aft and forward perpendicular

**Table 5.** Main parameters and dimensions of the ship.

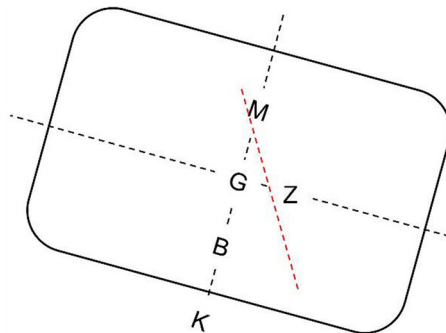
| LH <sub>2</sub> tanker parameters                                                                   | Values                 | Units          |
|-----------------------------------------------------------------------------------------------------|------------------------|----------------|
| Class                                                                                               | JAMILA                 | –              |
| Vessel type                                                                                         | LH <sub>2</sub> Tanker | –              |
| Total displacement ( $\Delta_{total}$ )                                                             | 230,000                | tonnes         |
| Lightweight (LWT)                                                                                   | 208,000                | tonnes         |
| DWT                                                                                                 | 22,000                 | tonnes         |
| LOA                                                                                                 | 370                    | m              |
| Length between perpendicular (LBP)                                                                  | 367.5                  | m              |
| Length on water line (LW)                                                                           | 367.9                  | m              |
| Extreme breadth (B)                                                                                 | 75                     | m              |
| Depth (D)                                                                                           | 35                     | m              |
| Draft (T) (full load condition)                                                                     | 10.012                 | m              |
| Draft (T) (unload condition)                                                                        | 9.263                  | m              |
| Block coefficient ( $C_B$ ) (full-load condition)                                                   | 0.819                  | –              |
| Block coefficient ( $C_B$ ) (unloaded condition)                                                    | 0.813                  | –              |
| Ship speed                                                                                          | 18                     | knots          |
| LH <sub>2</sub> cargo tank weight (Aluminium)                                                       | 87,819                 | tonnes         |
|                                                                                                     | (21,955 × 4)           |                |
| LH <sub>2</sub> cargo tank capacity                                                                 | 282,400                | m <sup>3</sup> |
|                                                                                                     | (70,600 × 4)           |                |
| LH <sub>2</sub> cargo weight                                                                        | 20,000                 | tonnes         |
|                                                                                                     | (5,000 × 4)            |                |
| LH <sub>2</sub> engine fuel tank weight (Aluminium)                                                 | 4,370                  | tonnes         |
| LH <sub>2</sub> engine fuel tank capacity                                                           | 14,099                 | m <sup>3</sup> |
| LH <sub>2</sub> engine fuel weight (20-day return journey + 2-day ship idle period + 100 t reserve) | 1,277.6                | tonnes         |
| Rate of boil-off from cargo                                                                         | 0.1 (20 t/day)         | % per day      |
| Fuel saving percentage due to boil-off                                                              | 29%                    | %              |
| Voyage range                                                                                        | 450–4,400              | Nautical mile  |
| Minimum propulsion power required for fully loaded condition                                        | 27.3                   | MW             |
| Combined cycle gas & steam installed                                                                | 50                     | MW             |

hemispherical end caps can be determined as follows:

$$t_w = \frac{rP_{LH_2}}{2\sigma_y} FOS. \quad (3)$$

The outer wall thickness relies upon the yield strength of the wall material and the design factor for safety (FOS), which is very significant to increase the tank safety, decrease the boil off, and increase the tank weight to ensure the stability of the ship when carrying a large amount of liquefied hydrogen. Finally, the weight of the tank ( $M_t$ ) depends on the tank material, which, in this study, is aluminium (4.4% Cu). The weight can be calculated as follows:

$$M_t = \rho_t \left[ \frac{4\pi(r+t_w)^3}{3} + \pi(r+t_w)^2 L - V_t \right]. \quad (4)$$



