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A SCALABLE AND PRISMATIC PRESSURE VESSEL FOR TRANSPORT AND STORAGE OF NATURAL GAS

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Abstract. This paper deals with a new, innovative concept for storage and transportation of gas, notably natural gas under cryogenic, liquefied, and pressurized conditions. This new prismatic pressure vessel design differs largely from traditional pressure vessels that typically are cylindrical or spherical shell structures. The current design principle is based on balancing the pressure on opposite outer walls by way of an internal, force transferring tension structure. This internal structure has the appearance of a lattice; thus, this type of tank is termed the "Lattice Pressure Vessel" (LPV). The LPV is fully modular and scalable in the three spatial directions. It has the potential of becoming a key component to facilitate the transition from heavy fuel oil and marine fuel oil to the much cleaner natural gas and hydrogen as fuel for propulsion of ships. The paper describes design principles, outlines how computational analyses have been verified by comparing results with four different, instrumented test tanks. Moreover, a series of examples of pressure vessel designs are given which illustrate the benefits of structural efficiency as well as the ability of fitting such pressure vessels within the limited space on board ships.

1 INTRODUCTION

The ambitious targets for sustainability and climate gas emissions set by the UN climate conference in Paris in 2015 must be followed up with concrete actions of regulations and practical measures of implementation. One example of such new regulations is the recently approved, strict emissions requirements from ships to be implemented from year 2020. Further, every country must act to reduce own emission of pollutants and green-house gases with concrete targets for year 2030. This means that renewable energy should replace dirty coal and oil fired energy production. Use of natural gas, rather than coal and oil, will be a key step towards using cleaner fuels in energy production and transportation. To this end a new global infrastructure for distribution, transport and storage of liquid natural gas (LNG) should be built within few years.

The key element in distribution and use of LNG is the storage tanks. Large amounts of LNG, at the atmospheric boiling point of -163 degrees C, can be transported with ships with large insulated, unpressurized containments from liquefaction plants to major distribution facilities on land or at sea. However, the gas itself may largely be used in smaller power production facilities or for transportation purposes where the fuel tanks are relatively small and, consequently, heat ingress will lead to increased gas boil-off. This problem can be dealt with by complicated and expensive regasification systems or simply by containing the LNG within tanks that allow for pressure build-up (emission of methane-rich gas to the atmosphere is not allowed). The latter solution is clearly preferably in most cases.

The paper describes a "first of its kind" type of pressure vessel which is fully scalable in size and prismatic in shape rather than cylindrical or spherical. The design principle is based on balancing the pressure on opposite outer walls by way of an internal, force transferring tension structure. This internal structure has the appearance of a lattice; thus, this type of tank is termed the "Lattice Pressure Vessel" (LPV). The LPV is fully modular and scalable in all three spatial directions. Unlike cylinders, the thickness of the outer shell/gas barrier does not increase with tank size; the stiffened plate structure only depends on the design pressure. The concept has several other advantages over current pressure tank design such as ease of thermal insulation, overall space utilization efficiency, a redundancy-based safety concept, and ease of fabrication with moderate plate thicknesses and flat panels.

2 THE IDEA AND DESIGN CONCEPT

2.1 Classification of LNG tanks

The classification of containments for LNG is set down by IMO and defined as independent tanks or integrated tanks. The independent tanks are again divided between Type A with low pressure and full secondary barrier, Type B with low pressure and partial secondary barrier, and Type C which are pressurized tanks with no requirement for secondary barrier. Further, the integrated tanks are typically referred to as membrane tanks, which are low pressure tanks and rely on the ship hull for providing strength. Main codes that apply are the International Gas Code (IGC) [1], and the International Fuel Gas Code (IFC) for gas fuel tanks [2], and ASME's boiler and pressure vessel code [3]. On top of this, any LNG tank must also comply with requirements set by the different classification societies.

The new pressure vessel described herein belong to the IMO Type C; however, IMO describes a pressure vessel as being cylindrical or spherical simply because prismatic pressure vessels have not been a consideration until now. In agreement with classification societies such as DNVGL the LPV is described as "Type C equivalent". Clearly, all requirements in the present codes also apply for Type C equivalent tanks.

