The Effects of Alternative Fuels on the Design of Harbour and Escort Tugs

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Synopsis:

The Paris Agreement has put considerable pressure on the marine industry to reduce Greenhouse gas emissions, with some companies committing to be carbon neutral in the coming years. This has spurred significant interest in alternative fuels as a path to net zero emissions. Numerous papers and studies have been published reviewing the efficacy of these fuels, but they are mainly targeted to large ocean-going vessels. This paper aims to address the relative merits of the leading alternative fuels and their impact on harbour and escort tug design. Proven solutions exist today for zero emissions operations, but they have limitations, and are not suitable for all applications. There are technological and logistical barriers that need to be overcome before a universally applicable zero carbon solution emerges. In the interim however, there are low carbon solutions that show significant promise to make an impact on carbon emissions now.

Introduction

The 2015 Paris Agreement has put considerable pressure on the marine industry to reduce greenhouse gas (GHG) emissions. The goal of limiting global warming to within 1.5°C requires emissions reductions from all sources of 45% by 2030 compared to 2008 with further reductions in subsequent years to reach net zero by 2050[1]. In support of this goal, the IMO adopted an ‘Initial Strategy’ in 2018 to reduce GHG emissions from international shipping by at least 50% by 2050 compared to 2008. The IMO Initial Strategy is set to be revised in 2023[2]. There have been industry-driven initiatives as well, such as a coalition of global cargo owners in the international maritime sector defining ambitions for zero-emissions shipping by 2040[3]. Several leading shipping companies have also outlined their roadmaps to carbon neutrality, including A.P. Moller-Maersk committing to net zero CO_2 emissions by 2050[4] in part by construction of a series of methanol-fueled containerships and strategic partnerships to supply green methanol across several regions in the world[5]. The need to decarbonize extended to the global tug fleet as well, spurring significant interest in alternative fuels as a path to substantially reducing GHG emissions.

Low Carbon Solutions

Thankfully for owners and operators of tugs, several solutions exist today which help cut GHG emissions, though all solutions come with their own set of pros and cons. This paper will discuss these solutions and their impact when it comes to their implementation and outcomes on modern compact tugs specifically.

Battery Electric

Before discussing alternative fuels, it is worth examining the role of batteries in tug propulsion system. Hybrid propulsion systems on tugs have been around for many years, starting with diesel-electric hybrid vessels with varying levels of battery capacity. As battery technology has progressed and energy density has improved, overall cost per kilowatt-hour (kWh) has decreased to the point that tugs powered primarily (or solely) by batteries have become attractive, particularly for tugboats less than 500 GT. These vessels can perform all their operations from batteries and charge from shore power. Battery-electric tugs have recently entered service in New Zealand and China. More are planned or under construction, including the Robert Allan Ltd ElectRA series.

Battery electric powering on tugs represents a clear pathway to net zero emissions, provided sources of electrical shore power are also green. When operating solely on batteries, the “tank-to-wake” emissions are zero. However, this is not the complete picture when it comes to GHG emissions. The “well-to-tank” emissions should also be considered. On a battery-electric tug, this means looking at the source of electrical power for recharging. Sustainably produced, clean electric power is becoming available in many parts of the world where hydro or wind power is abundant, however this is not the case everywhere. In much of the world, electrical power is produced from fossil fuels, including coal. Figure 1 shows a breakdown of the sources of electricity for the European Union. From 2020 data, over 35% of the power is still produced by fossil fuels[6].