### 3.2. Thermal sizing

In this study, the insulation is chosen such that the LH<sub>2</sub> need not be refrigerated during the journey. This significantly increases the size of the tank but obviates the need for expensive and complex refrigeration equipment on board; thus, the trade-off is considered acceptable. An iterative approach is implemented, and the insulation thickness of the polyurethane foam is initially assumed to be 1 m. This would limit boil-off to 0.1% of the total LH<sub>2</sub> quantity for each tank on board to keep the liquefied hydrogen inside the tank at a constant pressure during the journey. The authors assumed no air in the polyurethane rigid closed-cell insulation foam due to the aluminium (4.4% Cu) wall thickness, which was calculated as 0.434 m to protect the polyurethane rigid closed-cell foam from the air; this thickness was distributed across two walls. The outer wall is made of aluminium (4.4% Cu) with 0.217 m thickness, and the inner wall has the same material and thickness as shown in Figure 1. The pressure in the tank containing the liquid hydrogen cargo will not increase owing to the boil-off of hydrogen because the boiled-off hydrogen will be extracted directly from the cargo tanks and supplied to the power plant of the ship as fuel. However, the design pressure of the tank is greater than the highest tank pressure during the voyage owing to the high insulation wall thickness of the tank; the design pressure of the tank is related to the value of the safety factor, which is high in this study. It is expected that a standby venting system will be needed on board for the occasions when the loaded ship is waiting in a harbour. Figure 1 shows the heat transfer processes and temperature variation through the insulation layers of the liquefied hydrogen tank. The figure shows the temperature transitions from the external ambient temperature  $T_\infty$  to the insulation surface temperature  $T_{surface}$ , and finally the internal tank temperature of liquefied hydrogen  $T_{LH_2}$ . The iterative process involves the calculation of the boil-off and the mass of insulation. The iteration starts with an estimation of the aforementioned insulation thickness. The insulation surface temperature ( $T_{surface}$ ) depends on the heat flow into the insulation layer via convection and radiation along with the heat flow into the tank by conduction through the insulation wall (Colozza and Kohout 2002); this value is assumed to be within the range of 258 K i.e. the base temperature to 318 K i.e. the most extreme temperature, to support the ship's voyage in various environments. Then, it is confirmed that equal amounts of heat flows into and out of the liquefied hydrogen inside the tank through the tank insulation. Finally, the authors determine whether the boil-off meets the required targets (Colozza and Kohout 2002; Goldberg

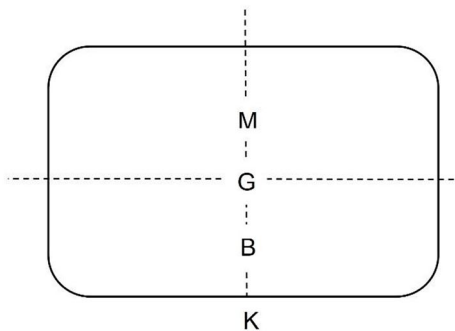


**Figure 4.** Righting arm (GZ) with the vessel heel due to external force.

**Table 6.** Centres of gravity under the unloaded condition

| Component                                         | Mass (t) | VCG (m) | $I_T$ (m.t)  |
|---------------------------------------------------|----------|---------|--------------|
| LH <sub>2</sub> cargo tanks                       | 87,819   | 16.350  | 1,435,840.65 |
| LH <sub>2</sub> fuel tank                         | 4,370    | 30      | 131,100      |
| Engine and stern gear                             | 8,000    | 10      | 80,000       |
| Hull structure                                    | 51,334   | 17.5    | 898,345      |
| Deck gear, anchor, cables, pipes, crew            | 5,000    | 37.5    | 187,500      |
| Accommodation                                     | 2,200    | 42.5    | 93,500       |
| LH <sub>2</sub> tanks accessories and equipment's | 52,000   | 10.25   | 533,000      |
| Fuel                                              | 1,277.6  | 30      | 38,328       |
| Low-pressure hydrogen                             | 1,000    | 16.350  | 16,350       |
| $\sum^m$ oment about the keel                     |          |         | 3,413,963.65 |
| Unloaded KG = 16.028 m                            |          |         |              |

