14th World Congress in Computational Mechanics (WCCM)
ECCOMAS Congress 2020
19 – 24 July 2020, Paris, France

DESIGN OPTIMIZATION, COST AND RISK ANALYSIS OF CNG VESSELS TRANSPORTATION

A. Clarich[1], Z. Wen[1] and G. Fratti[2]

[1] ESTECO Spa, Padriciano 99 Trieste (Italy), italy.eng@esteco.com, http://www.esteco.com
[2] CNGV, Veliki trg 17 Izola (Slovenia), info@cng-v.eu, http://www.cng-v.eu/

Key Words: *Optimization, compressed natural gas, transportation.*

The GASVESSEL Project, financed by the EU under H2020, aims to prove the techno-economic feasibility of a new CNG (Compressed Natural Gas) transport concept, enabled by a novel patented Pressure Vessel manufacturing technology and a new conceptual ship design including safe on- and off-loading solution.

In this paper we illustrate how the process automation and web-based collaboration software from ESTECO have been used by the partners in the different phases of the Project for the design of the system.

In function of each different geographical scenarios (which includes East Mediterranean, Barents Sea and Black Sea) and gas demand, parameters such as ship size and number, storage and facilities units at the ports have been optimized in order to reduce the transportation costs and therefore gas tariff.

Components of the gas vessels, in particular material and type of the fibers that wraps the liner, have been then optimized to minimize weights while respecting high value of safety factors.
Finally, a CFD study is performed to analyze the risks related to gas leakages and explosions.

INTRODUCTION

A key part of ensuring secure and affordable supplies of energy to Europeans involves diversifying supply routes. This includes identifying and building new routes that decrease the dependence of EU countries on a single supplier of natural gas and other energy resources.

This article reports the main achievements of the European project called ‘GASVESSEL’, which aim to open up new possibilities to exploit stranded, associated and flared gas where this is currently not economically feasible (the alternatives are too much expensive) as well as to increase the gas transport possibilities of currently exploited gas fields with a new cost effective CNG (Compressed Natural Gas) transport concept (fig.1). The outcome of the project may help to rebalance the European and global energy security equations.

The GASVESSEL project concerns the development of a novel, financially viable offshore and onshore CNG transportation system to collect, transport and unload natural gas (NG) from offshore and onshore oil and gas (O&G) fields into the distribution network.

GASVESSEL will innovate different steps in the value chain: from a decision support model to simulate and benchmark costs of the novel CNG concept against alternative gas transporting systems until the ship design and manufacturing process of the innovative lightweight Composite Overwrapped Pressure Vessels (PV's). The innovation of the CNG transport concept is enabled by a novel patented solution for the manufacturing of up to 70% lighter Pressure Vessels compared to steel alternatives, enabling new CNG ship designs with much higher payloads and as a consequence dramatically lower transportation cost per m^3 of gas.

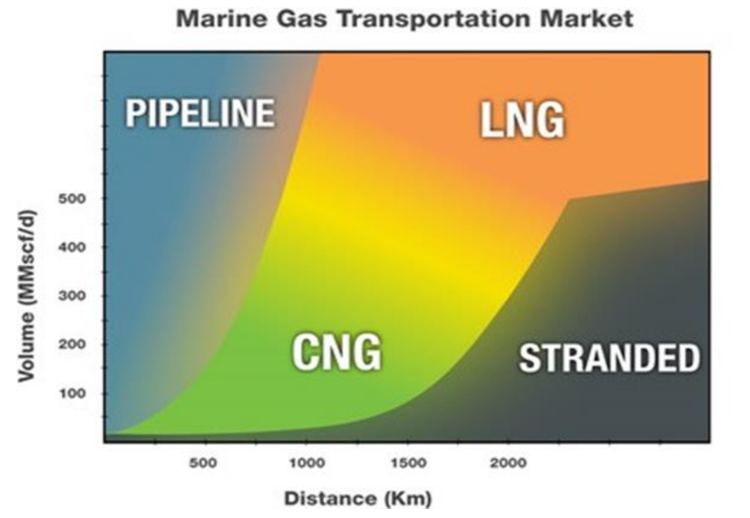

Figure 1: Gas exploitation opportunities with CNG (Compressed natural gas)

1. TRANSPORTATION SCENARIO OPTIMIZATION

In the framework of GASVESSEL Project, one of the primary tasks is the optimization of the gas delivery from the identified source locations to the identified markets for different scenarios and geographical areas, providing indications such as optimal ship size, ship speed and fleet size in order to reach the lowest gas transport costs per unit volume (fig.2).