2.2 Design concept

The basic concept of the LPV is that pressure on the gas barrier shall mainly be carried by an internal load carrying structure rather than by the gas barrier itself as for cylindrical and spherical shell structures. An exemplification of this principle is shown in Figure 1 where the pressure on opposite walls of a prismatic pressure vessel is balanced by way of a series of parallel panels that the combine the two. A panel provides connection between both horizontal surface panels and between vertical surface panels; this implies that the panel obtains a very efficient load and stress utilization. Clearly, the end plates require special attention since they are not directly supported by parallel panels. For large end plates this problem is dealt with by a special “end box design” which efficiently resolves this problem.

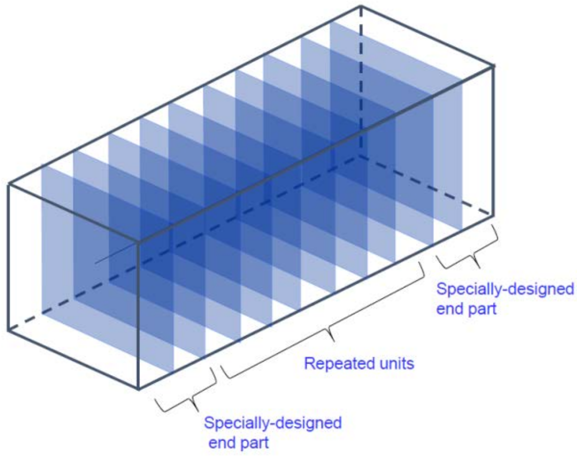


Figure 1: Internal load carrying structure with parallel panels

Figure 2 illustrates the LPV principle in some further detail. Stiffening is required for the parallel panels for reasons of lateral strength and stability. Further, the outer skin is supported with stiffeners between the parallel panels to withstand the internal design pressure. All corners are rounded to minimize stress concentrations that in fact would be prohibitive for pressure vessels with sharp corners. All in all, the design is based on carefully balancing stiffness and deformations in such a way that the LPV deforms uniformly and the stress utilization is optimized without generating undesirable “hot-spots”.

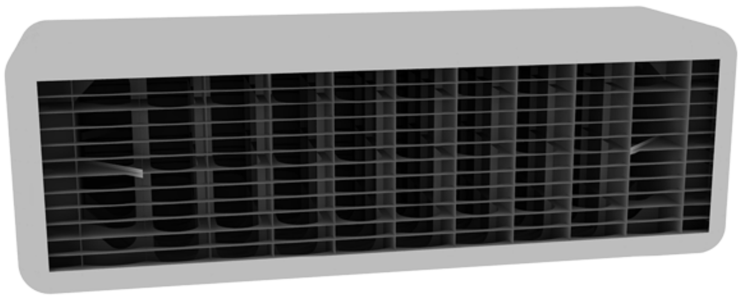


Figure 2: LPV with panels, skin stiffeners and rounded corners

The internal structural system outlined in Figure 2 is not the only alternative that has been explored for LPVs. For instance, reference [4] deals with an internal structure that is composed of so-called X-beams. Normally the parallel panel design is more efficient than the X-beam design dealt with in the reference. Several patents have been obtained for the lattice designs, see e.g. [5] and [6].

3 ANALYSIS AND ENGINEERING

3.1 Design loads

The problem of designing partly liquid filled pressure vessels under cryogenic conditions onboard a moving ship in the ocean may be further understood when considering the number of load conditions that such tanks must be designed for. Table 1 shows an overview of such load cases that must be analyzed and designed for.

Table 1: Load cases that must be analyzed and designed for

Load type	Loads	Analysis reports
Permanent	Gravity, External	Structural analysis of LPV under dead load
Functional	Internal pressure, test	Structural analysis of LPV under internal pressure
	Static heel	Structural analysis of LPV under static heel loads
	Cargo weight	Structural analysis of LPV under cargo weight
		Ultimate load analysis
	External pressure	Structural analysis of LPV under external pressure
	Thermal	Temperature distribution of LPV
		Thermal stress analysis of LPV
		Temperature distribution around LPV
		Heat transfer analysis
	Vibration	Modal analysis of LPV
	Construction and Installation	Stress analysis of lifting components
		Stress analysis of supporting structures
		Estimation of support load
Environmental	Ship motion	Estimation of liquid pressure load
	Sloshing	Estimation of sloshing load
Accidental	Collision, flooding	Impact analysis of LPV
Combined	Combined loads	Structural analysis of LPV under combined static loads
		Structural analysis of LPV under combined dynamic loads
		Structural analysis of complex loading cases for LPV
		Fatigue and fracture analysis of LPV
		Buckling analysis of LPV

