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Development of new technologies for shipping natural gas by sea

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ABSTRACT

In recent years dynamic increase of orders for ships intended for liquified natural gas (LNG) shipping has been observed with simultaneous trend of increasing their transport capability. This results from the fact that natural gas has become today the third energy source worldwide just next to crude oil and coal. The fast growth of demand for natural gas and its limited resources would cause growth of its price, therefore better solutions of natural gas transport technology with respect to economy, ecology and safety should be searched for. This paper presents various technologies for natural gas transport by sea with special attention paid to some alternative methods of transport, namely: CNG and NGH ransport technologies in contrast to LNG one.

Keywords: natural gas; LNG carriers; liquified gas; CNG carriers; compressed gas; NGH carriers; gas hydrate; operational cost of gas transport

INTRODUCTION

Natural gas industry plays greater and greater worldwide role both in economical and political sense. Growth of gas consumption is associated with its great popularity as the most ecological source of energy. Ecological features of natural gas as well as its wide range of applications a.o. to electric power production, combustion engine driving and chemical production, make the demand for it still growing. The demand increases by about 2 % every year.

The largest natural gas resources are found in the Persian Gulf (abt. 41% of worldwide resources) and Russia (abt. 32% of worldwide resources), moreover in North Africa and the region of the Mexican Gulf and Carribbean Sea, Fig. 1, [2]

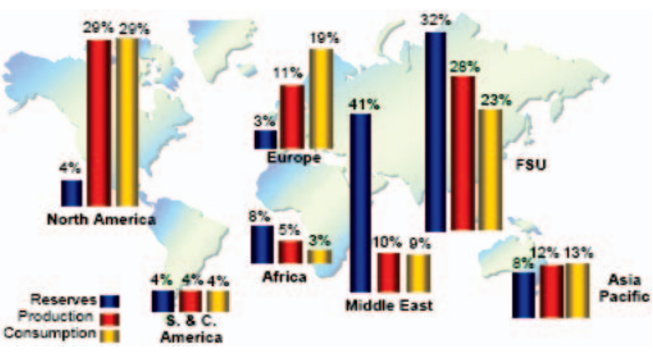


Fig. 1. Natural gas all over the world [2]

In Poland natural gas deposits are located mainly in West Pomerania, Wielkopolska region and Carpathian piedmont; rather small amounts of the gas were also found in sea-bed deposits in Polish economical zone of the Baltic Sea.

Therefore the increase of number of orders for natural gas carriers with simultaneous trend for increasing their transport capability reaching today as many as 250000 m^3, is observed. The boom in production of gas carriers has contributed, due to strong competition, to the downward trend in their production costs. However it does not change the fact that gas carriers belong to very expensive ships because of difficulties in their production and operation.

Natural gas can be shipped by sea in the liquified state (LNG), compressed state (CNG), or in the form of hydrate (NGH) - the technology being still in the phase of design considerations. The CNG and NGH technologies are promising, applicable in short-range shipping up to 3000 Mm, more profitable, safe and ecological than LNG technology. Characteristic features of the natural gas shipped in the three forms are presented in Fig. 2.

A type and design of ship intended for the transporting of the raw material as well as equipment of gas loading terminal depends on a state in which it will be shipped.

For many countries, including Poland, gas shipping by sea with the use of gas carriers is really the only alternative to be independent from gas delivery from Russia and this way to greatly improve safety of energy supply to the country.

CHARACTERISTICS OF LIQUIFIED GAS TRANSPORT TECHNOLOGY

The most popular transport technology of natural gas cargo is its liquified form – by means of LNG (liquified natural gas) carriers in – 163° C temperature and a little elevated pressure of 0.17 MPa (1.7bar). Due to so low temperature LNG must be contained in a cryogenic tank. After liquefaction process