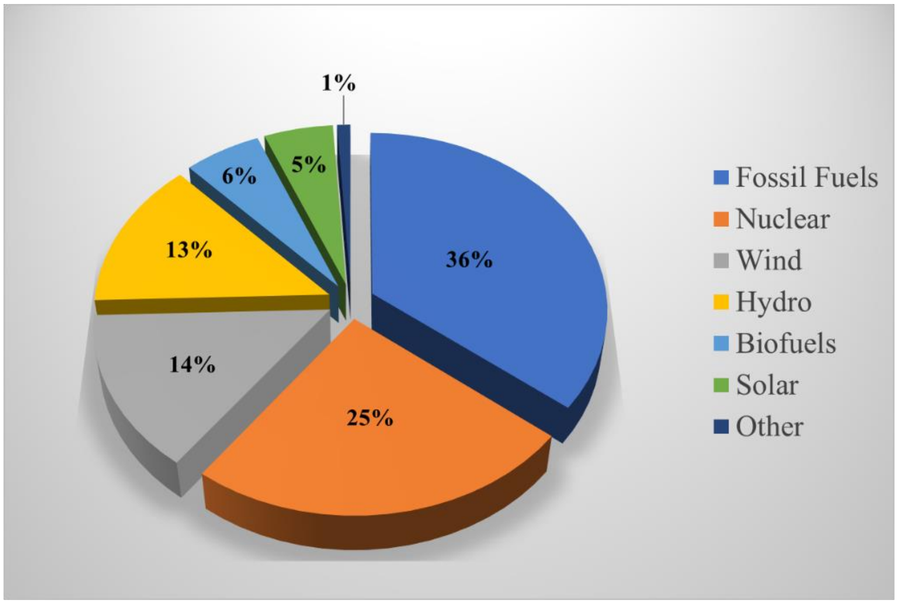

Figure 1: EU Electricity production by source, 2020

While battery-electric tugs can result in zero or near zero GHG emissions, they are not suitable in every tug application. They can be an excellent solution for ship-handling tugs that operate in harbour settings with a predictable operational profile, within a fleet mix that can accommodate recharging, and where shoreside charging infrastructure is available. However, for larger more powerful tugs with more demanding power and endurance requirements, such as escort tugs, fitting batteries with sufficient capacity can be prohibitive from size, weight and costs perspectives. Establishing the necessary shore charging infrastructure can also be a barrier where tugs operate at remote locations, away from established power grids.

With battery technology continually progressing, it is reasonable to expect that energy densities and costs will continue to improve and battery-electric powering may become practical on larger and more powerful tugs in time. Even seeing the energy density of marine batteries reach parity with automotive batteries would represent a substantial improvement. For the time being, however, alternative fuels are the best avenue to reduce the GHG emissions from tugs requiring more power and endurance than battery-electric tugs can offer using present battery technologies. These alternative fuels will be the focus of this paper.

Alternative Fuels

When looking at alternative fuels to reduce GHG emissions on compact tugs, the main candidates of interest today include:

- Liquefied Natural Gas (LNG)
- Methanol
- Hydrogen
- Ammonia

These are described below, along with and their pros and cons when it comes to using them on tugs.

Carbon-based Fuel Options

LNG

LNG, consisting primarily of liquefied methane, was one of the first alternative fuels to be used commercially to replace diesel on ferries and tugs. LNG is attractive because of its relatively low cost as a fuel and reductions in NOx, SOx, and particulate emissions possible, even with dual fuel engines. LNG can also reduce CO_2 emissions by about 25% when compared with diesel engines[7], however this can this be quickly offset by methane slip, given that methane has a 100-year global warming potential 28-32 times that of CO_2[8].

Being cryogenic, pressurized, and low flash (having a flashpoint below 60° Celsius), the safe integration of LNG into vessels required new rules to be developed. This led to the framework that is now the IGF code[9]. The IGF code is the predominant regulatory reference for the fuels discussed subsequently and is the basis for most classification society rules today.

LNG has the highest volumetric energy density (GJ/m^3) of the alternative fuels discussed here. However, when accounting for the space requirements for the LNG tank hold and associated equipment, its ‘effective’ energy density decreases substantially.

Methanol

Methanol (CH_3OH), or methyl alcohol, has become the centre of much attention as of late. Typically derived from natural gas or coal, it is a colourless liquid at room temperature and is therefore non-cryogenic and non-pressurised. As a low flash fuel, it falls under the IGF code, however some class societies, including ABS[10], have published guidance which helps reflect the inherent differences between methanol and LNG, most notably that methanol can be placed in irregularly shaped tanks integrated with the hull structure and adjacent to the hull shell below the waterline, considerably improving volumetric storage efficiency compared with LNG on small vessels like tugs.