It is apparent from this table that almost all branches of computational mechanics must be resorted to fully provide the required documentation of acceptable performance. Not only will the tank have to be analyzed with respect to stress and deformations, typically by way of finite element simulations, but also additional analyses will include heat conduction and thermal deformations, fluid phase transitions, dynamics, cracking and fatigue, stability and nonlinear failure analyses, fluid-structure interactions (sloshing), and even interaction between the ship and the LPV. Fortunately, current state-of-the-art of computational mechanics makes such analyses possible and good computational tools are available for this purpose. It will hopefully be understood that it will not be possible here to go into details about how these analyses are done in practice, however, the tasks themselves may be said to be interesting and challenging. It is also to be noted that the classification societies require full documentation of these aspects with reports more than 20 in number for the specific tank application considered. It may be of interest that the LPV design has an advantage over traditional shell or membrane tank solutions in that the LPV has internal structure that very efficiently dampens the fluid motion and the dynamic fluid pressure are small and without consequence. Still, it must be documented that sloshing is no problem for each case.

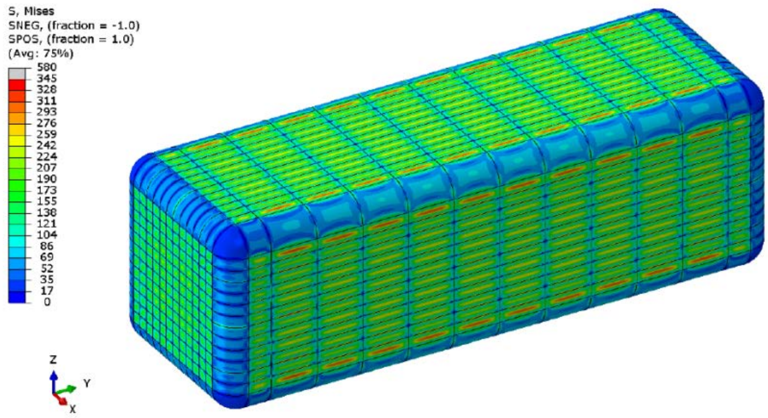


Figure 3: Stress results for the outer skin of a LPV

Figure 3 shows surface stresses for a pressurized LPV. Note the remarkably smooth and repetitive stress distribution patterns. The corners are clearly less stressed than the rest of the outer skin. Maximum stresses are noted along the midst of the plate fields next to the corners where the outer surface fibers are under compression. The codes allow higher stresses in the case where there is bending through the thickness rather than for uniform tension through the surface skin (as in a cylindrical shell).

3.2 Supports and interaction with the ship

For LPVs onboard a ship a consideration is to establish about how the LPV interacts with the ship itself. Clearly, this problem depends not only on the LPV, but just as much on the motion and deformation of the ship hull and the closest structural elements in the ship. Further, the pressure vessel will contract considerably due to the cooling to down to cryogenic conditions, such as down from ambient temperature to – 163 deg C for LNG; such contraction may be as much as 10 to 20 cm for a large tank. Thermal deformations and stresses are function of temperature change in relation to ambient temperature and the thermal expansion (contraction) properties of the material. For the case where the entire tank is subject to uniform cooling there will be no thermal stresses generated, however, the support conditions must be allowing for uniform contraction.

Figure 4 shows an example of support system for a prismatic LPV tank. There are essentially two types of support, one that allows for constrained sliding in a prescribed, horizontal direction, and another that allows for free horizontal sliding and gives only vertical support. The support blocks are made of compressed wood that provides necessary insulation between the cold tank and the ship. Tracks in the wood blocks and steel guides provide necessary constraints for that force the sliding to be confined to the prescribed direction. The concept requires that one point is selected as fixed reference points and that all sliding supports should allow for motion in the direction from the support towards this fixed point. The function of the guides is to keep the tank in place and to be able to absorb gravity and inertia forces during ship motion.