The complete optimization process is managed by the ESTECO Enterprise solution VOLTA. VOLTA is a web-based, collaboration environment that orchestrates simulation data and multidisciplinary business processes, enabling conscious decision-making and innovative product development.

From the dedicated interface, any authorized user to access the project can set up the ranges of the optimization variables (such ship capacity and velocity), the scenario parameters (such as gas requirements and ports distances), and the optimization criteria (such as transportation cost or minimum gas storage). Simulations can then be run over the selected computational queue, and results can be analyzed.

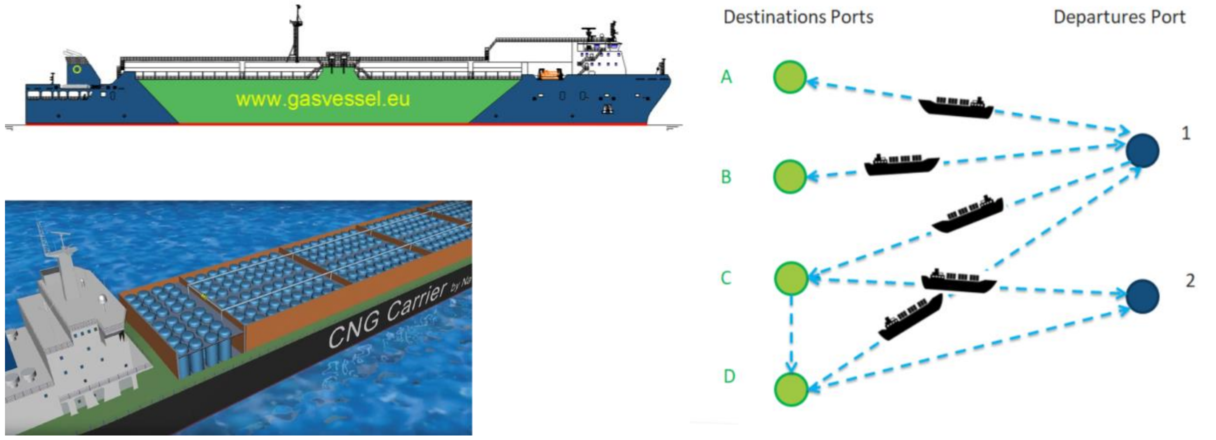

Figure 2: Gasvessel ship and example of CNG transportation scenario

Any authorized user of the VOLTA platform can then visualize a report of the optimization results. Choosing the optimal configuration, a text file reports all the information related to the scenario, including fleet size, ship sizes and velocities, ship usages and destinations.

At the present time, the tool is going to be used in three different geographical areas: Barents Sea (delivered to Norway), Black Sea (from Bulgaria to Ukraine) and East-Mediterranean region (from Cyprus to Greece, Lebanon and Egypt).

2. STRUCTURAL OPTIMIZATION OF GAS VESSELS

Using traditional pressure vessels whenever the gas is carried by ship without being liquefied is not contemplated: the relevant thickness of the walls induces both a significant weight of the vessels and a limited ratio between the volume of the transported goods and the total one, comprehensive of the tanks themselves. To overcome these issues, it is possible to manufacture the tanks using an internal thin metal liner wrapped with several layers of fiber-reinforced composite materials (filament winding); the obtained structure, being light and stiff, assures that the transportation of the compressed natural gas can be competitive in the market (fig.3, left).

The filament winding is a popular fabrication method (fig.3, right) suited to the manufacture of light and stiff axisymmetric structures as the pressure vessels or the pipes. Strands of filaments impregnated with resin are wounded around a rotating mandrel by a translating guide that can move along one or more axes [1]. The wrapped vessels are subjected to the autofrettage treatment [2]: an internal pressure higher than (generally about 1.5 times) the maximum expected operating pressure, or MEOP, is applied to the tank to partially deform the metal liner over its elastic range.

