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New methodology for estimating the minimum design vapor pressure of prismatic pressure vessel for on-ship application

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ABSTRACT

This paper presents a methodology for estimating the minimum design vapor pressure of prismatic pressure vessels for on-ship application. Engineering authorities guide the codes for a novel concept design such as a prismatic pressure vessel using a design by analysis (DBA). DBA methods enable high efficiency because they directly calculate the loads to avoid inherent conservativeness that exists in a design by rule (DBR). However, in DBA methods, the designer should conduct a finite element analysis (FEA) and evaluate the results iteratively to meet the design criteria. In this paper, we propose a new approach to estimating the minimum vapor pressure of a prismatic pressure vessel that follows the design philosophy of an IMO Type C independent tank. The procedure of the proposed method was demonstrated based on a case study. An FEA was also conducted for verification purposes. The results show that the proposed method can effectively estimate the required minimum shell thickness and designed vapor pressure without conducting an iterative FEA. In addition, minimization of the tank shell thickness is made possible because the proposed method directly calculates the crack propagation rate to avoid an unnecessary margin while satisfying the fatigue crack propagation criteria.

1. Introduction

The research and development of liquefied natural gas (LNG)-propulsion ships have been ongoing as a promising response to the SOx emission regulations that will go into effect in 2020 (Wan et al., 2015; Schinas and Butler, 2016). LNG fuel is the most reasonable solution, and can satisfy the current and upcoming regulations for the principal types of emissions (NOx, SOx, CO_2). Among the fuel types considered, LNG has the advantages of a low price (Klein, 2011). However, there are some critical impacts of using LNG fuel in a ship design. Because conventional oil fuel is stored under atmospheric conditions, it can be easily stored in hull structural tanks. However, when using LNG fuel, there are several aspects that require special consideration. First, the density of LNG (0.45 ton/m^3) is more than twice lower than that of heavy fuel oil (HFO) (0.98 ton/m^3). Considering the heat values of two fuels (LNG-49 MJ/kg, HFO-40.6 MJ/kg), the required volume of an LNG fuel storage tank becomes 1.8-times that of an HFO fuel storage tank to obtain the same engine output. Secondly, LNG is a liquified gas that operates at cryogenic temperature. It requires insulation, and most of the tanks that store liquified gas are cylindrical pressure vessels. Comprehensively, the capacity of the LNG storage tank should be 3- to 4-times larger than that of an oil tank in order to obtain the same engine output (Van Rynbach, 2014).

Thus, it is clear that the critical issue for an LNG fuel storage tank is to maximize the volume efficiency. Considering the volume efficiency issue, conventional membrane type tank or IMO type B tank have been the best option since those can be constructed as prismatic shape. However, since the both tanks are non-pressure vessel, the design vapor pressure is limited not to exceed 0.7 barg by rule (IMO, 2016a,b). Even though a reasonable insulation system is designed, heat leakage in the tank causes LNG to continuously evaporate as BOG (Choi et al., 2016). The pressure build-up due to the BOG must be handled by a strengthened thermal insulation or a BOG re-liquefaction system to ensure that the generated vapor pressure should not exceed the 0.7 barg during the voyage. Even though the membrane tank has been widely used for the LNG carriers, still lots of research and developments are going on regarding the thermal insulation system (Niu et al., 2017; Choi et al., 2016) and the BOG re-liquefaction system (Yoo, 2017; Tan et al., 2016), meaning that still it has some challenges to overcome. On the contrary, IMO type C tanks which are conventional cylindrical pressure vessel are designed to

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withstand the pressure build-up due to the BOG (IMO, 2016a,b). This means that IMO Type C tanks have high flexibility in the BOG handling and that CAPEX and OPEX can be saved accordingly (Natural Gas Global, 2017). However, main weakness of these pressure tanks was the low volume efficiency (Lee et al., 2017). The newly developed pressure vessel can overcome this weakness.

Chang and Bergan (2012) developed a prismatic pressure vessel based on a new concept, a so-called lattice pressure vessel where the internal structure acts as a pressure loading part to withstand the high internal pressure. Ahn et al. (2017) proposed a prismatic pressure vessel for a gas-fueled ship. In their research, it was proved that a prismatic pressure vessel can be applied to cryogenic pressure vessels installed on a ship.

Many different studies on the development of a prismatic pressure vessel have been conducted. However, currently there are no clear standards for estimating the minimum design vapor pressure of a prismatic pressure vessel in the initial design stage.

From the thermodynamic point of view, the "minimum design vapor pressure" can be interpreted as the lowest pressure build-up due to the BOG generated by the heat leakage of the LNG cargo loaded at normal pressure in the LNG storage tank during the voyage. The generated vapor pressure is the dependent on the thermodynamic characteristics of the designed tank including heat ingress rate due to the surface area of the tank, insulation performance, etc. Choi et al. (2015) proposed a method that simultaneously considers the vapor pressure and the liquid pressure in dynamic condition for prismatic LNG storage vessel. That research estimated reasonable design pressure considering dynamic force by ship motion and actual state of the LNG. However, the limitation of it is that the storage vessel that were used for case study was not a pressure vessel and also it didn't consider fatigue crack propagation that must be considered for Type C independent tank to prevent cargo leakage at the life cycle operation.

