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Material selection for the gas containment system of a compressed natural gas carrier fleet

M. Gaiotti [a], C.M. Rizzo [a], E. Rizzuto [b], G. Vernengo [a,*]

[a] Department of Electric, Electronic, Telecommunications Engineering and Naval Architecture (DITEN), University of Genoa, Italy
[b] Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Italy

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ABSTRACT

In this work, the possible exploitation of fiber-reinforced composites in the context of maritime transportation of compressed natural gas (CNG) is investigated. In addition to a more conventional steel configuration, two different fiber materials, carbon and glass, are considered as construction materials for pressure vessels (PVs) to be stored on board ships, with thickness optimized by FEM analysis.

The considered scenario is represented by the transportation of CNG from an offshore well to a terminal on shore. Fleets of ships carrying CNG in pressure vessels manufactured with the investigated materials are generated by means of a ship synthesis model (SSM) software and compared on the basis of technical and economical indicators.

The choice of the construction material influences considerably the weight of the PVs, which represent a major item of total ship weight and reflects directly on the general transport performances in terms of resistance, seakeeping and reliability in the service. On the other hand, capital as well as operating expenditures are considerably affected by the choice. When exploring the design space, the ship synthesis model is able, at a preliminary stage of the design, to account for the various technical and economical aspects, their implications and relationships. Results are presented of computations carried out in a specific case, identified by the annual gas production and other characteristics of the well terminal and a cruising route for the ships. The comparison is carried out on the basis of the cost per transported unit of gas and of the percentage of success in the transportation process. The computations show that the choice of the PV material has a key influence on the results in terms of optimal number, dimensions and speed of the ships.

1. Introduction and motivation

The present work is aimed at evaluating, from both a technical and an economical viewpoint, the introduction of composite materials for pressure vessels in a marine transportation context.

Fiber reinforced plastic (FRP) materials have been used for decades by the marine industry, particularly in the field of small recreational boats. More recently, FRP has been used in larger and larger structures such as airplanes, wind turbine blades and, in the marine field, for the whole hull of naval vessels like mine-hunters, superstructures of passenger ships, various ship equipment and components, parts of offshore structures for the oil and gas industry [1].

The low material density, combined to the possibility of improving the mechanical properties by designing the material for specific purposes, makes FRP an interesting option when weight savings have to meet with structural requirements; in particular, composite materials are usually employed to produce slender, high strength structures for advanced performances.

In the present case, the adoption of a composite containment system for CNG is considered and compared to a more traditional solution, i.e. steel PVs: the impact of the choice of FRP materials for the gas containment system and of the corresponding redefinition of scantlings for the pressure vessels and of lightweight for the ship is assessed with reference to the design of a fleet of CNG carrier ships.

The motivation of this investigation stands in the quite high percentage of the ship lightweight and of the total ship displacement allocated to the PVs in CNG carriers. To give a general idea, in a preliminary computation for a ship carrying CNG in about 500 steel PVs, at a realistic pressure for this type of transportation (230 bar), the gas storage system accounts for as much as the 75% of the ship's lightweight. It is to be noted that the CNG cargo features quite a low specific density equal to about $0.2t/m^3$ at the loading pressure and to about $0.02t/m^3$ at the unloading pressure.

* Corresponding author.
E-mail addresses: gverneng@mit.edu, giuliano.vernengo@unige.it (G. Vernengo).

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The higher construction cost of PVs realized in FRP is likely to be compensated by a significant reduction in the ship displacement, which is in turn reflected in lower operational costs. The possibility of standardizing the dimensions of the PVs and to produce them in quite a large number of samples is seen, too, as a promising factor for keeping the manufacturing price relatively low.

Some studies on the use of composite material for the gas containment system have been published. Advantages of the composite solution were illustrated by Nikolaou et al. [2]. They analyzed the relations between the distance of the marine transport, the gas production rate and the net present value (NPV) comparing LNG technology with the CNG one, using both metal and composite material vessels. Economides et al. [3] investigated the economic feasibility of CNG technology concluding that this type of transport should be very competitive for short distance trades, especially using new generations of ad-hoc designed ships. Examples of novel ship designs specific for CNG transport can be also found in [4,5] or in [6]. No information about actually trading ships has been found to the best of the authors' knowledge. Meanwhile of some of these concept designs some classification society have developed their specific rules to classify this new carriers (see for example [29,27,23]).

Another relevant topic related to the design of the gas containment system deals with the thermodynamics of the gas during the loading and unloading operations and with the possible use of the gas itself in the propulsion system. Those subjects, faced with different approaches for example in [7,8] or in [9], have a relevant impact on the design of the ship and on the overall trade economics.