The composite overwrap remains in its elastic range and, when the internal pressure is unloaded, tends to its original undeformed shape, inducing on the liner a compressive stress field. When the operative load is applied, the stresses acting on the structure occurs to be lower than those obtained without the autofrettage treatment.

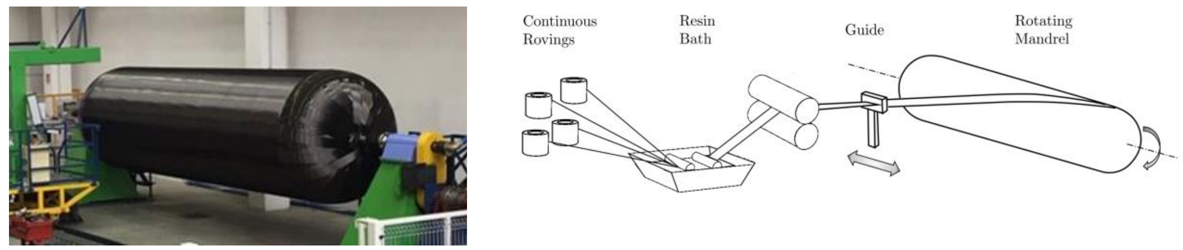

Figure3 Example of vessel storage (left); filament winding process (right)

In order to reduce costs, while keeping satisfied the necessary safety standards, it is necessary to set up an optimization procedure using modeFRONTIER software.

In the first section of the optimization workflow (fig.4), an internal (nested) loop of optimization is defined in order to find, for a given winding angle distribution, the minimum number of winding layers which are necessary in order to respect the structural constraints (reach maximum admissible stress in the central cylindrical portion of the vessel at burst pressure 900 bar) using an analytical model of the mechanical behavior of the pressure cylinder provided by the project partners.

Since the internal optimization simply uses a Python script to evaluate the constraints, the nested optimization process can be completed in a few seconds.

The winding data (winding angle in function of the number of windings) are therefore used by the following application node of the automation process, the script which controls the execution of the software CADWIND [4], by means of API commands to execute the software in a batch mode.

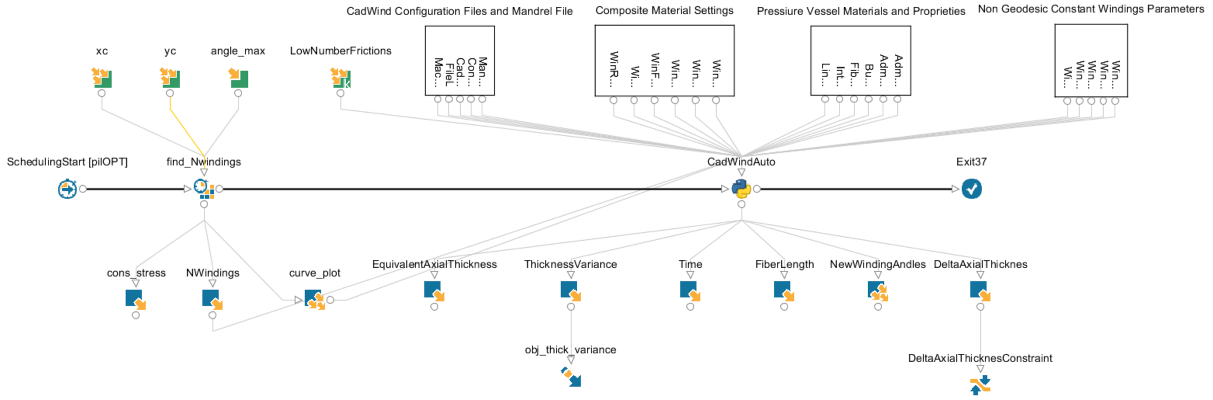

Fig. 4 Workflow in modeFRONTIER for winding optimization

CADWIND adapts the input data to simulate the winding process from the manufacturing point of view, which means that winding angles may be variated with respect to the theoretical ones in order to cover completely every area of the vessel, and produces the file that is used by the winding machine to realize the composite windings around the vessel.