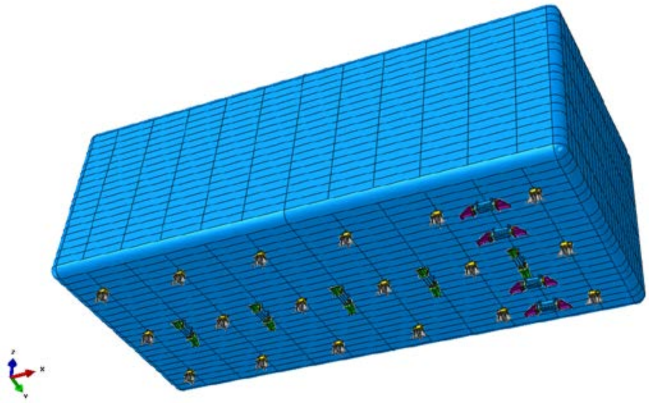


Figure 4: Example of support system

The tank has also to be checked for thermal stressing during certain filling conditions in which there may be significant temperature gradient within the tank. The uniform structural system of the tank gives relatively small thermal stresses during such conditions. Moreover, an unventilated LNG tank is also subject to internal pressure build-up due to heat ingress; typical pressures to be designed for are 3 to 10 barg (0.3 to 1 MPa). The uniformity of the internal load bearing system leads a rather uniform expansion of the tank which is nicely dealt with the support system described before.

3.3 Thermal insulation

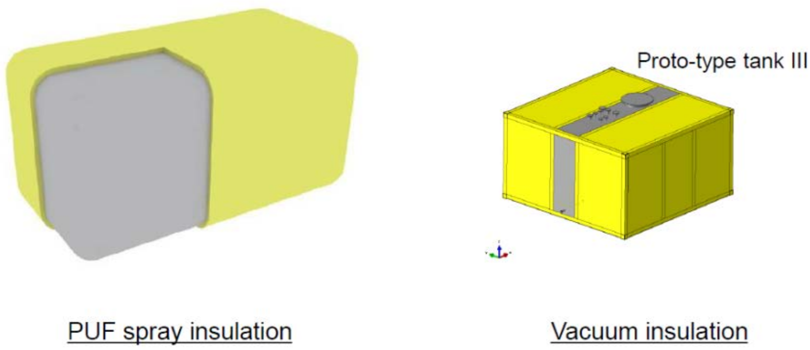


Figure 4: Alternative ways of thermally insulating a cryogenic tank

There are mainly two types of insulation used for cryogenic pressure vessels: polyurethane foam (PUF) and vacuum insulation. In the former case layers of PUF are sprayed onto the external surface of the tank, normally laid to thickness of 30 to 40 cm. Vacuum insulation is generally only used for relatively small tanks. In such case the insulation is provided by vacuuming a layer of perlite that is filled between the outer surface of the tank and an air tight plated external frame structure. An advantage by vacuum insulation is that the insulation layer only needs to be about 10 cm thick which means that there is more room for the tank itself within a given installation space in the ship. The heat ingress can be calculated along with determining the balance between liquid and vapor, and on this basis the holding time before reaching maximum allowed pressure can be accurately calculated.

4 TEST TANKS

4.1 Testing of four LPVs

Although the state of the art in computational mechanics is highly advanced, it has been necessary to carry out physical tests and demonstrate the performance and safety of the new LPV concept to classification societies as well as to the market at large. Four different test tanks have been built for this purpose with various volumes, shapes, materials and design pressure. Pressure testing has been carried out with pressurized water whereas cryogenic testing has been carried out using liquid nitrogen at – 196 ^{o}C. All tests have been extensively instrumented with monitoring of pressure, deformations and strain. In all cases the maximum applied test pressure was 1.5 times the design pressure.

Prototype tank	I	II	III	IV
Design pressure, barg	9.5	10.0	10.0	5.0
Hydraulic test pressure, barg	15.0	15.0	15.0	7.5
Dimension, H (m) x W (m) x L (m)	4 × 4 × 5	2.2 × 2 × 11.8	1.8 × 3.6 × 3.6	1.8 x 3.6 x 3.6
Volume, m^3	80	50	22	22
Material	SA-516	High Manganese	SA-240	High Manganese
Target fluid	Water for test	LNG	LNG	LNG
Certificate	ASME U2	Design approval from KR	ASME U2 (Consent Letter from ABSC)	Design approval from KR

Figure 5: Overview of 4 LPV test tanks

The results monitored for all test cases were fully in line with prior computational analyses and were thus highly satisfactory. Measured stresses, "hot-spots" and deformations were fully consistent with the numerical analyses and within the code requirements. The first tank with the design pressure 9.5 barg was in fact tested up to more than 20 barg (2,0 times the design pressure) without observing any indication of weakening. Extensive nonlinear finite analysis revealed that actual failure load would be more than 40 barg for this case. Further nonlinear simulations of various tanks confirmed that the design principles and structural layout of the LPV is soundly safe due to exceptional ability for the tank to redistribute forces due to structural topology and redundancy. In fact, the outer skin, which is the gas barrier, is the least stressed part of a LPV. This property is quite different form cylindrical and spherical in which the gas barrier is also the only load bearing structural component; a weakening or crack in this barrier can easily lead to total tank failure.