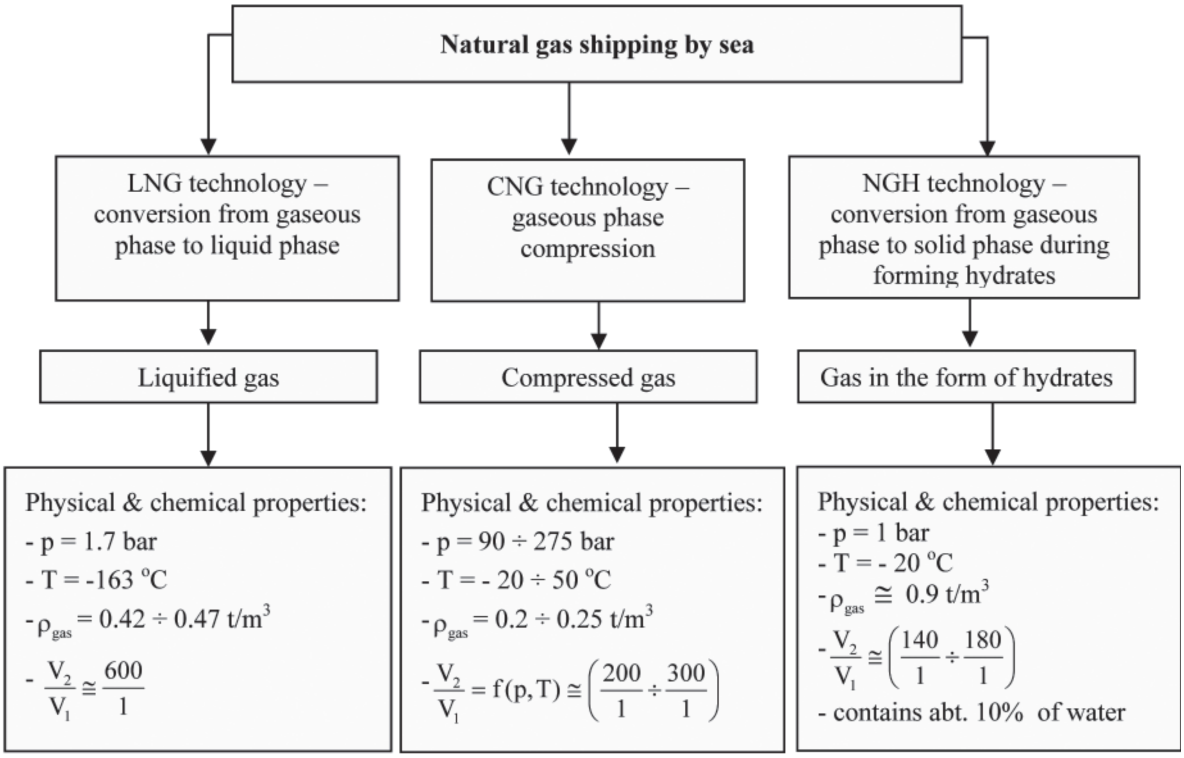


Fig. 2. *Forms of gas cargo for shipping it by sea and its main properties [the author's elaboration]*

its volume is reduced abt. 600 times against its initial state, that constitutes its main advantage for shipping and storing. In worldwide trade more than 1/4 of natural gas amount is shipped just in this state.

The LNG is called the concentrated energy as:

- after regasification, from 1m^3 of LNG abt. 600 m^3 of network gas is obtained
- from 1 t of LNG abt. 1380 m^3 of network gas is obtained.

LNG transport chain

LNG delivery chain begins in natural gas deposits from which gas is transported through piping network to a liquefaction facility which delivers the gas to an export terminal and from this point it is transported, already in the liquefied form, by means of special LNG carriers to a import terminal and from it, after regasification, it is pumped to gas piping network to be delivered to its consumers, Fig. 3.

According to statistical data from the end of 2008 the world fleet of LNG carriers was consisted of 280 ships [10], most of which were of over 100 000 m^3 capacity. During two last years number of built Q-flex and Q-max ships of capacity greater than 200 000 m^3 each, has increased.

LNG carriers can be divided with respect to their size as follows:

- medmax LNG carriers of the cargo capacity $V_Ł = 75\,000$ m^3
- conventional LNG carriers of the cargo capacity $V_Ł = 125\,000 \div 145\,000$ m^3
- new LNG carriers of the cargo capacity $V_Ł = 155\,000 \div 170\,000$ m^3
- Q-flex LNG carriers of the cargo capacity $V_Ł = 216\,000$ m^3
- Q-max LNG carriers of the cargo capacity $V_Ł = 265\,000$ m^3.

