PRADS 20117 - Features of CNG Carrier Design

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Abstract

This paper briefly introduces the rationale for marine transport of compressed natural gas (CNG) and, then, clarifies key features of the design and design process for large capacity CNG Carriers. The influence of the client's needs, project drivers, and marine standards are addressed by authors who have been intimately involved in the evolution of the first CNG Carrier ship designs and standards for international CNG transport.

Application of the principles of CNGC design is demonstrated as implemented for a project solution currently under development in association with world-class ship owner, shipyard, and energy companies.

Keywords

Natural gas; CNG; ships; cylinders; stranded; offshore.

Nomenclature

scm = Standard cubic meters, referring to the volume the gas cargo would occupy at standard atmospheric conditions; "scf" is similarly "standard cubic feet";

Introduction

The concept of transporting large quantities of compressed natural gas (CNG) by water has been around for decades. However, only in the past decade has the concept garnered serious attention among the international shipping and energy industries due to the development of high strength materials, especially high strength steels with low temperature toughness, and commercially attractive concepts for CNG handling and containment. This surge in interest is also based on dramatic increases in the costs of energy and more specifically on the apparent differential between the cost and environmental impact of oil versus gas as fuel.

Therefore, a new class of maritime assets is developing with the introduction of designs for ships and barges as CNG Carriers (CNGCs). Although the IMO Gas Carrier Code does not directly address the design and operation of CNGCs, the world's leading classification societies have developed the necessary guidance through interactions with pertinent maritime administrations as well as the CNG transport promoters themselves.

This paper discusses the design process and features being incorporated in ship and barge based CNGCs by EnerSea Transport LLC, their strategic partners, and their naval architects, Alan C. McClure Associates Inc (ACMA). The CNG transport system design approach uses a Volume-Optimized Transport and Storage (VOTRANS™) concept wherein the gas cargo is chilled down to about -30C so that it may be stored at moderate pressures (90-130barg) in long cylinders made of high strength steel pipe. This concept provides relatively high cargo-to-containment mass ratios for storage enabling rational ship design. High pressure, ambient CNG storage concepts carry at least a 50% weight penalty that heavily impacts the ship design and system commerciality.

Marine CNG Transport

CNG marine transport allows emerging, energy-hungry markets around the globe to access gas reserves that would otherwise remain stranded. As compared to other solutions for de-stranding of gas reserves (LNG & GTL technologies), the shipping of CNG offers a solution that significantly limits the wastage of gas resources that are needed in the emerging markets and the amount of captive investment required of operators. Such value-adding features make this breakthrough technology and the new class of ships attractive to gas and power players on a global scale.

Industry has now recognized that technology allowing marine transport of CNG provides flexibility that changes the economics for marginal fields. This is especially true for associated gas or gas fields in ultra-deep waters or locations remote from suitable markets. VOTRANS technology offers a highly efficient solution for handling, storing, and transporting gas that is making many in the energy industry appreciate the breakthrough potential for marine CNG as a means to commercialize stranded gas in remote reservoirs around the world. A new class of ocean-going vessels and gas handling facilities will play key roles.

CNGC Ship Design

General

EnerSea has developed a large CNGC carrier design focused primarily on cargo capacities between 11E6 and 23E6 scm gas storage capacity that has the CNG cylinders oriented vertically, as shown in Fig. 1 below. The ships designed to this arrangement are called "V-ships" to recognize both the vertical cylinder orientation and the application of the ships in VOTRANS gas transport. The helm is placed aft and is relatively high to provide the visibility needed for navigation. The hull is typically double-sided with a relatively deep inner bottom to accommodate the weight of the heavy cargo cylinders. The wing tanks are relatively wide as compared to other hazardous cargo carriers (e.g., oil tankers or LNGCs). The hold enclosures defining the extents of the hold spaces above the main deck are watertight and provided with pressure relief fittings that allow the holds to be pressurized slightly above ambient during operations. The perimeters of the holds are insulated to maintain the chilled atmosphere within.