These studies focus on specific aspects of the transport of Natural Gas, concentrating on solutions of PV design and arrangement or on aspects regarding the gas treatment. The present work aims at more holistic approach, merging technical and economical elements regarding aspects of the CNG transport with other ones typical of the ship transport system. The aim is to explore how specific choices on the construction material may affect the overall selection of the characteristics of the fleet of ships able to satisfy the transport requirement. The investigation is carried out at a preliminary design stage and is based on relatively simplified models for the single aspects covered: for instance in the present study the energy required for the compression of the gas is evaluated by simple thermodynamic computations accounting for the compression and expansion of the natural gas and such information are used to choose the size of the compressors, with inherent weight and cost.

Data on unit weights and costs were fed in the procedure described in the paper. Such data were derived from information available to the authors by various sources and were selected to be as much realistic as possible. The numerical results and the ranking of solutions depend on the values adopted; thus, the use of different data, which can anyway be easily fed into the procedure, may provide different results. It is here remarked, however, that the main result of the study is to show how a choice regarding the PV material is likely to impact all the major parameters identifying the optimal solution to the ship transportation problem.

2. Investigated arrangement and characteristics of the PV

2.1. Arrangement of pressure vessels in the cargo area

The investigated layout for the CNG carrier ships is shown in Fig. 1. All the PVs feature the same shape, i.e. a cylinder with two spherical ends, and show the same circular cross-section having an internal diameter of 2.0 m. The PVs are arranged in a vertical position in regular rows. The height of the PVs is kept constant within the same ship, but changes for each investigated ship configuration. The arrangement described above will be considered for all the analyses presented in this paper.

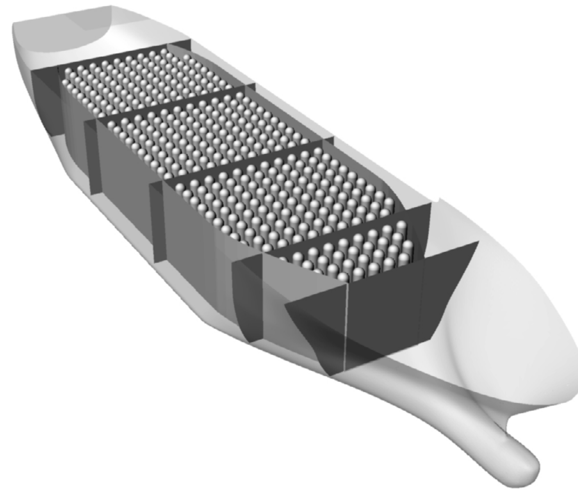

Fig. 1. Lay-out of the ship cargo area.

2.2. Materials for the pressure vessels

In the following, a typical steel used for PVs in other fields, such as ASTM/ASME A/SA 533 Type C, DIROS^{TM} 500 HT steel, has been compared with two alternative materials for gas containment, represented by plastics matrices reinforced by E-glass and carbon fiber, respectively.

The characterization of the mechanical properties of these materials features different degrees of uncertainty. For isotropic steel, the identification of such properties is based on relatively straightforward and well-established experimental tests, whose results are reliable and reproducible, while for a fiber reinforced plastic material a correct mechanical characterization is often a challenge.

Even neglecting the influence of resin composition on the interaction with the fiber surface (wettability), the parameters governing the curing reaction such as ambient temperature, post curing, exothermal peak, humidity, etc., have a direct influence on the mechanical properties of the 'as-built' composite. The fabrication method and the quality of the procedure is also very influent, see e.g. [10,32].

In the present paper, average values of mechanical properties have been considered, derived either by experimental tests previously carried out by some of the authors or by well-established literature data.

For PVs realized in composite materials, a liner consisting of a thin, non-structural layer often made of a metallic material provides a barrier between the CNG and the composite structure, thus preventing leaks, which can occur through matrix micro-cracks, and chemical degradation of the structure.

The presence of the liner has been neglected in the analysis: the approximation in terms of weight is very small, because of the very limited thickness of the liner (of the order of fractions of a millimeter). As regards the cost, an economic impact could be present, slightly affecting the comparison between the steel PVs and the composite ones. Due to lack of data, the cost, too, of the liner has been ignored, but could be easily included in future versions of the model.

2.3. Steel

ASTM/ASME A/SA 533 Type C is a vacuum treated quenched and tempered fine-grained steel. It is predominantly applied for pressure vessels where weight saving is a very important parameter [28] as well as e.g. in offshore and marine structures. Due to its production process and its chemical composition, this