et al. 2017), as follows:

$$Q_{in} = Q_{convection} + Q_{radiation}, \quad (5)$$

$$Q_{out} = Q_{conduction}, \quad (6)$$

where  $Q_{in}$  is the amount of heat flow to the tank insulation; this amount is a result of the incorporation of convection  $Q_{convection}$  and radiation  $Q_{radiation}$  heat flows.  $Q_{out}$  is the heat flowing out of the insulation layer to the liquefied hydrogen inside the tank, which represents the value of the conduction  $Q_{conduction}$  heat flow. Each element of the heat transfer is calculated as follows:

$$Q_{conduction} = \frac{K(T_{surface} - T_{LH_2})}{L}, \quad (7)$$

where  $K$  is the insulation thermal conductivity, which depends on the insulation material, and  $T_{LH_2}$  is the internal tank temperature.

$$Q_{convection} = h(T_{\infty} - T_{surface}), \quad (8)$$

where  $h$  is the convection coefficient of the air surrounding the tank, and  $T_{\infty}$  is the value of the temperature transition from the surroundings.

$$Q_{radiation} = \varepsilon \sigma (T_{\infty}^4 - T_{surface}^4), \quad (9)$$

where  $\sigma$  is the Stefan–Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ), and  $\varepsilon$  is the emissivity of the insulation surface. The following equation is used to calculate the convection coefficient:

$$h = \frac{N_{UD} K_g}{D}, \quad (10)$$

where  $N_{UD}$  is the Nusselt number, whose value depends on the geometry of the tank;  $K_g$  is the thermal conductivity of air; and  $D$  is the diameter of the tank. The next step is to calculate the Nusselt numbers for spherical and cylindrical shapes and add the obtained values to

**Table 7.** Centres of gravity under the loaded condition

| Component                                      | Mass (t) | VCG (m) | $I_T$ (m.t)  |
|------------------------------------------------|----------|---------|--------------|
| LH <sub>2</sub> cargo tanks                    | 87,819   | 16.350  | 1,435,840.65 |
| LH <sub>2</sub> fuel tank                      | 4,370    | 30      | 131,100      |
| Engine and stern gear                          | 8,000    | 10      | 80,000       |
| Hull structure                                 | 51,334   | 17.5    | 898,345      |
| Deck gear, anchor, cables, pipes, crew         | 5,000    | 37.5    | 187,500      |
| Accommodation and crew                         | 2,200    | 42.5    | 93,500       |
| LH <sub>2</sub> tank accessories and equipment | 52,000   | 10.25   | 533,000      |
| Fuel                                           | 1,277.6  | 30      | 38,328       |
| Hydrogen cargo                                 | 20,000   | 16.350  | 327,000      |
| $\sum^m$ oment about the keel                  |          |         | 3,724,613.65 |
| Loaded KG = 16.054 m                           |          |         |              |

determine the correct Nusselt number for the LH<sub>2</sub> tank design:

$$N_{UD, cylinder} = \left( \frac{0.60 + 0.387 R_{ad}^{\frac{1}{4}}}{\left[ 1 + \left( \frac{0.559}{PR} \right)^{\frac{9}{16}} \right]^{\frac{1}{4}}} \right)^2 \text{ and } N_{UD, sphere} = \frac{2 + 0.589 R_{ad}^{\frac{1}{4}}}{\left[ 1 + \left( \frac{0.469}{PR} \right)^{\frac{9}{16}} \right]^{\frac{1}{4}}}, \quad (11)$$

where  $PR$  is the Prandtl number, and  $R_{ad}$  is the Rayleigh number. These can be calculated using the following equations:

$$PR = \frac{\alpha}{\nu}, \quad (12)$$

$$R_{ad} = \frac{B_v(T_{\infty} - T_{surface})D^3}{\nu \alpha}, \quad (13)$$

where  $B_v$  is the volumetric thermal expansion coefficient, and  $\nu$  and  $\alpha$

