Simulative Comparison between Ship and Airship for the Transport of Waste Natural Gas from Oil Wells

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Abstract: This paper proposes an innovative system for transporting natural gas from a site of extraction to a site of consumption, through the employ of drone airships. The airships contain slightly compressed methane within the hull volume and employ hydrogen as lift gas.

In the paper the authors carry out a comparison between the proposed solution and a solution involving the employ of CNG ships. The comparison produced interesting results, from which emerged that the airship solution is advantageous in terms of transport costs, due to the absence of the gas compression phase.

Keywords: Drone airship, logistic study, cost of transport.

1.Introduction

Wells produce, in combination with the oil, a certain amount of natural gas as by-product; such natural gas is most of the times burnt in flare, since its flow rate is not sufficient to justify the construction of a pipeline, which would not be economically feasible. This produced gas is therefore lost, notwithstanding its flow rate which can reach hundreds of tons per hour. If the oil well was situated in open sea or near the coast, this natural gas flow rate might be recovered by the use of compressed natural gas (CNG) vessels for methane transport.

In this paper the authors propose an alternative solution for recovering this gas and transporting it within a certain distance range, by an airship. The proposed airship stores the natural gas into the large hull volume at a pressure slightly higher than atmospheric pressure, while using as lift gas hydrogen, contained inside the hull too, in apposite chambers. Natural gas is stored at a pressure slightly higher than the atmospheric one (about 1.46 bar as explained in the next sections), in order to have the same density of air for balance reasons: in fact, the airship shall have to keep the same balance configuration both when full of methane, in the travel from the well to the discharge point, and when empty, in the travel back to the well.

In this paper the proposed airship solution is compared with a CNG ship solution to understand the feasibility and the economical advantages. After the introduction, the paper describes the overall features of the proposed airship solution; then, in section 3 the comparison between the ship and the airship solutions is carried out, by making the main hypotheses regarding the oil-natural gas site and by applying the formula for determining the capacity of the transportation means basing on the loading flow rates, the number of means employed, the cruise speed and the travel distance. In the same section, the transportation costs are determined for the ship and the airship basing on the calculation of the fuel consumption for the travel; also, the cost for the natural gas compression is calculated, for the ship solution only; in fact the airship will store the gas at lower pressures than the gas outlet pressure from the well. Finally, the conclusions of the study are drawn.

2.The drone airship

In this section are described the overall design characteristics of the airship.

The airship is thought as a drone mean and shall be commanded from the earth to avoid fatal accidents.

The airship is of the rigid type. The large volume of the airship is divided in two zones: one is filled with methane at 1.46 bar during the travel from the well to the discharge point and is filled with air during the travel back from the discharge point to the well. The pressure value of 1.46 bar was chosen because at this pressure the methane density is equal to the density of air at the flight altitude (2000 m). In this way, the vehicle balance (Acanfora and Lecce) is the same during the travel from the well to the discharge point (when the airship is full of natural gas) and during the travel back to the well (when in place of the natural gas, the volume is filled with air).

The second zone of the airship volume is filled with hydrogen at atmospheric pressure, which works as lift gas. The choice of hydrogen is motivated by the fact that it is lighter than helium. The employ of helium instead of hydrogen as lift gas would not improve significantly the system safety level, since the airship volume is already filled with the potentially explosive gas to be transported (natural gas).

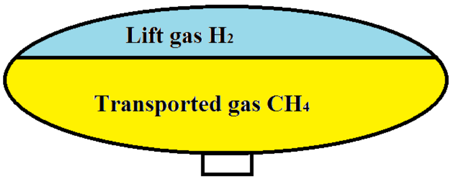

Figure 1: Configuration of the airship.

3. Comparison between Airship and CNG Ship

In this section, the authors aim at carrying out the comparison between the two proposed transport solutions, the airship and the CNG ship, in relation to a real natural gas transport situation. In the following paragraphs, the main hypotheses of the transport are described, the application of the logistic principles is carried out in order to compare on equal terms the two solutions and the costs related to each solution are calculated. Finally, the choice of the most reasonable transport configuration (i.e. number of means and their size) is defined basing on the calculations.

3.1 Hypotheses on the methane well

The transport situation to be fulfilled is the following:

- the well in object produces a natural gas flow rate of 200 t/h (about 55 kg/s);
- the produced flow rate needs to be transported to a distance of 700 km.

The transport can be carried out by the use of CNG ships or by the use of the proposed airship solution; for both the solutions, it is still to be defined the number of means required to carry out the transport and their size.

3.2 Application of the load capacity formula

After defining the hypotheses about the well and transport distance, the study was continued by determining the load capacity required for each transport solution to satisfy the requirements of a real situation.