The data produced by CADWIND can therefore be used to evaluate the overall thickness of the composite layers in each point of the vessel, and therefore the standard deviation of this distribution: the minimization of this value becomes the objective of the external loop of optimization, since it is required to avoid an excessive accumulation of layers in some regions in place of others.

The design variables optimized in the external loop to satisfy this objective are therefore the parameters which define the winding angle distribution.
The distribution has to be, for manufacturing reasons, a not decreasing function of the winding pattern number. For this reason, in order to define a continuous and regular curve function of a minimum number of parameters (to simplify the optimization task), we have adopted a Bezier curve of four control points [6].

By changing the coordinates of the two internal control points (the first and the last one are fixed), it is in fact possible to modify the shape of the curve in a continuous and regular way. Using an additional parameter, a factor scale, we can control the value of the maximum winding angle.

As a result of the optimization performed by modeFRONTIER, we can compare in fig.5 the different solutions obtained with the Bezier parameterization. In particular, in ordinate there are reported the number of winding patterns (objective of the inner loop of optimization) and in abscissa the objective of the outer optimization loop, i.e. the variance of the winding layers.

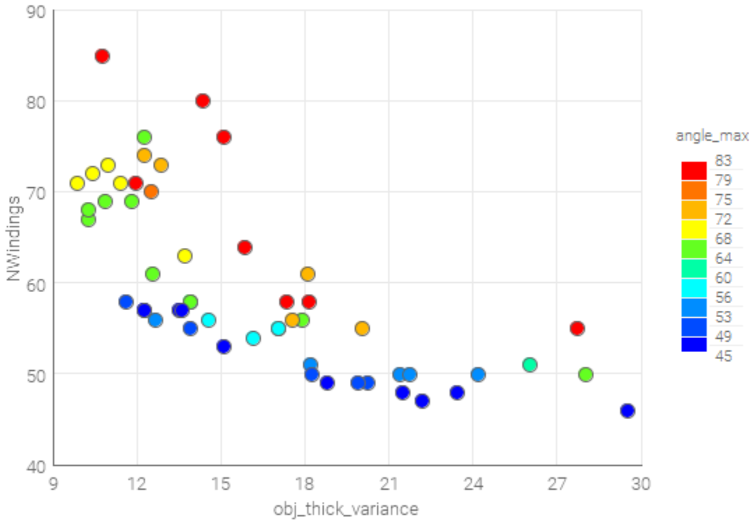

Fig. 5 Optimization results: number of windings vs thickness variance

The color of the points in the chart indicates the maximum angle of the winding layer with respect to the axis of the cylinder. Optimal results are characterized by a lower value of the angle (45°), with respect to the cases where the layers have an higher radial component (higher angle).

At least four different optimal configurations have been chosen by the partners, and validated through a FEM analysis, to verify the satisfaction of the constraints. In figs.6-7 below we report the analysis results for one of the candidate solutions