**Table 8.** Hydrostatic results under different drafts.

|                                            | 9.263<br>(Unloaded) | 10.012<br>(Loaded) | Unit           |
|--------------------------------------------|---------------------|--------------------|----------------|
| Draft Amidships m                          |                     |                    |                |
| Displacement                               | 213,000             | 232,000            | tonnes         |
| Draft at FP                                | 9.263               | 10.012             | m              |
| Draft at AP                                | 9.263               | 10.012             | m              |
| WL Length                                  | 367.869             | 367.979            | m              |
| Beam maximum extents on WL                 | 75.000              | 75.000             | m              |
| Wetted Area                                | 28,916.458          | 29,550.906         | m <sup>2</sup> |
| Waterplane Area                            | 24,676.961          | 24,836.773         | m <sup>2</sup> |
| Prismatic coefficient ( $C_p$ )            | 0.818               | 0.824              | –              |
| Block coefficient ( $C_b$ )                | 0.813               | 0.819              | –              |
| Midship section area coefficient ( $C_m$ ) | 0.994               | 0.995              | –              |
| Waterplane area coefficient ( $C_{wp}$ )   | 0.894               | 0.900              | –              |
| LCB from zero pt. (+ve fwd)                | 201.807             | 201.002            | m              |
| LCF from zero pt. (+ve fwd)                | 192.414             | 191.578            | m              |
| KB                                         | 4.840               | 5.233              | m              |
| KG                                         | 16.028              | 16.054             | m              |
| $BM_L$                                     | 50.358              | 46.606             | m              |
| $BM_L$                                     | 1,113.397           | 1,040.893          | m              |
| $GM_L$                                     | 39.171              | 35.785             | m              |
| $GM_L$                                     | 1,102.209           | 1,030.072          | m              |
| $KM_L$                                     | 55.199              | 51.839             | m              |
| $KM_L$                                     | 1,118.237           | 1,046.126          | m              |
| Immersion ( $TP_c$ )                       | 252.939             | 254.577            | tonne/cm       |
| $MT_c$                                     | 6,381.661           | 6,495.982          | tonne.m        |
| RM at 1 deg                                | 145,611.654         | 144,893.560        | tonne.m        |