In order to determine the loading capacity of a transportation mean, it is possible to apply the following formula (Giribone and Revetria):

$$Q = \frac{2\frac{D}{v}}{\frac{N}{\lambda} - \frac{1}{\lambda_L} - \frac{1}{\lambda_U}} \qquad (1)$$

where: Q is the loading capacity of the transportation mean; D is the distance between the gas well and the unloading point; v is the speed of the ship or airship; N is the number of means employed for the transport; λ is the natural gas flow rate produced by the well; λ_L is the natural gas loading flow rate of the ship or airship; λ_U is the natural gas unloading flow rate of the ship or airship;

This formula was applied to the required transport situation by imposing values of λ_L and λ_U equal to 3000 t/h (about 833 kg/s). The value of Q was calculated for different numbers of means involved in the transport (up to 4), for the ship and the airship. The speed to be introduced in the formula was set as, respectively, 30km/h for the ship and 180 km/h for the airship.

In Figure 2 is reported the diagram representing the loading capacity for different numbers of means for the ship and airship solutions. As visible, the loading capacity decreases with the number of means employed, tending to an asymptote for large numbers of means.

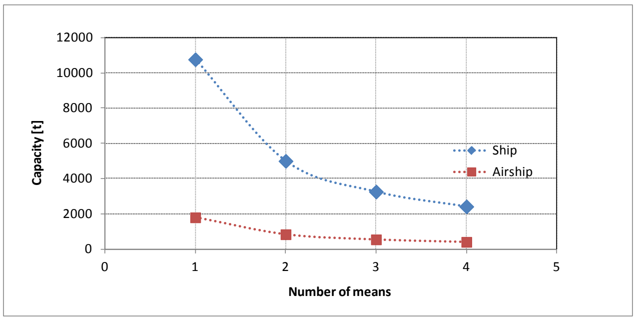

Figure 2: Load capacity in function of the number of means.

3.3 Simulation model

The transport situation of this problem is schematized in the following Figure 3, where λ_P, λ_L, λ_U and λ_G are respectively the flow rates of the well, of the airship or ship loading, of the airship or ship unloading and of the natural gas grid, and Q is the ship or airship capacity. Between the well and the loading pipe a reservoir is placed, so as between the unloading pipe and the grid.

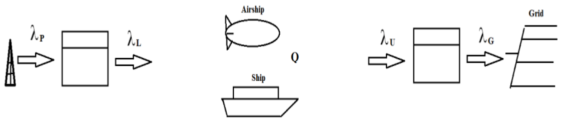

Figure 3: Scheme of the transport situation.

The transport situation was modelled through a DES model, whose states are listed as follows

(Holimchayachotikul and Derrouiche; Guizzi and Murino; Guizzi and Gallo; Romano and Guizzi; Guizzi and Miele):

- waiting for mooring in the loading site;
- in loading;
- end of loading;
- in navigation towards the unloading site;
- waiting for mooring in the unloading site;
- in unloading;
- end of unloading;
- in navigation to the loading site.

In this scheme, there are four random variables: the navigation time (both from the well site to the grid site and backwards) and the loading and unloading time. In the following, the description of these random variables is provided.

1) the navigation time is defined as Tnavigation = Distance/Speed. The speed was modelled as a function of the type of ship/airship and of the weather conditions. In particular, for the ship the weather conditions are represented by the wave height, whereas for the airship by the wind speed. To simulate the weather conditions variation, two scatter diagrams of the wave height and wind speed were built. The route is discretized into segments, for each of which two random numbers are extracted: the first one for indicating the wave height or the wind speed, and the second one for indicating if these are increasing or decreasing. If the weather conditions are for example getting worse, according to the second random number extraction, the scatter diagram is limited to the higher wave height or wind speed values.

2) The loading and unloading time is a random variable since the initial level of the reservoirs is not known. When e.g. the loading reservoir gets empty during the loading operation, the transportation mean can be loaded only with the well flow rate value, λ_P . Therefore, the time for loading can be written as:

$$T_{loading} = \frac{Q'}{\lambda_L} + \frac{Q''}{\lambda_P} \qquad (2)$$

where Q” = Q – Q’. Similar considerations can be done for the case in which the reservoir in the unloading site gets completely full during a downloading operation: the mean can be unloaded only with the grid flow rate λ_G.

The simulation model was implemented in Java, utilizing the jDisco package, which is a software tool turned to the simulation of both continuous and discrete processes. The system in exam, in fact, has both the features, being characterized by a discrete part (the simulation of the transport by ships or airships) and a continuous part (the simulation of filling and emptying of the reservoirs).