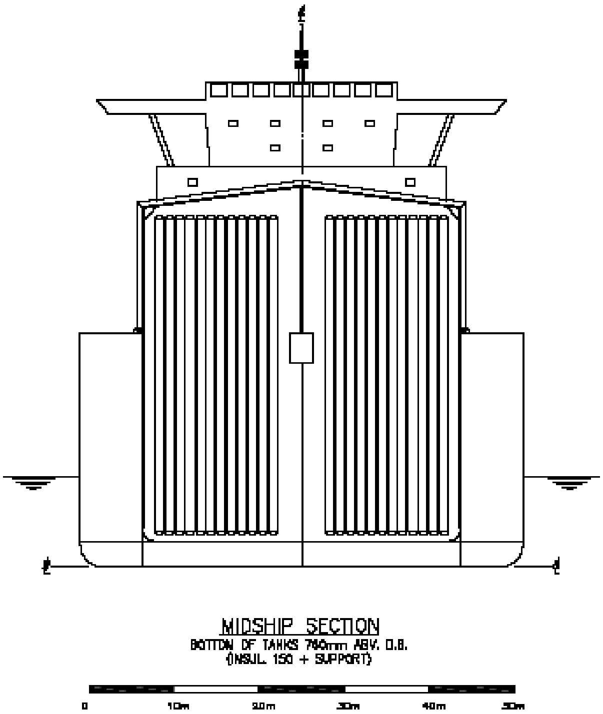

Fig. 1: "V-ship" CNGC Cross-section

CNGC Design Process Basics

The basics of the CNGC design flow process are depicted in Fig. 2 and described in the following.
Besides the obvious fact that the required volume of CNG to be transported determines the size of the CNG ship, the most influential and limiting factors of ship size are a) cargo cylinder arrangement in the holds, b) restrictions on lightship draft, and c) the block coefficient target.

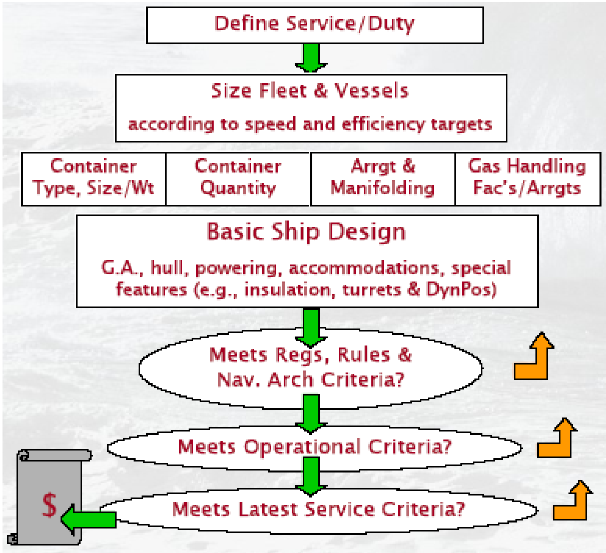

Fig. 2: CNGC Design Flow Process

The cargo cylinder arrangement in a hold is mainly determined by the cylinder piping arrangement as a function of the loading and unloading process where a non-freezing fluid, typically an ethylene glycol-water mix, is used to displace the CNG. A typical cargo hold cylinder arrangement is presented in Fig. 3.

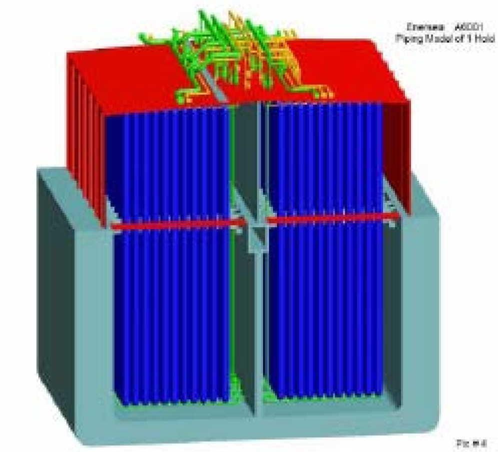

Fig. 3: CNGC Hold Arrangement

The lightship design draft constraint is dependent on the worldwide availability of repair yard dry docks or graving docks with sufficient keel block depth and the capacity to accommodate the heavy CNG ships.

The choice of a suitable block coefficient in the design will ultimately be proven in subsequent ship design iterations, resulting in acceptable ship length, beam, wing tank width, stability, longitudinal strength, propulsion power requirements, and overall ship cost.

The more recent CNG ship sizing exercises indicate that, for the same CNG volume transported and maintaining a constant block coefficient, the shorter ships with associated wider beams have higher storage efficiencies. Storage efficiency is expressed by the ratio of gas weight to ship hull steel weight. In other words, and all other things being equal, the shorter the ship, the less hull steel weight, the lower the initial ship hull cost. However, the wider ships would have a somewhat higher resistance while underway. Consequently, a somewhat larger and costlier propulsion power plant, and hence, higher fuel cost in the long run, which could offset the initial cost advantage of the shorter hull.