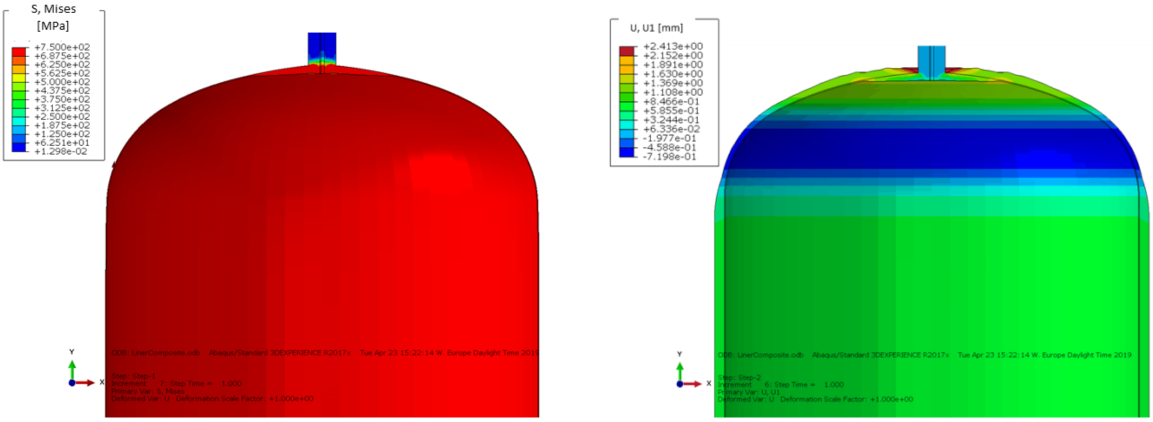

Fig. 6 Autofrettage: Stress (left, Von Mises) and radial displacement (right) after unloading

The steel liner reaches the yield stress in each point during the autofrettage phase (fig.6 left), while in the unloading phase a big portion of the cylinder retains a yield stress. This situation is not problematic, because the residual deformation in radial direction is rather small, in the range of 1 mm (fig.6 right). Moreover, during the operating conditions the stress on the central portion of the liner reaches average values around 300 MPa (fig.7 left), with maximum radial displacements around 6mm.

During the autofrettage, the composite overwrap reaches its highest stresses (around 1600 MPa in the central part, with some higher peaks in the spherical part) which are lower than the material limit (2470 MPa). During operative conditions also the spherical portion of the overwrap reaches stresses below 1400 MPa (fig.7 right).

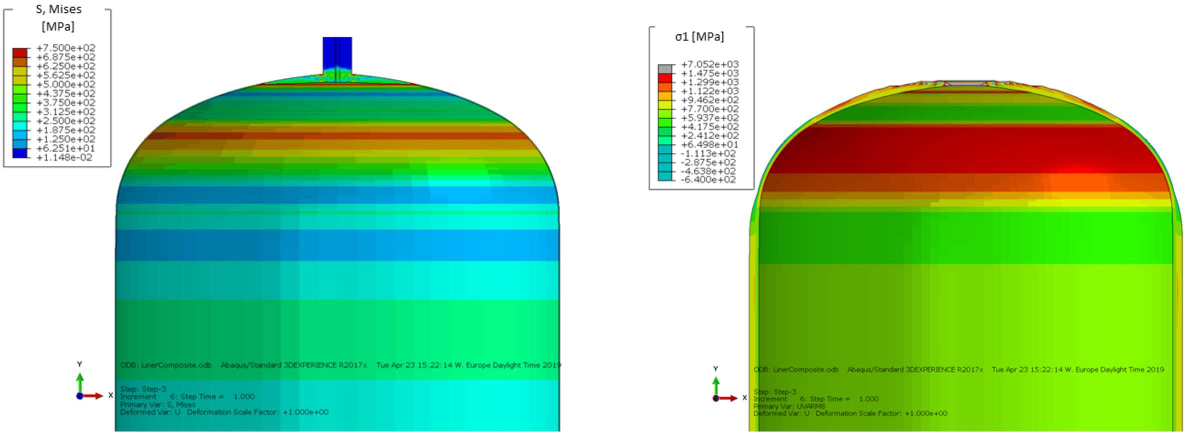

Fig.7 Operative conditions: stress field on steel liner (left, Von Mises) and composite overwrap (right, fiber direction σ1)

3 RISK ANALYSIS

As required by ABS (American Bureau Shipping) regulations, all the risks related to possible gas dispersions from valves, piping and flanges inside the ship should be analyzed in detail, and accordingly to the results of the analysis, a proper solution should be identified to reduce the risk.

Numerical simulations can be used to predict the effect of gas leakages in various areas of the ship (and of various intensity), with the goal of analyzing locally the gas concentration and therefore determining how much high is the risk of an explosion.
Though some places inside the ship are protected by an inert atmosphere (in particular the holds containing the gas vessels, where Nitrogen is present), it is necessary to analyze how the gas is dispersed and which temperatures and pressures are reached, to understand if any structure could be damaged.