3.4 Calculation of transport cost

Ship

For the ship solution, the following hypotheses were made:

The ship can travel at a cruise speed of 30 km/h.

The ship stores the natural gas into a number of special vessels whose size was hypothesized to be: a diameter of 1.2 m; a height of 38 m. The vessels are disposed within the ship hull in a rectangular area, whose extension will define, with the opportune corrections taking into account the need for room for the auxiliaries (engine room etc.), the length and width of the ship itself.

The natural gas is stored in the vessels at a pressure of 250 bar, to which corresponds a gas density of about 160 kg/m^3.

The disposition of the vessels within the ship was decided in a way that the number of vessels in the ship longitudinal direction is 6 times that in the ship cross direction. Known the total volume of compressed gas to be stored, it is possible to determine the number of vessels required and thus the length and width of the ship.

Once determined the ship length and width and its draft (supposed 10 m), it is possible to calculate the power required for motion in water through Equation 2:

$$P_r = \frac{1}{2}\rho S C_d v^3 \qquad (2)$$

where ϱ is the sea water density; S is the ship wet surface; v is the ship speed; C_d is the drag coefficient in water, which is known from the ship Reynolds number through the semi empirical formula:

$$C_d = \frac{0.075}{(\log(Re) - 2)^2} \qquad (3)$$

where Re is the Reynolds number, calculated as:

$$Re = \frac{vL}{\nu} \qquad (4)$$

being v the ship speed; L the ship length and ν the seawater viscosity.
Through the power required for the ship motion, it is possible to obtain the energy amount employed for a travel, and thus the amount of energy required from the primary engine for the propulsion. The conversion efficiency, defined as the ratio between the energy employed for a travel and the primary fuel energy required by the ship engine was assumed as an average value of 0.35.
The fuel employed for the ship engine was assumed to be natural gas, with a lower heating value of 47000 kJ/kg. This value allows to calculate the mass of fuel required for a travel.

Airship

For the airship, a cruise speed of 180 km/h was imposed.

The airship stores the natural gas within its large volume as described in section 2. The storage pressure was imposed as 1.46 bar. The gas density at the cruise height (2000 m, at which can be imposed an external temperature of 280 K) was calculated as 1.01 kg/m3. These data allow to calculate the volume required to store the mass of gas desired, which was determined through Equation 1.

The total volume was calculated basing on the required buoyancy force to lift the structure of the airship by means of the hydrogen stored within the volume. In particular, the volume in which is stored the natural gas was imposed equal to 85% of the total volume, while the volume filled with the lift gas, was imposed as 15%.

This percentage value was determined carrying out buoyancy calculations based on the formula in Equation 5. Basing on the volume percentage parameter b, defined as the volume of the stored natural gas divided by the volume of the hydrogen, it is possible to calculate the buoyancy force developed by the lift gas and therefore the weight that the airship structure and all the auxiliaries must have to keep the vehicle in equilibrium at the cruise altitude.

$$P = (1-b)V_{tot}g(\rho_{air} - \rho_{H2}) \tag{5}$$

In Table 1 are indicated, for the different airship solutions resulting from the application of Equation 1, the volume required for the methane stored, the total airship volume and the maximum weight allowed for the vehicle structure.

Table 1. Masses and volumes for different sizes of airships

Number of means		1	2	3	4
Mass of methane stored	t	1795	833	543	402
Volume required for methane storage	m^3	1,78E6	8,28E5	5,39E5	4,00E5
Total airship volume	m^3	2,10E6	9,74E5	6,34E5	4,70E5
Maximum structure weight	t	296,44	137,63	89,62	66,44

The main dimensions of the airship were calculated under the hypothesis of an ellipsoidal form for the hull. Basing on the airship total volume, the diameter and length of the ellipsoid were calculated imposing a length to diameter ratio value equal to 6, resulting from the study of the dimensions of several existing rigid airships.
The diameter of the airship allows to determine its front area, which allows to calculate together with the cruise speed the power required for the airship motion through the known aerodynamic formula:

$$P_r = \frac{1}{2}\rho S C_x v^3 \tag{6}$$

where ρ is the air density; S is the airship front area; v is the airship speed; C_x is the drag coefficient, which can be imposed equal to 0.022.
Supposing an efficiency value of 0.35 for the engine power conversion, the primary fuel power required to move the airship can be calculated. From this value can be evaluated the amount of energy required for a travel and successively, through the fuel lower heating value assumed as 47000 kJ/kg, it is possible to derive the fuel mass required.