CNG Volume and Weights

The total required volume of CNG to be transported by the ship, a major factor impacting ship size, is dependent on client project requirements (the rate/quantity intended to be sold) and calculated to account for any gas that must be available as fuel, as well as any residual gas (the "cushion" or "heel" typical in the gas storage industry). Generally, each project targets gas of a given composition and specific gravity. The internal tank volume required is determined by the selected (optimized) storage conditions and the resultant volume reduction ratio (usu., 250-350:1) for chilled CNG. The wall thickness and total number of the cargo cylinders is based on the cargo gas composition and storage conditions. The weight of the cargo cylinders, including the weight of the heads, is developed to reflect the calculated wall thickness increased by mill tolerance and corrosion allowances, if any. The weight of the gas on board is determined by the values at standard or storage conditions. Weight allowance estimates must also be established for gas handling facilities, piping, controls, and cargo enclosures (with insulation).

Light Ship Draft

Impacting the design of the ship, but independent of the quantity of CNG to be carried, are the limits as to the maximum ship draft that can be accommodated by repair yard dry docks worldwide. It should be noted that the EnerSea CNG ships, without the cargo gas, fuel and other consumables, have a much higher lightship weight than other types of ships with similar dimensions, due to the weight of the cargo cylinders. Therefore, based on a limited number of available dry docks that can accommodate a draft exceeding 7.50 meters, this draft has been adopted as the upper limit for the lightship draft of EnerSea's CNG ship design.

Cargo Cylinder Arrangement

The vertically mounted cargo cylinders are horizontally restrained at the main deck level by a series of large transverse beams spaced such that each beam supports two transverse rows of cylinders. The individual cylinders of every "paired row" of cylinders are connected together to form one large (multi-cylinder) cargo tank. There are no valves between the individual cylinders.

The next major impact on the sizing of the CNG ship is caused by the CNG loading and offloading process where glycol is used to displace CNG in the cargo cylinders when offloading, and CNG is displacing the glycol when loading. To make this process more efficient, and not having to carry overly large amounts of glycol onboard, every third "paired row" of cylinders in a hold are loaded or offloaded at the same time (i.e., a loading group consists of 3 tanks or 6 individual rows of cylinders). This distributed loading/unloading practice spreads the displacement fluid loading over the double bottom structure. For each hold, the number of transverse rows of cargo cylinders will therefore be a multiple of six, i.e., 12, 18, 24, and so on. This means that adjustment of the number of cargo cylinders in one hold can only be in increments of 6 single transverse rows of cylinders.

Adding or subtracting one or more cylinders to or from each transverse row may result in a smaller adjustment of the total number of cargo cylinders in a hold. This will directly affect the width of the wing tanks, which may result in insufficient protection to side penetration damage in the case of a wing tank width reduction. Too much of an increase in wing tank width will result in a higher metacentric height (GM), and a much stiffer ship as the consequence. Varying the number of cylinders per transverse row while otherwise maintaining identical cylinder size and weight, gas weight and number of cylinders, changes the width of the cargo holds and consequently the width of the wing tanks when the ship's beam is being held constant.

For a given CNG carrying capacity, the use of heavier cylinders (i.e., in cases where high pressure, ambient temperature storage is practiced) will require an increase in ship beam to maintain identical GM.

The area occupied by a block of cylinders must include space for access to the individual cylinders and access around the block of cylinders in a hold. Also included are additional area allowances for the structure of the transverse bulkheads and thickness of thermal insulation where it is applied. Therefore, the ratio between the area occupied by the cylinders in a hold and the gross area of a hold is typically below 0.4 for the CNG ships with a centerline longitudinal bulkhead. For CNG ships without the centerline longitudinal bulkhead and box beam the area utilization can reach ratio can exceed 0.4.

Block Coefficient

The choice of block coefficient also impacts the size of a ship. For a given displacement of the ship, a lower block coefficient will result in a longer ship. Hence, more steel weight, and more cost. However, smaller block coefficients, indicating finer hull lines, will reduce propulsion power requirements (CAPEX and OPEX), especially at higher ship speeds.