The strong interest in methanol come from its potential as a net-zero carbon ‘energy carrier’ fuel. When it comes to tank-to-wake emissions alone, methanol can reduce CO_2 emissions by up to 10% compared to Marine Gas Oil (MGO)[11]. SOx, NOx and PM emissions are also substantially reduced. With “green” methanol, produced from sustainable biomass feedstocks (bio-methanol) or renewable electricity (e-methanol), well-to-wake emissions can approach net zero. Because it is relatively easy to store on board and the possibility of achieving net zero emissions, green methanol as a marine fuel is considered one of the post promising alternative fuel options for the near future.

Methanol's volumetric energy density is roughly 44% of that of diesel. This means that over twice the fuel storage capacity is required for methanol compared with diesel to achieve similar endurance.

Carbon-Free Fuel Options

Hydrogen

With no carbon in its molecular structure, hydrogen (H_2) is the 'purest' of the alternative energy carrier fuels and, from a tank-to-wake perspective is fundamentally a zero GHG emissions alternative fuel.

Hydrogen, a gas at room temperature, is nontoxic, but is explosive and flammable. Being a low flash fuel, it falls under the regulatory framework of the IGF code. Hydrogen's energy density on a mass basis is almost four times as high as diesel, however storage of hydrogen becomes difficult. Compressed gas hydrogen can be stored in pressure vessels (typically of composite construction) at 250 bar, or in liquid form at -253^{o} Celsius. Even in its liquid form, it would require about 4.2 times as much volume as diesel for similar endurance.

Hydrogen can be used in either fuel cells or in internal combustion engines (ICEs). Fuel cells provide approximately 33% better system efficiency when compared to an internal combustion engine[12]. However, the improvement in efficiency with fuel cells can come with a substantial capital cost, not only for the fuel cell equipment but also batteries which are typically needed for better dynamic performance on vessels like tugs.

Ammonia

Ammonia (NH_3), like hydrogen, has no carbon present in its chemical structure. As such, it can provide zero, or near zero (considering any pilot fuel) tank-to-wake carbon emissions.

Ammonia is a colourless gas at room temperature but can be stored as a liquid under pressure. In liquid form, ammonia's volumetric energy density is much lower than that of diesel and would require a little over three times as much storage capacity to provide similar endurance.

Ammonia has a distinct pungent odour similar to sweat or urine. According to WHMIS standards, ammonia is classified as a corrosive, very toxic, flammable gas. Inhalation of ammonia can cause death, with short term exposure having the potential to cause chemical burns on the skin and eyes. Toxic to not just humans, ammonia is very toxic to marine life. It readily dissolves in water and a spill of just 1m^3 can create a marine fatal radius of over 100m[13]. Consequently, ammonia has very restrictive hazardous and toxic zones, which will be discussed later.

Key Comparisons Between Alternative Fuels

Carbon Footprint

It is important to note that while hydrogen and ammonia have no carbon present in their molecules, the production of these fuels can be carbon intensive. In much of the world, production of these "energy carrier" fuels from non fossil fuel feedstocks can in fact lead to significant CO_2 emissions. In some cases, "green" production can be worse for carbon emissions than "grey" or "brown" production. This occurs where electricity is not produced from low-carbon, renewable sources.

An in-depth discussion on the carbon footprint associated with the production, transportation, and ultimate consumption for each respective fuel is outside the scope of this report, however, emissions factors for both upstream (well-to-tank) and downstream (tank-to-wake), are published by various sources including the marine classification societies such as ABS[14] and international organizations including the International Energy Agency (IEA)[15]. These provide valuable insight on the true well-to-wake emissions.

Energy Density

Energy density is critical to the viability of any fuel stored in the confines of a densely packed vessel like a tug. Energy density can be considered on a mass basis or on a volumetric basis. Table 1 shows the relative energy densities of the four fuels discussed, along with diesel[16]. The values are for the raw fuels, and do not consider system characteristics related to storage or power generation methods.