4.2 Materials and fabrication

Pressurized cryogenic tanks require special materials while normal carbon steels cannot be used. The reason for this is strict requirement pertaining to strength, toughness and ductility at low temperature. The most used materials for this purpose are stainless steel, nickel steels and aluminum. POSCO has developed a new type of cryogenic steel, called high manganese steel, that is significantly cheaper than stainless and nickel steels. Two of the test tanks (No II and No IV) were built and tested using this material. The results obtained, including testing with liquid nitrogen, were very good.

Building of the test tanks also served the purpose of gaining experience with fabrication of LPVs; this all proved to be very satisfactory. In many ways, it is simpler to manufacture a prismatic tank consisting of stiffened plates of moderate thickness as compared with building cylindrical tanks with rather thick, curved plates for which the requirements for tolerance and precision are very strict. In fact, manufacturing of LPVs may be said to be quite similar to making a plated ship structure; the LPV tanks thereby lends themselves to be made with well established, automated fabrication methods.

5 EXAMPLES OF DESIGN AND APPLICATIONS

5.1 Rounded corners

A main parameter in selecting the type of pressure vessel to be used in a ship is the volume efficiency. By this factor is simply meant the ratio between the volume of the tank compared with the volume of the installation space in which the tank, or multiple tanks, are placed. It has been experienced that it is not possible to design a prismatic pressure vessel with sharp corners; the reason for this is simply that stress concentrations arising in such corners turn out to be unacceptably high. This problem is dealt with by rounding the corners and providing design details that are not conducive to generating stress concentrations. As illustrated in the pictures in Figure 6, rounded corners may be made with smaller or larger radius of curvature. An option for relatively “flat” tanks is that the corner radius is selected as half of the tank height, thereby replacing the entire set of side walls with semi-cylindrical, rounded walls. This turns out to be structurally efficient and gives lighter tanks, whereas, as shown in the associated table, this is at cost of a slightly lowered volume efficiency. Though this round-wall LPV is lower in volume efficiency that the flat-wall LPV, it has much better volume efficiency than cylinders or multi-lobe tanks.

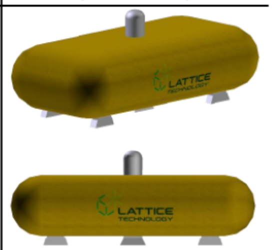
Item	FW-LPV (Flat Wall)	RC-LPV (Round Corner)	RW-LPV (Round Wall)
Type of tanks			
Type	Type C	Ditto	Ditto
Design pressure	2.0 ~ 20.0	Ditto	Ditto
Volume of unit tank	5 ~ 40,000	Ditto	Ditto
Volume efficiency	0.94 ~ 0.97	0.89 ~ 0.93	0.82 ~ 0.90
Weight (Cost)	Reference	0.7 ~ 0.8 of FW-LPV	0.4 ~ 0.6 of FW-LPV
Relative advantages	Higher Volume Efficiency		Lower Cost

Figure 6: Comparison of various degrees of rounded corners

5.2 Shape flexibility

As mentioned, an LPV may be made with any size and geometric proportions. The reason for this is that the concept is fully modular in the sense that a larger tank simply implies larger size parallel, internal panels and a larger number of such repetitive panels. A very important further property of the LPV concept is that the thickness of the stiffened outer skin does not increase with tank size; it only depends on the internal pressure and spacing between the parallel panels and stiffeners. This is much preferable as compared with cylindrical pressure vessels for which the wall thickness is directly proportional with the tank size as expressed by the radius. For the reason of increasing wall thickness a cylindrical pressure vessels cannot be made very large before they become practically and economically unfeasible; about 1000 m^3 seems to be a practical limit. The size of LPVs is not bound by such limitations.