Ship Design Ratios

Among the factors used in the design of ship hulls, certain values of dimensional ratios are commonly used to arrive at hull dimensions that will result in an effective design. For example, the hull length to hull depth ratio (L/D) impacts hull steel and hull deflections; both need to be balanced to give the least amount of steel for acceptable hull stress and deflections in a seaway. The hull length to width ratio (L/B) influences stability, ship motions and propulsion power. The range of values of these ratios is also an indication of vessel type. Commonly used values for L/D in the design of ships (LNG and container carriers) are in the range of 9 to 13; for L/B these values fall in the range of 5 to 7. Typically, the ratios for the CNG ships are in line with those of LNG carriers; these are in the range of 10 to 12 for L/D, and 5 to 7 for L/B. Both LNG and CNG ships have typical draft/beam ratios between 0.4 and 0.5, as compared to tankers with ratios ranging between 0.65 and 0.75.

Stability and Motions

A ship's resistance to a static heeling moment is routinely expressed by its metacentric height, GM. The higher the value, the higher the initial resistance to a heeling moment, but the stiffer the ship will be, with higher lateral accelerations from its roll motions in a seaway. However, lower initial GM values may be an indication of a greater range of stability, which is a beneficial factor in the dynamic stability characteristic of the ship. For the purpose of ship sizing, a GM value between 10 and 20 feet (3 to 6 meters) is used in the present CNG ship designs.

For damaged stability calculations, it should be noted that the permeability of the cargo holds must account for the presence of the permanent, impermeable cylinders, i.e., the ratio of the volume of water flooding the CNG cargo holds when damaged is reduced by the volume of the cylinders themselves. In VOTRANS ships, these cylinders are individually buoyant but would not lift off their foundations under typical flooding assumptions. High pressure steel cylinders (as used for ambient storage concepts) are not buoyant but would similarly reduce permeability in the holds.

Cargo Hold Arrangement

With a specified volume of CNG to be transported per voyage, the *required* number of cargo cylinders is determined. However, the *actual* number of cargo cylinders that the ship can carry is determined by the arrangement of the cargo cylinders in each hold and the total number of cargo holds in the ship.

The arrangement of the cargo cylinders in one hold, and ultimately the arrangement and size of the CNG ship, is determined by the number of cargo cylinders per transverse row, the number of transverse paired rows (6,12,18, etc.) of cargo cylinders, and the total number of cargo holds.

To achieve a total volume of CNG approaching the required total CNG volume, the following steps are required:

a) determine whether the base hold will contain 12, 18, or 24 transverse paired rows of cargo cylinders
b) make initial assumption of a number of cargo cylinders per transverse row per hold
c) select a practical number of holds (and partial holds).

The choice of the size and number of cargo holds will be based on considerations of damaged stability. For example, fewer but longer holds, especially those at either end of the cargo section, may result in unacceptable trim in a damaged condition, or in unacceptable loss of stability due to free surface effect from damaged compartments. Varying the number of cargo cylinders per transverse row in the holds may also be used to further fine-tune the design, such that all holds are identical with the same number of cargo cylinders in each hold. An additional variation, for damaged stability reasons, would be smaller holds, forward and aft, with fewer cargo cylinders.

In most cases, the above design process in determining the hold arrangements will result in an *actual* total volume that will differ from the total *required* volume. With too large a difference the above process should be repeated until an acceptable difference, and a practical arrangement, is found.

Block Coefficient

For ship speeds between 17 to 20 knots, block coefficients between 0.75 and 0.80 seem to result in acceptable propulsion power requirements. Below 17 knots, block coefficients may vary above 0.80. Above 20 knots, these values may be in the 0.65 to 0.75 range. In the most recent EnerSea CNG ship designs, block coefficients of 0.75 to 0.80, with 0.77 as an intermediate value, have been used.

Light Ship Draft

The starting point in the CNG ship design has been a maximum light ship draft of 7.50 meters. For the smaller ships of 10-12E6scm capacity, lesser drafts, down to 6.50 meters, were obtained with acceptable ship proportions. Any attempt to maintain 7.50 meters lightship draft when designing ships above 20E6scm capacity produces very large ship dimensions. More practical dimensions may be achieved if deeper lightship drafts are allowed for such large vessels.

Ship Dimensioning

With the hold arrangement of the ship determined as discussed above, and with proper allowance for transverse bulkhead stiffening and access clearance, the length of the total cargo section of the CNG ship can be determined. Ship length can be estimated based on variable input percentages of bow and stern length, and the calculated length of the cargo section as a percentage of the total length.

The depth of the hull is chosen so that acceptable L/D ratios are achieved in the subsequent design iteration process. However, it should be kept in mind that the horizontal restraint of the cargo cylinders at the main deck level determines the unsupported length of the cylinders above the restraint, which impacts the deflections of the top of the cylinders and their piping connections.