Fuel Source	**Diesel**	**LNG**	**Methanol**	**H_2 (liquid)**	**H_2 (gas)**	**Ammonia**
Density (t/m^3)	0.835	0.428	0.791	0.071	0.023	0.61
Lower Heating Value (GJ/t)	42.6	48.6	19.9	120	120	18.6
Volumetric Energy Density (GJ/m^3)	35.6	20.8	15.7	8.5	2.76	11.4
Volume normalized (m^3/GJ)	1	1.7	2.3	4.2	12.9	3.1

Table 1: Chemical and Thermodynamic properties by Fuel [5]

Perhaps the most important row in Table 1 is the volumetric energy density, normalized against that of diesel. As shown, methanol will require approximately 2.3 times more volume than diesel for similar endurance. Compressed hydrogen would require almost 13 times.

System Effective Energy Density (SEED)

When it comes to volume required for fuel storage, it is important to look beyond differences arising from energy densities alone. The fuel options have specific and physical storage configuration requirements that arise from safety and temperature/pressure storage states that are considerably different from diesel, particularly with LNG, ammonia, and hydrogen. As such, it is important to consider what Robert Allan Ltd refers to as the ‘System Effective Energy Density’ or SEED. The SEED value of a given fuel option is essentially a factor that represents a normalized comparison of the amount of energy that can be practically stored on a sub 500 GT tug. The SEED value accounts for, not only for a fuel’s volumetric energy density, but also the space impact of the fuel’s storage configuration and ‘extra’ volume taken up on board to accommodate the tanks safely. For the purposes of this paper, the focus will be on sub 500 GT tugs. Table 2 shows the SEED values of several Robert Allan Ltd. sub 500 GT tug designs, with Diesel assigned a value of ‘1’ by definition.

Tug Fuel	**Diesel**	**Methanol**	**LNG**	**Ammonia**	**LH_2**	**H_2 (gas-250 bar)**
Installed Fuel Quantity	200m3	100m3	40m3	50m3 (estimated)	40m3 (estimated)	45m3
SEED	1	0.22	0.12	0.08	0.05	0.02

Table 2: System Effective Energy Densities of Alternative Fuels

The referenced tugs are all 32m in length, with approximately 80t bollard pull. Accommodation arrangements are similar. Since ammonia and Liquid Hydrogen (LH_2) designs have not been fully developed, the SEED values shown are derived from early stages of design.

Interestingly, Table 2 shows that a methanol tug would have approximately *twice* the endurance of a similar LNG vessel despite methanol's lower energy density. This stems from the ability to fit methanol tanks against the hull shell or in irregularly shaped, prismatic tanks. This will be discussed further later in this paper. Fuels stored in Type C pressurized tanks have accordingly lower SEED values, suggesting for example that a tug fueled with ammonia (SEED = 0.08) may only be able to accommodate approximately 8% the energy onboard that a diesel tug could without increasing the volume built into the design for fuel storage. The situation with hydrogen, both as a liquid and a compressed gas at 250 bar is even more challenging, with SEED values of 0.05 and 0.02 respectively.

Table 2 only provides data for sub 500 GT vessels. Generally, as a tug gets larger, the effective energy density will improve. The opposite is true as tugs get smaller. As mentioned, the use of fuel cells can increase the overall efficiency of the system when compared to an internal combustion engine, thereby reducing the volume of fuel required to achieve similar endurance.

Fuel Comparison Summary

Table 3 summarizes key characteristics of the alternative fuel options.