LNG carriers belong to the group of very specialized ships, that results mainly from the applied cargo transport technology. The crucial problem is to ensure continuous cooling the cargo as well as to avoid its evaporation to the atmosphere.Therefore LNG transportation requires application of very effective insulation of tanks.

Among merchant ships LNG carriers are of the highest speed, their average service speed varies usually in the range of 19 ÷ 21 knots. LNG shipping specificity consisting in continuous loss of the cargo during voyage to some extent forced voyage period shortening to a minimum. The daily Boil-Off-Rate (BOR) amounts on avarage to 0.15 ÷ 0.2 % of gas cargo mass and the amount depends mainly on degree of insulation effectiveness. The evaporated cargo can be discharged to the atmosphere, again liquified or utilized onboard as fuel for main propulsion diesel engines, gas turbines or boilers delivering steam to turbines.

The largest LNG carrier („Mozah") built nowadays, fitted with five membane tanks is of 266 000 m^3 cargo capacity. It was built by Samsung Shipyard in South Korea for QGTC company. There are a few other ships like that under construction but their size, design or specification have not been disclosed so far.

Attention should be paid to the fact that safety of cargo in tanks and ship operation safety should be also ensured along with the increased size of the ships.

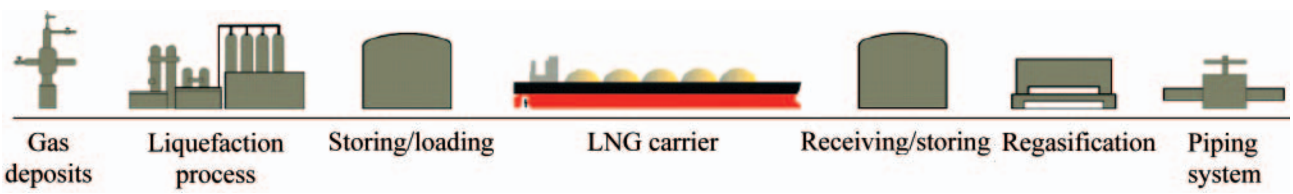


Fig. 3. *LNG transport chain with the use of LNG carriers acc. [4]*

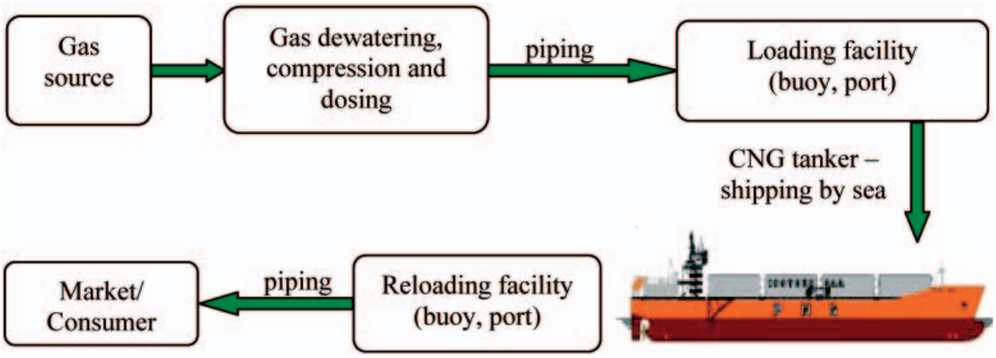


Fig. 4. *CNG transport chain by using special gas carriers [the author's elaboration]*

CHARACTERISTICS OF COMPRESSED GAS TRANSPORT TECHNOLOGY

The CNG is natural gas compressed under high pressure. The typical pressure range used to compress the gas is of 200 ÷ 250 bar. The compresion process is aimed at concentrating gas energy in unit volume. The higher pressure the greater amount of gas contained in unit volume. After the compression about 200/1 ÷ 300/1 units of gas can be achieved.