As the total width of the cargo holds between the wing tank bulkheads is determined by the number of cylinders in a transverse row, cylinder spacing and bulkhead clearances, the calculation of wing tank width is an iterative design process involving the determination of hull section modulus, hull weight and use of the input block coefficient. Subsequent iterations require variations on percentage lengths of the bow and stern sections and updating main scantlings to meet hull section modulus requirements to calculate new wing tank width, ship beam and associated ship length. While maintaining the given light ship draft and block coefficient, the iteration process is repeated until the calculated length and beam of the ship results in values of L/B, L/D and GM, which fall in the ranges discussed above.

If the aforementioned iteration has not produced practical ship dimensions, and unacceptable L/B and GM values, the most obvious remedy for the bigger ships is to change the limiting lightship draft to a deeper draft until the above iteration process results in acceptable ship dimensions. For the smaller ships, reducing the lightship draft to less than 7.5 meters has the same effect.

Varying the block coefficient is another option. For a given displacement, increasing the block coefficient will result in a shorter, and possibly wider, ship. A decrease in the coefficient will result in a longer ship with possibly less beam.

V-Ship Design Case

As a case study, consider a project involving transport of pipeline quality (lean) gas over a distance of approximately 2020km where a fleet of four(4) V-ships is designed to deliver approximately 6.8E6scm/day (~240mmscfd or 1.8E6 TPA). If these ships sail at 18kts (33.3km/h) cruising speed, logistics analysis has indicated that each should be capable of transporting 17.4E6scm of CNG. To provide this capacity, each vessel must be equipped with 2016 cylinders. The cylinder arrangement and design features described in the preceding are reflected in the ship depicted in Fig. 4 below. The ship has an LOA of 277m with a 52m beam.

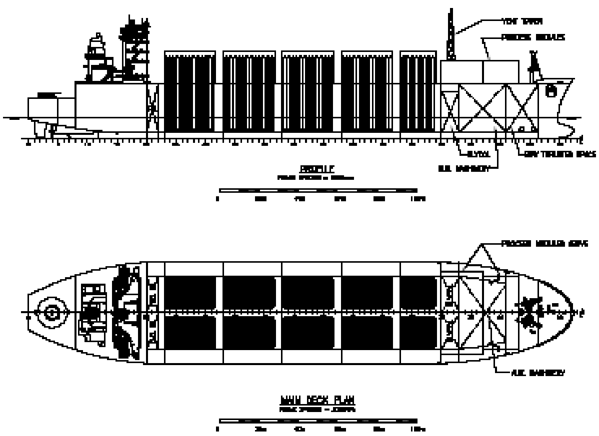

Fig. 4: “V-ship” CNGC example

Barge Design

General

In recent years, EnerSea has worked with ACMA to generate barge CNGC designs based on the Articulated Tug-Barge (ATB) concept for a number of projects involving relatively small transport rates and shorter distances (typically, <1E6 to 2E6 scm/d and 400-1200km). For barges, a horizontal cylinder arrangement has been adopted where cylinders of relatively great length are placed in a long “cold box” on deck. EnerSea calls the refrigerated deck cargo boxes “Z-Packs™” due to employment of the efficient design practice for minimizing the gas compressibility, Z factor.

Since the barges are designed to operate in ATB configuration and since relatively high transit speeds are required, relatively long fore and aft hull sections are included. Otherwise, the barge design is a straightforward deck barge design exercise once the size and quantity of Z-Packs have been determined recognizing that the Z-Packs are relatively tall, heavy cargos when filled. So, the stability of the barge must be carefully checked.

The tugs will be high powered and possibly dual-fueled to take advantage of the gas fuel supply onboard the barges. However, the most dramatic feature of the tugs will be the elevated pilot house that will provide visibility over the Z-Packs that may be more the 20m tall. The barges are also equipped with a very tall gas vent relief stack (>40m), but it is so narrow that it will not impair navigation.

Z-Pack Design Options

A barge may be designed to carry one or two Z-Packs. Currently, Z-Packs have been configured in 58m, 76m, and 94m lengths, to contain cylinders with 54.9m, 73.2m, and 91.4m long pipe bodies (incorporating 3, 4, or 5 60ft joints of pipes, respectively). The Z-Pack supports the cylinders on a series of strong racks with saddles to secure the position of the cylinders. These primary support frames and the transverse bulkheads must be spaced out to align with each other. Careful analysis has determined that 5 support frames provide a rational support system for the 76m box and appear to be adequate for the 94m box. The cylinders are secured to the central frame and allowed to slide over the fore and aft support frames on a low cost, low friction bearing material.