	Regulatory Framework	**Low Flash**	**Pressurised**	**Cryogenic**	**Haz. Zones**	**Toxic Zones**	**Volume per unit energy - Normalized**	**SEED**
Diesel	Ship Rules	No	No	No	No	No	1	1
Methanol	IGF	Yes	No	No	Yes	No	2.27	0.22
LNG	IGF	Yes	Yes	Yes	Yes	No	1.72	0.12
Ammonia	IGF	Yes	Yes	No	Yes	Yes	3.14	0.08
LH_2	IGF	Yes	Yes	Yes	Yes	No	4.2	0.05
H_2 (gas - 250 bar)	IGF	Yes	Yes	Yes	Yes	No	12.9	0.02

Table 3: Key characteristics of alternative fuels

Hazardous and Toxic Zones

All the alternative fuels discussed have flashpoints below 60° Celsius and are therefore designated as "low flash" fuels. Arrangements to store and distribute these fuels are therefore associated with hazardous zones as specified in the IGF code. For all intents and purposes, methanol, LNG, and hydrogen all have similar hazardous zone considerations. The hazardous zones are defined in the IGF code with some variations by class society for each specific fuel. While these zones impact design and operation, they do not prevent the viability of the design in a sub 500 GT vessel.

This cannot be said for the toxic zones associated with ammonia. Due to the severe health implications of ammonia exposure, the toxic zones are significantly larger than the hazardous zones of other fuels[17]. Of note, the toxic zones around the vent mast and bunkering manifold are 25m and 10m respectively. The associated hazardous zones for other fuels would instead be 10m and 3m. This has a substantial impact on tug design as discussed later.

Fuel Cells

As an alternative to internal combustion engines (ICEs), fuel cells can be used to meet a vessel's electrical demands. Fuel cells are commonly supplied with pure hydrogen; however, the source of this hydrogen can vary. The use of compressed or liquid hydrogen provides the simplest pathway, however both methanol and ammonia have the potential to act as hydrogen carriers. Hydrogen would be separated out from these fuels by means of a reformer. The overall efficiency of a proton exchange membrane (PEM) fuel cell can be up to 60%, compared to approximately 45% for medium speed diesel engines. This effectively increases endurance with the same fuel capacity.

While the efficiency of fuel cells looks attractive, there are other characteristics which are not so favourable. Fuel cells operate best under constant load and are not good at responding to rapidly changing power demand, a common situation on tugs escorting or docking ships. This means that where fuel cells are installed, they need to be paired with batteries or gensets to handle transient load response.

Fuel cells have the best lifespan when operated around 70% of their rated power, which can lead to having to install more nominal power than required operationally simply to meet lifespan targets. Perhaps most prohibitive to the use of fuel cells on small vessels is their capital cost. At present day, a fuel cell power system costs approximately $3000 per installed kW. Since the overall efficiency and emissions characteristics of fuel cells are promising, should the associated capital cost come down, fuel cells may become an attractive option for a net zero vessel. Currently however the cost is likely prohibitive for the sub 500 GT market.

Impacts on Tug design

With the above background on the alternative fuel options in mind, the design implications of fitting each fuel in a vessel can be examined. What follows is an examination of the differences in design due to fuel choice on a sub 500 GT tugboat with similar power and accommodation capacity. Many of the design drivers are common across the various fuels, and as such they have been grouped accordingly. In each section the applicable fuels will be noted. Due to the low energy densities among the alternative fuels, maximizing fuel storage capacity has been identified as a key driver.

Type C tanks

Applicable to: LNG, LH_2, Ammonia

Fitting Type C tanks within the confines of a sub 500 GT tug while complying with the IGF code is a difficult task. Type C tanks impact the design all the way down to the hullform. The IGF code specifies that a Type C tank must be located aft of the collision bulkhead, inboard a distance of one fifth the beam (B/5) from the design waterline, B/15 above the hull at centreline, and 800mm away from the hull shell in all directions. It is important to note that this applies to the tank shell that is directly touching the fuel. Put another way, for a cryogenic tank the above restrictions should be assessed in relation to the inner tank.

While not the only solution, orienting the tank longitudinally in the bow of the vessel below the lower accommodation is commonplace. This provides reasonably low impact on the overall design when compared to a standard diesel tug. Viewed from the shore, the deck layouts would be indistinguishable from their diesel cousins, and the engine room arrangement would remain similar.