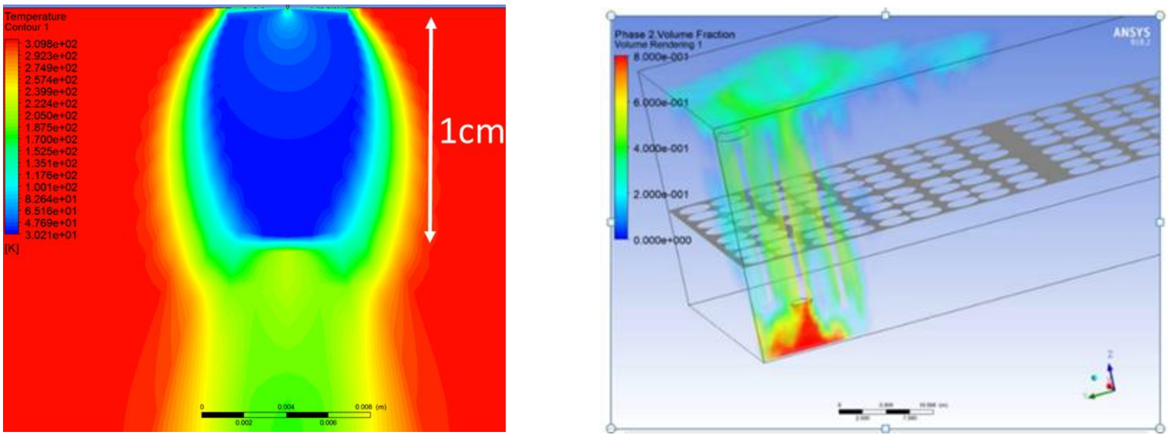

Fig.8 Joule-Thomson effect to define Temperature of gas leakage and CFD simulation of gas dispersion

Considering a iso-enthalpic expansion of the gas from the cylinders to the surrounding environment [7], by evaluating the gas state proprieties from real gas equations (Joule Thomson effect [8]), the temperature of the dispersed gas results to be much lower than the original temperature: with a gas temperature of 40°C and 300 bar of pressure inside the cylinders, the gas will exit in the 1bar Nitrogen protected hold with a (total) temperature of about -52°C. This value must be considered when designing the cylinders' supports, to prevent a structural damage in case of prolonged gas jets.
In fig.8 left, a local CFD analysis (2D, transient) reveals how the rapid expansion of the sonic flow from the orifice produce locally a supersonic expansion with local temperaturas very low (below 100K), that is dissipated within 1cm of distance, where the flow returns sonic. In these conditions, the closest steel supports are reached by a jet of -52°C at about 80m/s over an area of about 0.005m^2, that does not produce any significant dynamic and thermal effects, as confirmed by a structural analysis.

In addition, for a given mass flow leakage, a transient CFD analysis (fig. 8 right) can be performed to evaluate how concentration and pressure inside the hold changes in function of the time. This analysis is particular important because the internal structure of the hold may be damaged by an over-pressure higher than 0.2 bar, a situation that could be avoided by the installation of valves that extract the gas when the critical pressure value is reached inside the hold.

The application of modeFRONTIER to this problem is particularly useful to automatically explore the different risk scenarios, which can be characterized by different boundary conditions, such as position of the gas leakage, and mass flow intensity. Fig. 9 reports the results obtained, at the variation of mass flow, integrating in modeFRONTIER an analytical model of the gas mixture (methane with nitrogen) inside the hold, validated by CFD analysis.