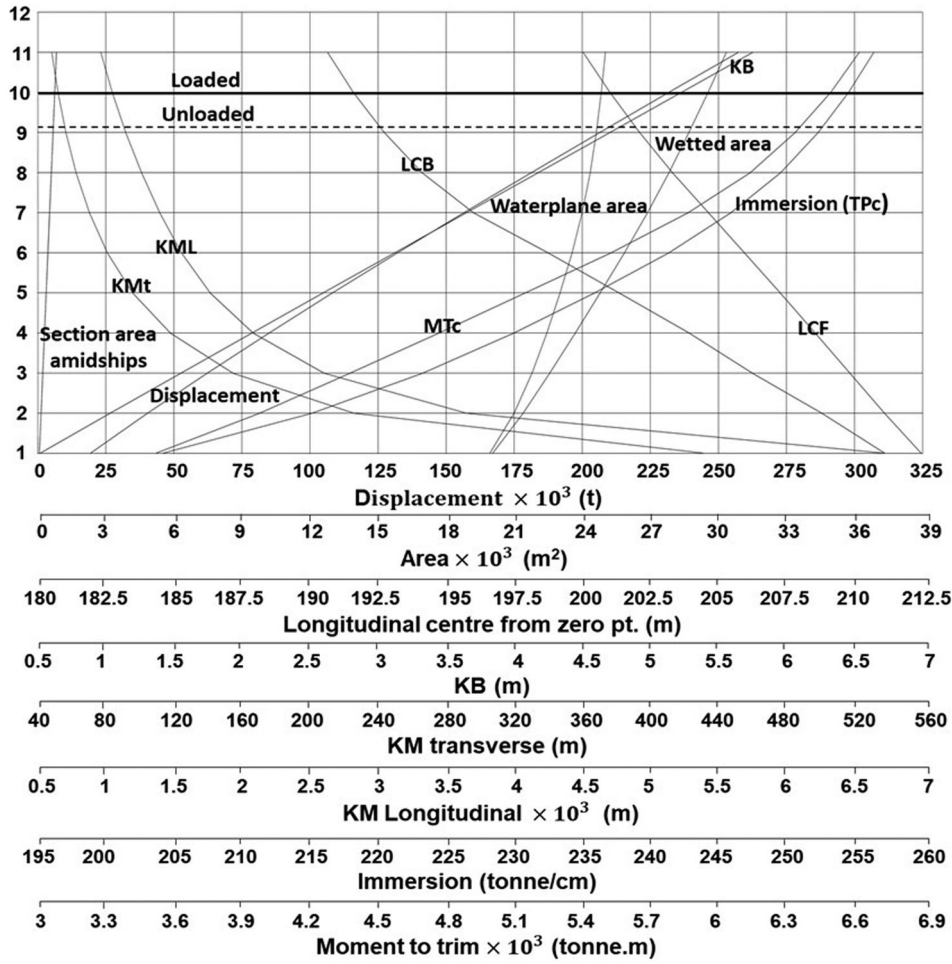


Figure 5. Ship hydrostatic diagram: characteristics vs draft (m).

can be calculated using the following equations:

$$\alpha = -3.119 \times 10^{-6} + 3.541 \times 10^{-8} T_{\infty} + 1.679 \times 10^{-10} T_{\infty}^2, \quad (14)$$

$$\nu = -2.079 \times 10^{-6} + 2.777 \times 10^{-8} T_{\infty} + 1.077 \times 10^{-10} T_{\infty}^2, \quad (15)$$

$$B_v = \frac{1}{T_{\infty}}. \quad (16)$$

The next step is to calculate the boil-off rate,  $M_{boil\ off}$  ( $\text{kg s}^{-1}$ ) of the liquid hydrogen using the following equation (where  $h_{fg}$  is the latent heat of vaporisation of liquid hydrogen):

$$M_{boil\ off} = \frac{Q_{conduction}}{h_{fg}}. \quad (17)$$

The following equations are used to calculate the inner insulation radius ( $R_1$ ), outer insulation radius ( $R_2$ ), and the insulation thickness ( $t_{insulation}$ ) required for the tank:

$$R_1 = r + t_w, \quad (18)$$

$$R_2 = R_1 + t_{insulation}, \quad (19)$$

where  $t_{insulation}$  is assumed to be 1 m following a scale up from Goldberg et al. 2017.

Finally, the mass of insulation foam can be calculated using the following equation, where the density of the rigid open-cell

polyurethane is  $32.1 \text{ kg/m}^3$ :

$$M_{insulation} = \rho_{insulation} \left[ \frac{4\pi(R_2^3 - R_1^3)}{3} + \pi(R_2^2 - R_1^2)L \right]. \quad (20)$$

The results of the thermal sizing calculations show that the insulation layer thickness and weight of the polyurethane foam are 1 m and 14.5 tonnes, respectively, and the boil-off rate is 0.1%. The calculation of boil-off is based on the range of the tank surface temperature, which is between 258 K to 318 K. This range is applicable to different weather conditions on most ship voyages; this changing in-tank surface temperature will produce a change in the boil-off rate. However, in the maximum surface temperature scenario, the boil-off rate will not breach the limit of 0.1%.

### 3.3. Tank liner

The tank liner is important for preventing the hydrogen gas from leaking through the walls. An impermeable layer is required to prevent  $\text{LH}_2$  loss in case the material of the tank wall structure becomes somewhat permeable. In this study, the tank liner thickness is assumed to be 24 cm, and the required mass of the tank liner is calculated using the following equation, where the aluminium alloy liner (Al-Mg 5086) density ( $\rho_{liner}$ ) is  $2,660 \text{ kg/m}^3$ :

$$M_{liner} = \rho_{liner} \left[ \frac{4\pi(r + t_{liner})^3}{3} + \pi(r + t_{liner})^2 L - V_t \right] \quad (21)$$