Things begin to differ when looking at the hull. Due to the form factor of a type C tank, there is a trade off between overall tank length and tank diameter. Volumetrically, the most gains are had when increasing the tank diameter. However, due to the implications on GT, increasing tank length is more beneficial to achieve maximum capacity. Thus, the length to beam ratios of these vessels are generally higher than their diesel counterparts. Due to the above, optimizing Type C tank capacity in a shorter tug becomes that much more difficult, tending to deeper vessels.

The overall form of the hull also differs in way of the tank. To be compliant with IGF code requirements, the bow of a tug with a type C tank is necessarily fuller than that of a more conventional design – assisting with both the radial and B/5 restrictions. The onset of the rise in stem at the bow is also farther forward – assisting with the B/15 restriction.

This increase in volume towards the bow helps support the added weight of the type C tank and associated structure, though it can increase resistance.

Most of the focus above has been around the location of the tank with respect to the hull shell, however there are also restrictions in relation to machinery spaces. Type C tanks and their tank connection spaces (TCS) must be 900mm away from any Category A machinery spaces. Due to this, it is generally advantageous to locate the TCS on the side of the tank instead of the aft end as this will provide more space in the engine room.

Methanol Tanks and Fuel Preparation Space

Applicable to: Methanol

While not as restrictive as the requirements outlined for Type C tanks, methanol tanks also need to comply with several requirements. For the present purposes, only integral tanks will be considered.

Methanol tanks may not be located in accommodations or category A machinery spaces. Therefore, the only remaining potential locations are either in the forward or aft holds of the vessel. The bunkering station must be located on the open deck and the bunkering lines must not run through the accommodation. The combination of these rules generally leads the methanol tanks and associated system to be equipped in the aft end of the vessel for an ASD tug.

Cofferdams, 600mm wide enclosed void spaces, are required around methanol tanks except where bound by the hull shell below the lowest waterline, or the fuel preparation space. Being able to locate tanks against the shell provides the greatest advantage when compared to Type C tank storage. Generally, the capacities achievable in the aft hold alone greatly exceed the capacities of a Type C tank which could be fit in a similar vessel. Figure 2 shows a representative methanol tank arrangement in the aft hold of an ASD tug.