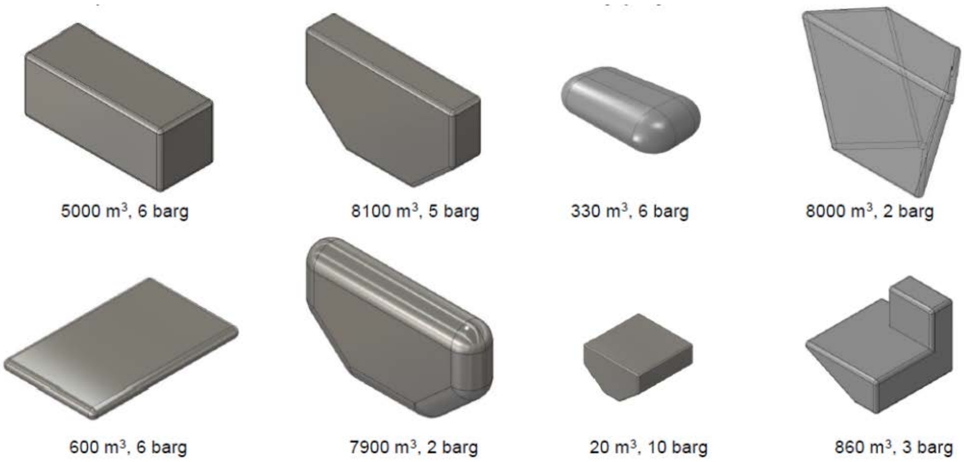


Figure 7: Example of different LPV tank shapes

The shape of an LPV is not limited to having essentially a box-like shape. Rounded walls have been mentioned as a variation on this. The internal load carrying structure makes it possible to design largely different tank shapes that fit rather awkwardly shaped rooms within a ship. Figure 7 shows a series of examples of tanks that have been designed and analyzed. Some of these are modifications of the box shape by “cutting off” corners and making wedge forms to adapt to the outer shape of the ship hull. The last example in the figure even shows a wedge shape tank with an “appendix” on the top. Clearly, this is capability goes far beyond what is possible with shell type pressure vessels.

5.3 Examples of ship and offshore applications

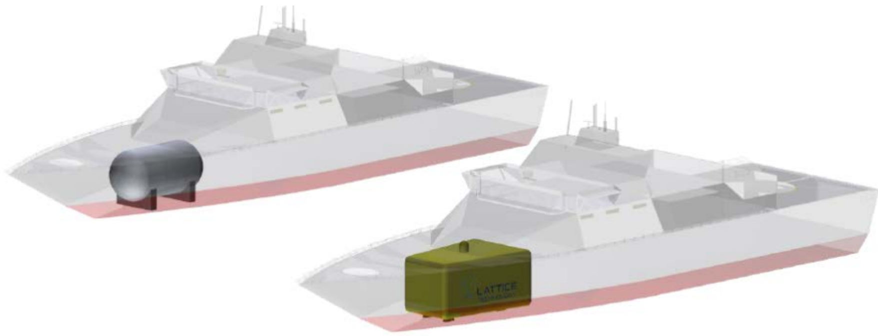


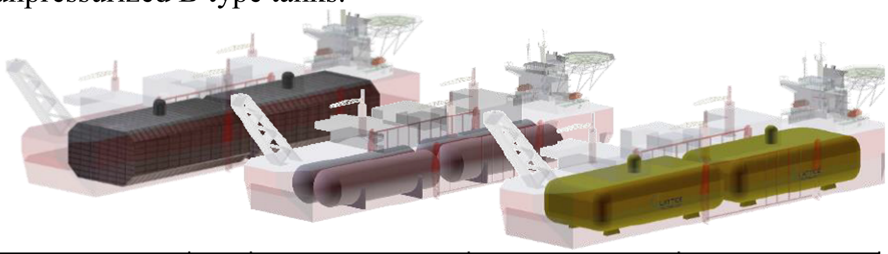
Figure 8: LPV vs a cylindrical pressure vessel onboard a patrol ship

A series of different applications have been studied. The first example shown deals with a fuel tank onboard a small vessel as shown in Figure 8. The only practical approach to a small size fuel tank is a Type C pressure vessel since handling of boil-off gas for unpressurized tanks could be too complex and costly. For the available installation space, there is only room for a 4 m^3 cylindrical tank whereas the LPV can be fitted to carry 10 m^3. The key here is not only that the LPV has a box-like shape, but it has also been given a wedge shape that is adapted to the hull shape. Clearly the LPV solution represents a new opportunity for fueling efficiency and operational range as compared with a conventional cylindrical tank.