Finally, in this stage, the total design weight of the  $\text{LH}_2$  tank is

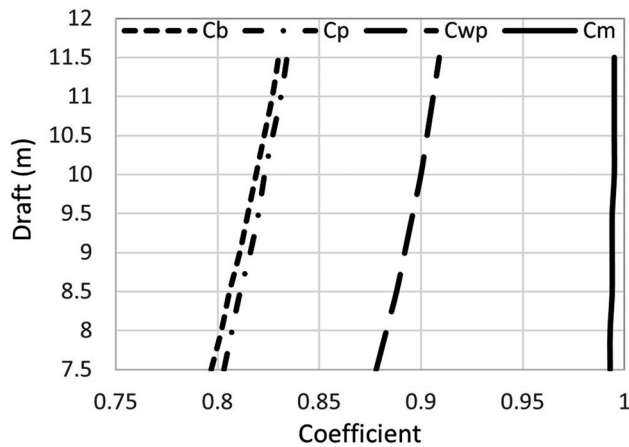


Figure 6. Ship coefficients for different drafts.

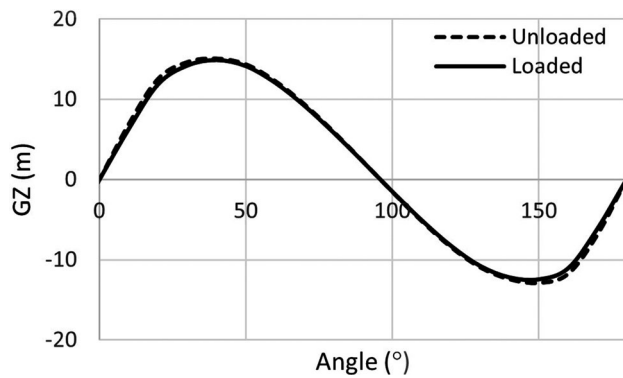


Figure 7. Righting arm curve (GZ).

determined to be the main element in the design and stability of the liquefied hydrogen ship, and it can be calculated using the following equation:

$$M_{\text{total LH2 tank}} = M_t + M_{\text{insulation}} + M_{\text{liner}}. \quad (22)$$

Figure 2 represents a Cross-section of the LH2 tank final design and Table 4 shows the output results of the liquefied hydrogen tank design model.

#### 4. Hull characteristics and stability evaluation

Once the tank dimensions were confirmed, the authors opted for a cylindrical bow and a twin-screw propulsion arrangement using an azimuthal podded drive system. The design of the cargo tanks was

followed by the design of a ship to fit the tanks. Figure 3 shows the final characteristics of JAMILA. These were the results of the detailed evaluations of the design dimensions of the ship hull, to commensurate with the unusually light ship deadweight. The curves in Figure 3b and 3c were produced using the Maxsurf Software (Bentley Systems 2016), taking into consideration certain key parameters of the ship such as, the block coefficient, the type of bow, the type of stern, and a few other details as the main inputs for the loaded and unloaded conditions. Table 5 presents the design values of the weights, dimensions, volumes, and power of the liquefied hydrogen tanker, which was powered by a 50 MW combined-cycle gas turbine. The increased weight of the liquefied hydrogen ship hull and tanks due to the high hydrogen volume will balance the density between LNG and LH<sub>2</sub>, which indicates similar power requirements for the liquefied hydrogen and liquefied natural gas tankers. The specifications of the LH<sub>2</sub> tanker are rather unusual. The design deadweight (DWT) is 20,000 tonnes, which is very low for a ship of this size. This is due to the exceedingly low density of the cargo.