Cost of transport

The cost of transport was calculated assuming a cost for the fuel (natural gas) equal to 1 Euro/kg in both the airship and the ship case.
Using these formulas, the cost related to the transport of natural gas from the well to the discharge point was calculated for the two solutions on a yearly basis. The results are described in the following Figure 4, which represents the cost of transport per kg of natural gas per year.

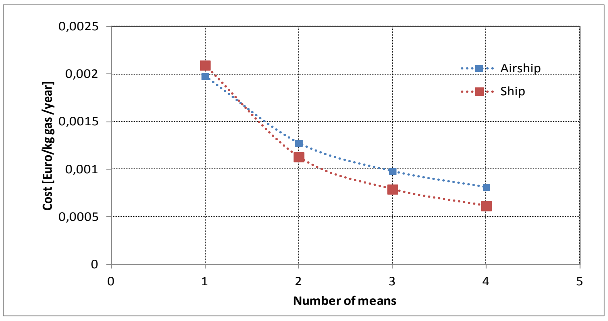

Figure 4: Cost of transport per kg of natural gas per year.

As visible, the two solutions are comparable for what about the transport cost.

3.5 Calculation of compression cost

To complete the comparison, the cost for the natural gas compression needs to be considered. Natural gas wells outlet pressure is normally high, in the order of 40 bar. Therefore, the ship solution, which provides the gas storage at 250 bar, requires a further gas compression phase, whereas the airship, in which the gas is stored at 1.46 bar, does not require this phase.

The energy required for gas compression was calculated by the following formula:

$$E_C = \frac{M c_p T_1}{\eta_C}\left(\beta^{\frac{k-1}{k}} - 1\right) \qquad (7)$$

where E_C is the compression energy required to compress the mass produced by the well in the period of one year; M is the mass of gas to be compressed in one year of production; c_p is the natural gas specific heat capacity; T_1 is the gas initial temperature; η_C is the compressor efficiency assumed as 0.85; β is the compression ratio, calculated from the initial and final gas pressure (respectively 40 and 250 bar); k is the ratio between the specific heat capacities at constant pressure and at constant volume.

The compression was supposed to be carried out through a dynamic compressor moved by a natural gas engine, whose efficiency was hypothesized 35%. Under these hypotheses, it is possible to calculate the mass of fuel required for the compression. Supposing a cost of the fuel equal to 1 Euro/kg, it is possible to calculate the total cost for the compression of the mass of gas produced in one year. From the latter value, it is possible to derive the cost per kg per year, which was calculated in 0.022 Euro/kg year. As visible, the cost for the methane compression is one order of magnitude higher than the transport cost. This rends the ship solution less economically advantageous than the airship solution.

4. Conclusion

In this paper the authors proposed a solution for recovering the natural gas produced from oil wells as by-product, which is often burnt in flare since it is not economically feasible to build a pipeline for such a small flow rate. In the case where the oil well is offshore or near the coast, the natural gas flow rate can be recovered by means of reservoir ships or, alternatively, with the use of an airship, as proposed by the authors.

In the paper a comparison is carried out between the two transport solutions: the ship and the airship, under a certain number of reasonable hypotheses.

The study took the authors to conclude that airship is a more economically feasible solution than CNG ship because of the compression cost of the gas.

Acanfora M., Lecce L., On the Development of the Linear Longitudinal Model for Airships Stability in Heaviness Condition, **The Journal of Aerospace Science, Technology and Systems.**

Giribone P., Revetria R., Testa A., Vernengo G., Rizzuto E., Longo R., et al., A Simulation Based Methodology for Supporting CNG Ship Design.

Holimchayachotikul, P., Derrouiche, R., Leksakul, K., Guizzi, G., B2B supply chain performance enhancement road map using data mining techniques, **International conference on System Science and Simulation in Engineering** - Proceedings,2010,336-341.

Guizzi, G., Murino, T., Romano, E., An innovative approach to environmental issues: The growth of a green market modeled by system dynamics, **Frontiers in Artificial Intelligence and Applications**,2012,246,538-557.

Guizzi, G., Gallo, M., Zoppoli, P., Condition based maintenance: Simulation and optimization, Proceedings of the 8th WSEAS International Conference on System Science and **Simulation in Engineering**, ICOSSSE '09,2009,319-325.

Romano E., Guizzi, G., Chiocca, D.,A decision support tool, implemented in a system dynamics model, to improve the effectiveness in the hospital emergency department, International **Journal of Procurement Management**, 2015,8,141-168.

Guizzi, G., Miele, D., Santillo, L.C., Romano, E.,New formalism for production systems modeling, **25th European Modeling and Simulation Symposium**, EMSS 2013,2013,571-576