Pressure vessels on a ship must satisfy the fatigue crack criteria during a ship's voyage. For the existing cylinder-type pressure vessel (Type C independent tank) used on a ship, a formula is used to determine the minimum vapor pressure based on the IMO design regulations (IMO, 2016a). The current formulae are established based on a cylinder-type structure, which is mostly affected by membrane stress, it is necessary to modify the structure when applied to a prismatic pressure vessel, which is mostly affected by the bending stress. The minimum design vapor pressure of the conventional pressure vessel is determined according to the DBR method based on experimental data that represent the amount of possible fatigue crack propagation under the most severe conditions that can occur during the 20-year lifetime of ship (Kime et al., 1977). It is possible to apply all possible conditions without calculating the dynamic load or fatigue crack propagation rate for each individual case. This enables an effective reduction in the overall design time. However, because the formula is based on the most severe loading condition when applied to each individual case, it is difficult to know how much margin it contains. If the estimated value is significantly higher than the original criteria, the structure can be over designed, and therefore it is disadvantageous from an economical perspective.

The engineering authorities guide the design codes (IMO, 2016b) for novel concepts such as a prismatic pressure vessel. A DBA can be applied using a numerical analysis (typically, a finite element analysis), and the results can be evaluated against the design criteria. Unlike a DBR, with this type of methodology the load required for each case is directly calculated, and thus a design can be created more economically and efficiently. However, a separate calculation of each load should be considered. In addition, it is difficult to reflect the correlation between the design variables and the various loads required, and thus the design should be conducted through trial and error, which leads to an increase in the overall design time (see Table 1).

If the minimum design vapor pressure of a prismatic pressure vessel can be determined based on the fatigue fracture criterion, such as in the conventional pressure vessel of a ship determined using a DBR method, it will not be necessary to reassess the pressure several times during the design process. In addition, for the current DBR method, the minimum design vapor pressure is solely determined from the viewpoint of the fatigue crack propagation irrelevant to the actual increased pressure due to the BOG or operating condition. If the actual vapor pressure, which can be pressure build-up during the operation condition or operating pressure is higher than the estimated minimum vapor pressure by rule, than the estimated actual vapor pressure is used for calculating the design vapor pressure. However, if the actual vapor pressure is lower than the estimated minimum vapor pressure by rule, the minimum vapor pressure by rule is used for calculating the design vapor pressure (Fig. 1). This kind of a standard is also requisite for the novel concept prismatic pressure vessel since there are no clear standards for estimating the minimum design vapor pressure of a prismatic pressure vessel in the initial design stage.

Table 1
DBR VS. DBA for the prismatic pressure vessel application.

	DBR	DBA
Pros	Can pursue design procedure efficiency	Can pursue economical design (Design efficiency)
Cons	1 Can be overdesigned (Inherent conservativeness) 2 Crack propagation model should be modified including the bending stress for the prismatic shape application	1 Difficult to reflect the correlation between the design variables and the required various load 2 The design should be conducted through trial and error which leads to an increase in the overall design time

The final design should also include pressure build-up due to BOG, buckling, and sloshing in addition to these fatigue crack propagation criteria. However, the existing type C rule only considers fatigue crack propagation criteria and liquid pressure when estimating the minimum wall thickness (Senjanović et al., 2006). Buckling or sloshing criteria are satisfied by considering additional buckling rings or swash bulkheads. Similarly, in this paper, the scope is limited to calculating the minimum vapor pressure of the novel concept pressure vessel based on the design criteria of fatigue crack propagation.

In this paper, we propose a combined methodology using DBA and DBR methods that can achieve both design efficiency and convenience in estimating the minimum design pressure for a novel prismatic pressure vessel in compliance with the IMO pressure vessel design philosophy. For verification, the results of the proposed method are compared with those determined through an FEA.

2. Background

In this section, in order to describe the general procedure of the proposed method three things are priory discussed. First, in section 2.1–2.3, the general procedure for estimating the design pressure of a pressure vessel used on a ship, in compliance with the IMO pressure vessel design philosophy, is described. The design pressure consists of the sum of the maximum liquid pressure and the design vapor pressure. The design vapor pressure determined using the DBR method was reviewed to examine both its advantages and disadvantages. Secondly, in section 2.4, the general characteristics of prismatic pressure vessels and the simplified formula for estimating the maximum stress are described. Lastly, in section 2.5, modified fatigue crack propagation model considering bending stress are described.

2.1. Design pressure

The method and philosophy for estimating the design pressure of a