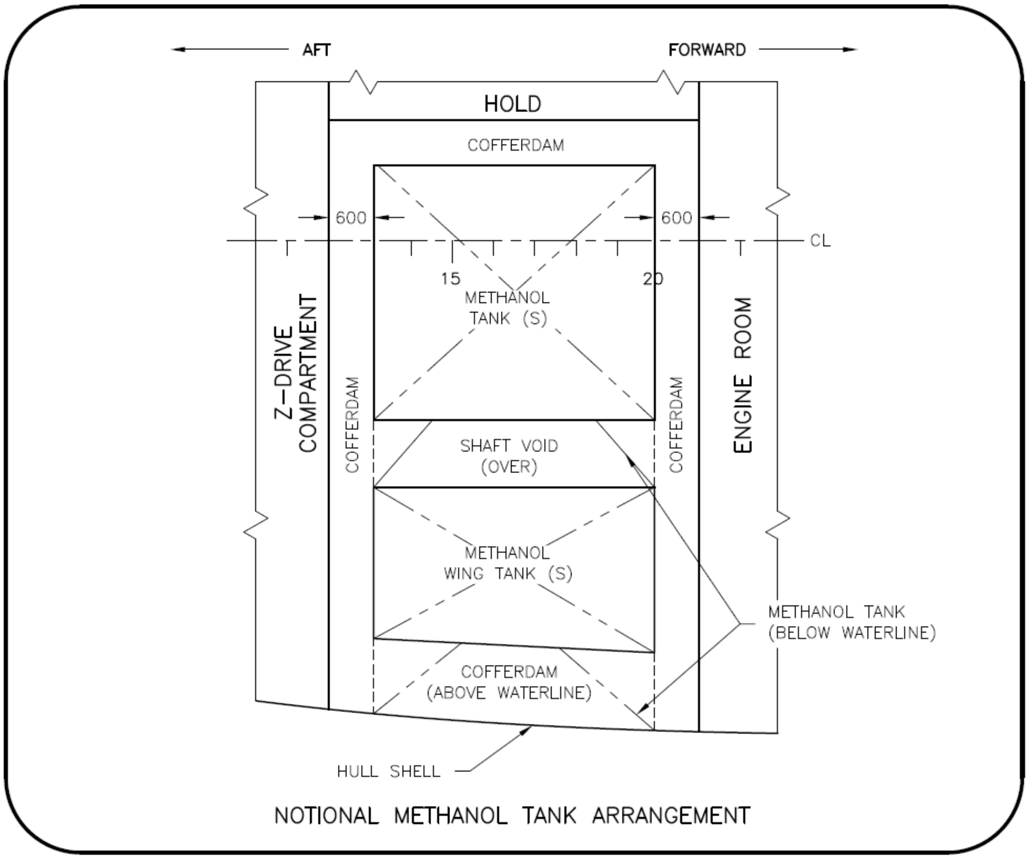

Figure 2: Methanol Tank Arrangement in Hold

Hazardous Zones

Applicable to: All fuels

Hazardous zones are areas where an explosive gas is or may be expected to be present. As mentioned previously, hazardous zones must be considered for all the alternative fuels. Hazardous zones are well defined by the IGF code with some variations by class society for each specific fuel. For tugs, hazardous zones are typically present near fuel system vents, access points to hazardous tanks, and bunkering stations. Hazardous zones should be considered as early in the design as possible, with particular attention to ventilation intakes and outlets, as well as entrances to accommodations. All electrical equipment within a hazardous zone must have a suitable enclosure rating as per class rules. Mechanical deck machinery should be positioned outside of hazardous zones wherever possible. Without detailing every restriction and location, the key items of concern are listed below.

Fuel system pressure relief vents and vent outlets:

The largest hazardous zones are usually associated with pressure relief vent outlets from tanks. The hazardous zone extends 4.5m around vent outlets. Also to be considered is a 6m minimum clearance to the working deck, and a 10m clearance to the exhaust and accommodation openings. To address this, on Robert Allan Ltd tug designs the vents in question are commonly run up the mast in a proprietary doublewalled pipe to a sufficient height where they are not encroaching on any of the accommodation or control space intakes or entryways. The vessel’s exhaust pipes must also be considered in relation to this zone.

Bunkering Station:

Bunkering stations also create large hazardous zones, but typically they are inerted after use and therefore the hazardous zones are only present during bunkering operations. As such, the power supply of mechanical deck machinery in this zone can be locked out during bunkering. For methanol this does not present a significant design complication as the tanks are generally located aft with the bunkering station on the main deck. However, for Type C tanks (LNG, LH_2, ammonia) this station is commonly located forward closer to the accommodation.

Tank Access Points:

This is predominantly a concern for methanol vessels where the tank access points are on the main deck. Care should be taken in arranging these access points to minimize the impact on escape hatches and aft deck equipment.

Toxic Zones

Applicable to: Ammonia only

Ammonia is classified as a highly toxic chemical and long-term exposure to low levels of gas can cause death. As such the toxic zones considered for ammonia are pervasive and restrictive. The toxic zones around the vent mast and bunkering manifold are 25m and 10m respectively. Within the confines of a vessel that is approximately 32m in length, fitting these toxic zones make the design impractical for a sub 500 GT tug as is illustrated in Figure 3. While seemingly impracticable to compact tugs, ammonia may be a viable solution on large vessels where the hazardous zones are comparatively smaller.