Figure 9: LPV compared with cylindrical pressure vessels for container ship

Another case studied is to provide 15000 m^3 LNG fuel capacity for a large container carrier by use of a single LPV tank. Figure 9 compares this solution to the conventional solution with 15 cylinders. A major problem with the cylinder solution is that it requires a lot of gross space due to the very low volume efficiency by multiple cylinders whereas the LPV solution has very high volume efficiency and thereby saves a lot of potential cargo space. The difference between the two solutions corresponds to a loss of additional 900 TEU container units by using cylinders which is equivalent to an annual loss of revenue of about 9 million USD per year. Clearly, there are also other advantages by a one tank solution over the multiple cylinder solution; this is caused by less heat ingress and pressure build-up for the one tank solution, less instrumentation and piping, and not at least much simpler operation.

It should also be mentioned that comparisons between using LPV as an alternative to a single Type B (unpressurized) prismatic tank. Both these solutions have good volume efficiency; however, there are main differences in the way the two types of tanks must be operated. For Type B tanks the boil-off gas must be dealt by special equipment and pressurized before feeding the engine. The whole bunkering operation is also quite complicated and prolonged for tanks that can sustain only 0.2 barg pressure. There are also requirements for partial secondary barrier on the insulated fuel tank and thermal insulation and protection of the ship hull. These matters are overcome with type C pressurized tanks which require no boil-off gas compression, no gas process unit and no insulation of the ship hull. In conclusion, the new LPV solution has major advantages over both pressurized cylinders and unpressurized B type tanks.



Category	Item	Unit	FSRU With Membrane tanks	FSRU With Bi-lobe Tanks	FSRU With RW-LPV
Ship	Length O.A.	m	100.0	Ditto	Ditto
	Breadth	m	20.0	Ditto	Ditto
Cargo tanks	Type		Membrane	Type C	Ditto
	Design pressure	barg	0.7	3.0 (↑430%)	Ditto
	Volume of two tanks	m3	30,000	21,800 (↓27%)	27,300 (↓9%)
	Weight of two tanks	ton	-	-	1,160
Other Comparison measures	Inner hull Secondary barrier Gas detection system Heated cofferdam Pump tower BOG handling		Required	Not required	Not required
	Sloshing risk		Probable	No risk	No risk

Figure 10: LPV compared with cylindrical pressure vessels for container ship

Figure 10 shows a final example of alternative tank solutions for a floating LNG storage and regasification unit (FSRU). To the left in the figure is shown a solution where a membrane tank is fitted into the hull of the floater, the middle case is a pressure tank solution with a so-called bilobe tank (two overlapping cylinders), and finally a LPV solution. The membrane tank has the best utilization of the hull space, the bilobe has 27 % less and the LPV

9 % less. The most important features are associated with other aspects such as requirements for secondary barriers, gas leak detection and barriers, pressure pumps and handling of boil-off gas which are maters of disadvantage for the membrane solution. More importantly, FSRU storage tanks will contain all levels of filling under operations. Membrane tanks may have a serious problem with possible damage due to sloshing of the liquid gas; this is a problem that does not exist for the LPVs.

6 SUMMARY

The paper deals with a new type of pressure vessel denoted LPV, Lattice Pressure Vessel. The unique feature with this technology is that it allows for pressure vessels to have a box-like shape, a possibility that previously has not existed for pressure vessels that rather are cylindrical or spherical shell structures. Further, the LPV may even have modified box form with sloping or wedge like shape which means that it can fit and fully utilize an installation space of almost any form. The LPV concept is also fully scalable which means, because of its modular, repetitive internal structure, can be scaled up to almost any size. It can also be dimensioned for almost any desirable pressure. The paper discusses a series of structural, operational and practical advantages by the new LPV technology as compared to conventional technology. This also includes outline of a wide range of interesting and challenging requirements for computational analyses for LNG tanks onboard ships and offshore structures. Finally, the paper outlines and discusses several cases of designs that have been made. The overall conclusion is that the newly available LPV technology represents a major opportunity of improved safety and efficiency over conventional pressure vessel technology; thus, this technology emerges as key for facilitating an infrastructure for more environmentally friendly LNG for power production and for fuels in the transport sector.

ACKNOWLEDGEMENT

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