Storing and transporting the CNG is carried out in special tanks, under high pressure. Capacity of such tanks – usually cylindrical vessels – depends on working pressure, temperature as well as chemical content of natural gas. The tanks having different values of length and diameter, are made of steel or light composite materials.

CNG transport chain with application of gas carriers

CNG delivery chain begins in natural gas deposits from which the gas is sent through piping system to compression facility and next through loading system (buoy, port) to a ship which transports it in the compressed form to reloading terminal (buoy, port). In the terminal gas can be reloaded to underground stores or directly to gas piping network after passing through internal installations of the terminal [9]. Fig. 4 shows the schematic diagram of the CNG transport path.

Concept of gas transportation in the compressed form is not entirely new as the first attempts to CNG transporting for commercial purposes were made by Columbia Gas Company, in the 1960s, but it is one of alternatives for LNG transport, especially to servicing local markets and satisfying the needs without signing any delivery contracts.

According to available analyses CNG transport technology by sea within 3000 Mm delivery range becomes competitive to LNG mode of transport as well as to that by undersea piping systems. An advantage of CNG technology is avoidance of building an expensive liquefaction facility for natural gas, its storing and building tanks to its regasification which are often placed close to areas of large density of population, that impairs its safety. The new natural gas transport technology by using CNG carriers is associated only with building the facility for gas compression to over 200 bar pressure in the receiving port, that leads to large cost savings within the whole gas transport chain.

During CNG transport the cargo can be reloaded far offshore by using loading buoys anchored in a safe distance from coast.

Transport of gas in the compressed form is characterized by many advantages, a.o. the following:

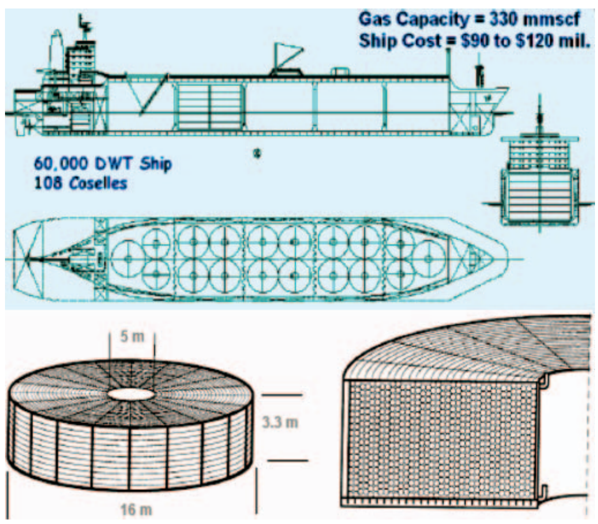
- *safety nad ecology* – gas loading and reloading can be performed far offshore by using loading buoys; in the case of occurrence of a possible leakage CNG does not explode but evaporizes and disperses in the atmosphere; when combusted it emitts less contaminations to the atmosphere than oil or coal, lowering this way emission of noxious products such as: CO, CO_2, NO_x
- *flexibility of gas delivery chains* – it means a.o. possibility to adjust amount of gas delivery to current demand of the market
- *savings in transport and storage costs as well as investment cost of the reloading port* (abt. 80% of the whole investment cost is connected with CNG carrier - Fig. 8).

Concepts of CNG carriers and design solutions of cargo tanks

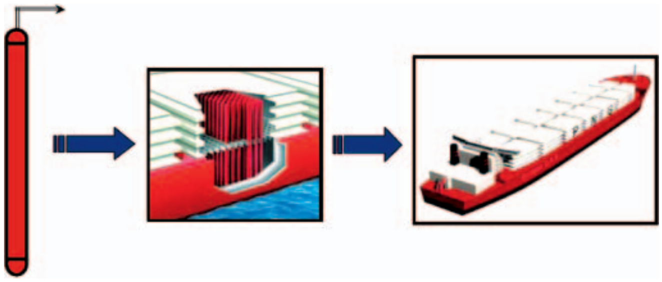
In recent years big gas concerns have discovered great possibilities in CNG transport technology; many of them have elaborated their own CNG transport technologies and designs of CNG carriers. The following ones belong a.o. to the most important:

- **Coselle (Williams)** – gas is transported in turns of steel, thick-walled pipes of the diameter D = 0.168 m and of l = 1700 km in length on average, winded onto the so called „carousel", in ambient temperature, under 275 bar pressure. The Coselle CNG transport system is modular and intended for extension. It means that CNG transport system may begin from delivery of gas in small amounts and then be developed by adding more and more greater number of the gas carriers. Gas cargo capacity of such ships is contained in the interval of 1.4 ÷ 56 mln m^3 within 2000 Mm range of delivery [6, 8].