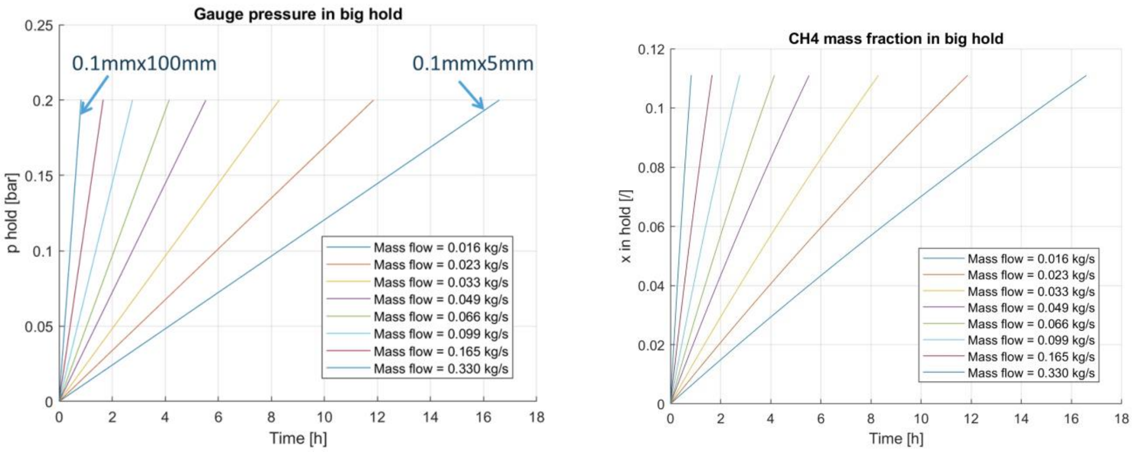

Fig.9 Hold pressure variation (left) and CH4 concentration (right) in function of leakage massflow

The 0.2 bar over-pressure can be reached within the hold after a number of hours that changes from 1 to 10, depending on the intensity of the mass flow leakage.

In these conditions, a vent mast system is designed, in order to extract the gas content of the cylinders in case the critical overpressure in ship's hold is reached in presence of leakages.

Fig.10 Vent mast system: methane mass concentration for most critical case

In fig.10 the CFD analysis reports the concentration of methane when the mast system is activated at maximum ship speed (16.5kn) and maximum opposite wind (50kn). Only the red area report a mass concentration of methane higher than the combustion limit (2.56%), while the critical structures of the ship (main deck, engine and accomodation rooms) are in safe conditions (concentration in blue area is less than 0.1%).

Finally, a leakage analysis has been repeated for the compressor room, that in this case is not protected by inert gas (since pressure vessels are not contained in the room), but by a ventilation system that reduces the critical concentration of gas in presence of gas leakage (fig.11 reports a possible ventilation configuration, to be refined when the actual structure is designed). Position and load of ventilators and extractors, can be optimized integrating the CFD analysis with modeFRONTIER, defining as objective the minimization of methane concentration in the room.

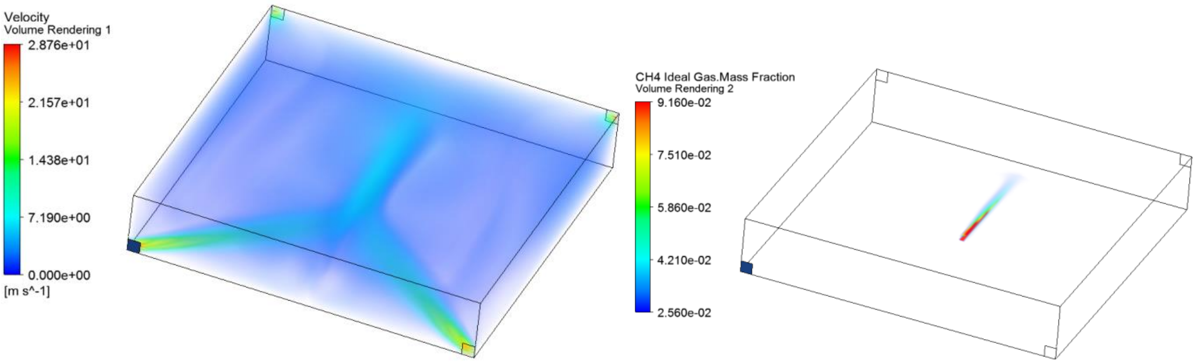

Fig.11 Ventilation system in compressor room: velocity field (left) and critical concentration of methane (right)

CONCLUSIONS

This paper describes the preliminary numerical analysis that have been performed in the framework of Gasvessel project, which aims to design an innovative concept of CNG gas transportation, by means of lightweight composite overwrapped pressure vessels and ships with higher payloads.

Important design parameters such as transportation logistic, pressure vessel material and geometrical parameters, and details of the safety measures to prevent risks of explosions, are optimized through the integration of the numerical simulation models in a process automation platform for an efficient optimization process, and in the web-based collaboration platform of ESTECO that facilitates the collaboration and the decision making process from the partners of the project.

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