#### 4.1. Ship stability estimation

To calculate the ship stability (Figure 4), the metacentric height (GM) was determined (Lewis 1988; Barrass and Derrett 2011) as follows:

$$GM = KM - KG = KB + BM - KG. \quad (23)$$

The value of KG can be calculated using the following equation:

$$KG = \frac{\sum \text{moment about the keel}}{\Delta_{\text{total}}}. \quad (24)$$

To calculate the transverse moment of inertia ( $I_T$ ) of the water-plane about the centreline, the weight of the ship's components and the distance of those components from the keel need to be estimated based on the data in Tables 6 and 7. The weights of the ship components were determined using an estimation-based iterative process through comparison with similar types of ships (Moore 2010). There is a small uncertainty in this hydrogen tanker data. This uncertainty is small in relation to other component weights. Other uncertainties also arise from the integration of the tanks into the hull; hence, the masses of tank structure, auxiliaries, and equipments are relatively large. Moreover, some of these components were placed on the ship to optimise the vertical centres of gravity under the loaded and unloaded conditions. The flexibility of the turboelectric propulsion system is helpful in this context.

Table 9. IMO ship criteria under the unloaded and loaded conditions (IMO 2019).

| Criterion                                                                       | Values & units | Status | Actual (unloaded) | Margin % (unloaded) | Actual (Loaded) | Margin % (Loaded) |
|---------------------------------------------------------------------------------|----------------|--------|-------------------|---------------------|-----------------|-------------------|
| 3.1.2.1: Area 0–30                                                              | 3.1513 m.deg   | Pass   | 272.2031          | Very Large          | 256.9222        | Very Large        |
| 3.1.2.1: Area 0–40                                                              | 5.1566 m.deg   | Pass   | 421.3774          | Very Large          | 403.4944        | Very Large        |
| 3.1.2.1: Area 30–40                                                             | 1.7189 m.deg   | Pass   | 149.1743          | Very Large          | 146.5723        | Very Large        |
| 3.1.2.2: Max GZ at 30 or greater                                                | 0.200 m        | Pass   | 15.055            | Very Large          | 14.893          | Very Large        |
| 3.1.2.3: Angle of maximum GZ                                                    | 25.0°          | Pass   | 39.1              | +56.36              | 40.0            | +60.00            |
| 3.1.2.4: Initial GMt                                                            | 0.150 m        | Pass   | 39.205            | Very Large          | 35.793          | Very Large        |
| 3.1.2.5: Passenger crowding: angle of equilibrium                               | 10.0°          | Pass   | N/A               | +100.00             | N/A             | +100.00           |
| 3.1.2.6: Turn: angle of equilibrium                                             | 10.0°          | Pass   | N/A               | +100.00             | N/A             | +100.00           |
| Angle of steady heel shall not be greater than (<=)                             | 16.0°          | Pass   | 0.1               | +99.64              | 0.1             | +99.64            |
| Angle of steady heel / Deck edge immersion angle shall not be greater than (<=) | 80.00%         | Pass   | 0.57              | +99.29              | 1.06            | +98.67            |
| Area1/Area2 shall not be less than (>=)                                         | 100.00%        | Pass   | 281.34            | +181.34             | 290.64          | +190.64           |

## 4.2. Ship stability verification

The metacentric height has a positive value, which indicates that JAMILA exhibits suitable stability characteristics. The manually calculated values were verified with the aid of a software (Bentley Systems 2016). In general, the following results provide a partial answer to the question, 'what would a hydrogen ship look like?' Table 8 shows the validation of the manually calculated stability values, specifically, the main ship characteristics and coefficients under the loaded and unloaded conditions. These results are used to confirm the primary output values of the ship stability calculations. A small difference exists between the results under the two conditions owing to the extremely low density of the cargo.

Figures 5–7 show the hydrostatic curves, geometric coefficients, and stability details of the ship, respectively. These figures present the outputs of the Maxsurf evaluation for the inputs mentioned earlier. Figures 5–7 clearly indicate the hydrostatic values in the loaded and unloaded conditions of the ship.

Based on Table 9, the intact stability of JAMILA is subject to the 2008 IMO Intact Stability Code (ISC) (IMO 2008):

- (1) Metacentric height ( $GM$ )  $\geq 0.15$  m.
- (2) Area under the static stability curve ( $GZ$ ) up to  $30^\circ \geq 0.055$  mrad.
- (3) Area under the static stability curve ( $GZ$ ) up to down-flooding angle ( $\varphi_f$ ;  $40^\circ$ )  $\geq 0.090$  mrad.
- (4) Area under the static stability curve ( $GZ$ ) from  $30^\circ$  to  $\varphi_f$  ( $40^\circ$ )  $\geq 0.030$  mrad.
- (5) The righting lever  $GZ \geq 0.2$  m at the angle of heel is equal to or greater than  $30^\circ$ . The maximum value of the righting lever ( $GZ$ ) occurs at  $\varphi > 25^\circ$ .