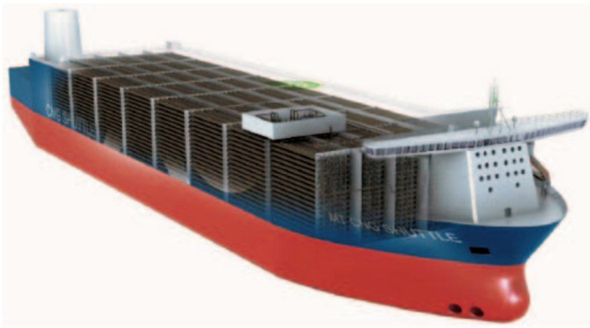
  According to literature sources the technology is the least expensive alternative of CNG delivery which could bring 30 % cost savings.



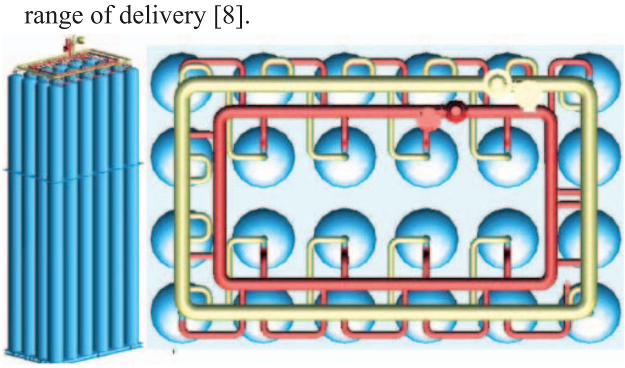
- **Knutsen OAS – PNG** (*Pressurized Natural Gas*) system characteristic of vertical cylindrical tanks (of the dimensions: h = 18 ÷ 36 m in height, D = 1.04 m in diameter) in which gas is transported in ambient temperature under 250 bar pressure. The gas cargo capacity of such ships varies in the interval of 2 ÷ 30 mln m^3 of compressed gas within the 3000 Mm range of delivery [6].
  Technical details of the concept have not been revealed so far hence it is not clear in which way its cargo tanks differ from other technologies.



- **CETech** – a common concept elaborated by three partners: *Statoil*, *Teekay* - a Canadian firm, and *Leif Höegh & Co* – a Norwegian one. The planned ships will be equipped with steel horizontal pipes capable of transporting the CNG compressed up to about 200 ÷ 250 bar, in ambient temperature. CNG cargo capacity of the largest of them will reach 20000 t.

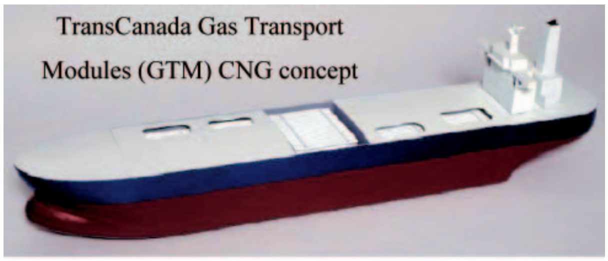


- **EnerSea – VOTRANS –** the firm has proposed a little different method of CNG transport, namely that in which gas is compressed to an appropriate pressure (90 ÷ 130 bar), and next cooled to the temperature in the range of –20 ÷ – 40 °C. The so low temperature is applied to achieve greater gas density.
  CNG is transported in a set of pipes made of carbon steel, placed horizontally, or vertically in the case of smaller capacities. The pipes are insulated thermally from the surrounding, in relevant tanks. Ship's cargo compartment is consisted of 100 tank modules of the height h = 24 ÷ 36 m. Every module contains 24 longitudinal tanks of the diameter D = 1m each. The tank modules are insulated by cooled nitrogen. Cargo capacity of such ships varies in the interval of 5.6 ÷ 57 mln m^3 of CNG, within the 200 ÷ 3000 Mm range of delivery [8].