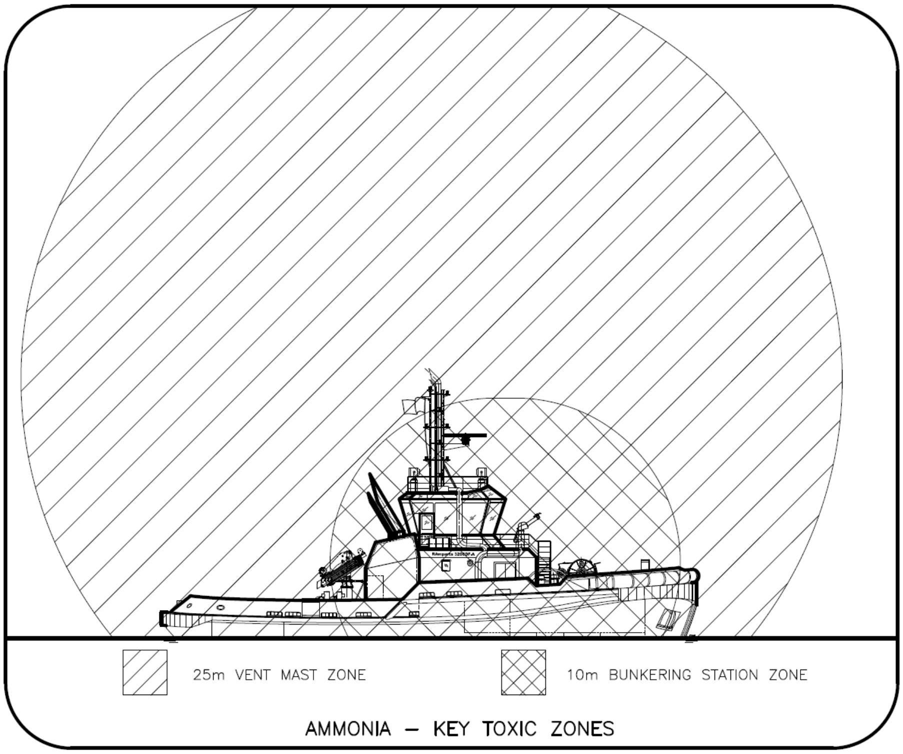

Figure 3: Ammonia Toxic Zones

Equipment Availability

Applicable to: LH_2, Methanol, Ammonia

At present, there are few engine options available to run off methanol, ammonia, or hydrogen. While engine manufacturers are developing solutions, it is unclear as to which fuel(s) each manufacturer will focus on in the near term and what technologies will be adopted. While some (if not most) options will be compression cycle engines, spark-ignited Otto cycle engines may also become realistic options for tugs. Using medium speed engines necessitates a deeper vessel, a larger engine room, and will increase the lightship weight substantially when compared with high-speed engines, the status quo for sub 500 GT diesel tugboats.

Small impacts

While the main impacts to design have been discussed, other minor impacts need to be considered. These include but are not limited to: insulation requirements, ventilation requirements, inclusion of an inert gas system, and fire suppression implications. In the case of cryogenic fuels, material grades and standards need to reflect the expected temperatures. It is also important to note that the regulatory framework is continually evolving, with some rules varying by classification society.

Conclusions

The alternative fuel space continues to develop with LNG, methanol, ammonia, and hydrogen as the leading options. Outside of batteries, there are no viable solutions for tugs that will reduce tank-to-wake emissions to zero. LNG will remain an important transitional fuel in the years to come, given the maturity of engine and storage technology, proven track record in service, and availability of natural gas and/or

LNG in many ports. Hydrogen could be a promising solution in the future but without a way to reduce the volume required for hydrogen storage, and the cost of fuel cell systems, hydrogen as an alternative fuel will pose significant challenges in a sub 500 GT tug. Ammonia is unsuitable for tugs under 500 GT due to the large toxic zones attributed to it, though it might be a good solution for larger vessels. In terms of overall design, a green methanol tug will most closely resemble a diesel tug and will provide the best endurance of all the alternative fuels.

Until such time as the storage requirements, equipment availability, and overall system costs of carbon free fuels improve, they will remain challenging to implement in a sub 500 GT vessel. Thus, with the aim to reduce GHG emissions, given the points outlined in this paper, it is expected that green methanol will be the dominant alternative fuel in the coming years.

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