## 5. Conclusion

The LH<sub>2</sub> tanker ship assessed in this research is 370 m long, 75 m wide, and draws 10.012 m under the fully loaded condition. The fully loaded displacement tonnage is 230,000 tonnes to transport 20,000 tonnes of hydrogen. Its power system is a combined-cycle gas turbine of roughly 50 MW. The size and displacement of the ship depend largely on its required capacity to transport liquefied hydrogen (a very light but voluminous substance) at 0.5 MPa.

The specifications of the LH<sub>2</sub> tanker are highly unusual. The DWT is slightly larger than 20,000 tonnes, which is very low for a tanker of these dimensions. This is the result of the very low density of the cargo and should be expected for any LH<sub>2</sub> tanker. Another outcome of the low density of the cargo is a relatively small difference in the draft (slightly less than 1 m) between the loaded and unloaded conditions of the ship. The proposed design includes a high freeboard. This is not unusual in shipping applications, for which LNG carriers, cruise ships, and aircraft carriers are designed with high freeboards or very high and long superstructures.

The calculations for the ship evaluation were performed conventionally and verified using a special software. Although the preliminary design proposed herein is not the only solution, it is a viable one and offers a philosophical view of what a LH<sub>2</sub> tanker could look like. There are several aspects that require further attention, but they are not expected to have a major impact on the overall ship design and characteristics.

The ship resistance, power requirements, and power plant performance were evaluated, and these are described in the next stage of this investigation, which will be published separately. The power required was estimated to be approximately 50 MW under the fully loaded condition to enable a service speed of 18 knots. A hydrogen-fuelled combined-cycle gas turbine is proposed for this purpose.

There is a growing consensus that the need to decarbonise human activities will elevate the importance of hydrogen in our everyday lives. The high cost of its implementation is gradually becoming more acceptable in view of the environmental and economic benefits that it offers. The design proposed here is a viable one. Investments on ships that are similar to the vessel evaluated herein are an important prerequisite for the decarbonisation process.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Appendix

### Morrish and Munro-Smith formulas to estimate ship stability

The total displacement of the ship is  $\Delta_{total}$ , and the transverse moment of inertia is  $I_T$ , which is equal to the original moment and the moment of the weight added minus the moment of the weight discharged. The Morrish formula is used for estimating the vertical centre of buoyancy ( $KB$ ) (Roh and Lee 2018; Wilson

2018):

$$KB = \frac{1}{3} \cdot T \left[ 2.5 - \frac{C_B}{C_W} \right], KB_1 = 4.9 \text{ m (Unloaded)}, KB_2 = 5.3 \text{ m (Loaded)}, \quad (25)$$

where the waterplane area coefficients ( $C_W$ ) in the unloaded and loaded conditions are assumed to be 0.894 and 0.9, respectively, and the corresponding drafts are 9.263 and 10.012 m, respectively. The metacentric radius ( $BM$ ) is estimated using the Munro-Smith formula:

$$BM = \frac{I}{\nabla} = \frac{B^2}{T} \cdot \frac{C_w^3}{2C_B(1 + C_W)(1 + 2C_W)}, BM_1 = 50.5 \text{ m (Unloaded)}, BM_2 = 47.0 \text{ m (Loaded)} \quad (26)$$

where  $I$  is the moment of inertia. The metacentric heights ( $GM$ ) are

$$GM_{T1} = 4.9 + 50.5 - 16.028 = 39.3 \text{ m (unloaded)}, \quad (27)$$

$$GM_{T2} = 5.3 + 47 - 16.054 = 36.2 \text{ m (Loaded)}. \quad (28)$$



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