EnerSea has developed a spreadsheet tool to track the design properties for Z-Packs based on the results of the case specific engineering performed for the 76m case. This tool allows the designer to assess 1 or 2 box configurations for barges to rationally meet a specific transport capacity. This allows the barge details to be well defined with relative ease.

Barge Design Case

ACMA and EnerSea have developed and analyzed a Z-pack (and barge-tug) design for a specific gas transport opportunity to a depth of detail that allowed ABS review for Approval In Principle. In that case, a fleet of two tugs would drive four barges over a 550km transit to provide a continuous supply of natural gas to a power plant at a rate of about 7.5E5scm/d. Logistics analysis indicates that each barge would need to carry about 1.36E6scm of CNG contained in 84 cylinders in a Z-Pack approximately 76m long. The barge configured for this case is depicted in Figures 5 & 6 below.

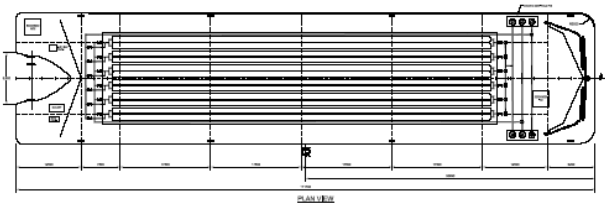

Fig. 5: Plan View of Z-Pack on A-T-Barge

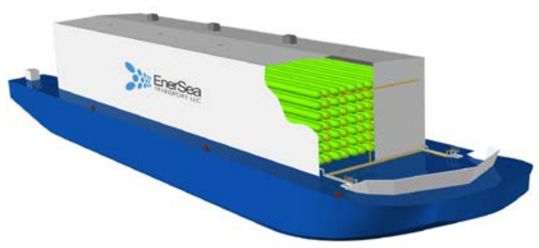

Fig. 6: "VO-Barge" CNGC image

Small Ship Design

General

Most recently, EnerSea and ACMA have adapted the Z-Packs with horizontal cylinders to a deck cargo ship CNGC design for project opportunities that demand higher speed transits than offered by the ATBs and capacities between the barge and V-ship concepts. Since these ships are based on application of the Z-Pack concept refined for the ATBs, EnerSea calls them Z-ships.

Hull Sizing

Hull sizing is dominated by the CNG cargo capacity requirement and the selection of the Z-Pack configuration. The spreadsheet tool developed for barge cases serves to set the baseline parameters that drive ship hull sizing. It is clear that the ship hull length is impacted by rather large discrete steps in Z-Pack sizing. There is limited flexibility in setting these step sizes predicated by pipe industry manufacturing standards (typically, 12m or 18m joints). In addition to the Z-Pack(s) placed on the open cargo deck, many Z-ship designs will also be required to provide deck space forward and payload capacity for a substantial amount of gas handling equipment.

Although current project development requirements do not allow the disclosure of details about a specific design case, an example of this efficient small gas carrier concept is presented in Fig. 7 below.

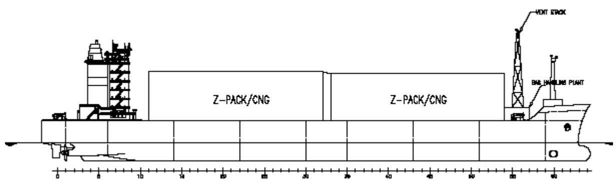

Fig. 7: Profile of CNGC for Z-Pack Transport

Conclusions

Marine transport of compressed natural gas is evolving as a new industry to support the needs of both energy producers with stranded gas assets and energy-hungry markets that wish to avoid the pollution and high prices that currently characterize oil-based consumption. The need for CNG Carriers is driving the development of guidance for safe design, construction, and operation of CNGC fleets by class societies and regulators. It is, of course, also driving the evolution of new designs to serve a range of supply-market demands and conditions. This paper has described the process and key principles being applied to the design of barges and ships intended to serve as CNG Carriers for a range of project opportunities around the globe.

Acknowledgement

The authors would like to acknowledge their appreciation to EnerSea Transport LLC for supporting the development of this technology and to the classification societies such as the American Bureau of Shipping, Bureau Veritas, and Det Norske Veritas for establishing the guidance necessary to introduce CNGCs safely to the world-wide fleet.

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