- **Trans Ocean Gas - *Cassettes*** – the firm has proposed a unique method of CNG transport consisting in using pressure tanks made of glass fibre reinforced plastic (FRP). CNG is transported in ambient temperature under 250 bar pressure. Cargo- carrying capacity of ships of the concept amounts at the most to 28 mln m^3 of gas. The cargo tank is designed in the form of „cassettes" inside of which are placed 18 vertical pressure cylinders of the dimensions: the height h = 12 m and the diameter D = 1.04 m (in three groups of 6 cylinders in each). In the cassette of 12 x 12 x 3 dimensions the natural gas cargo of about 48110 m^3 in volume can be stored. It is approximately equivalent to a 10-feet TEU container [1]. Weight of fully loaded cassette of standard dimensions can reach about 200 T. An advantage of such FRP pressure tanks, as compared with traditional steel ones, is their lower weight by abt. 30 % and higher resistance to corrosion and cracks. A main disadvantage of the technology in question is a very high production cost of FRP tank, greater than that of steel tank by 100%.

- **TransCanada CNG Technologies** – in such design concept natural gas is transported in long pipes of the dimensions: the length l = 12.4 ÷ 36.6 m and diameter D = 1.04 m, in a close to ambient temperature, under pressure of abt. 210 bar. The pressure tanks made of high strength steel are based on CRLP concept. Outer surface of the pipe is covered by glass fibre and resin, that contributes to a significant drop of its mass.The concept is intended to be applied to small ships/barges of cargo capacity of abt. 2.83 mln m^3 of gas.



In Tab. 1 examples of the main design parameters of CNG carriers of existing concepts are presented.

CNG ships, resembling bulk carriers, can be built in large and medium shipyards as they are not so much sophisticated like LNG and LPG carriers are.

Tab. 1. Main design parameters of CNG carriers based on different transport technology concepts (acc. the author's elaboration)

Concepts of CNG carriers	Gas volume [m³]	L_{pp} [m]	B [m]	H [m]	T_{max} [m]	D_{max} [t]	DWT [t]	M_{SP} [t]	V [w]	Cylinders [units]	Propulsion power P_B [kW]
EnerSea –Votrans *)	6.226.000	191.12	34.14	20.0	8.26	42621	6431	36190	14.0	1296	22000
Knutsen OAS	20 000 compres-sed gas	260	54	29.0	13.5	-	33000	-	15.5	2672	-
EnerSea -Votrans V-800	-	267	46.9	27.6	10.4	102935	25395	77660	18.0	2184	40000
Trans Canada	2.830.000	134.0	29.0	-	9.0	-	15700	-	11	-	-
Coselle **)	9 339 000	243	38.0	28.0	10.3	-	60 000	-	15.5	108 „coselles"	-

*), **) - the ships taken to further considerations.

Tab. 2. *Values of weight of the tanks and volume of gas shipped in them for two concepts of CNG ships (the author's elaboration)*

CNG ship:	of EnearSea – Votrans design	of Coselle design
Characteristics of cargo tank	Modules of gas cylinders: 1 module = 24 cylinders Standard dimensions of the tank: h = 24 ÷ 36 m. D = 1.04 m wall thickness t = 0.0335 m - (assumed for calculations)	Diameter: D = 0.168 m Wall thickness: t = 0. 0055 m Length of pipe turns: l = 17702 m Total volume: V = 351 m³ Gas storing temperature: 10°C Gas storing pressure: 240 bar
Weight of steel tank/ Weight of pipe turns in one „carousel" [t]	$P_{zb} = \frac{\pi}{4}[D^2-(D-2t)^2]*H*\rho_S$ **P_{zb} = 19.8 ÷ 29.8**	**P_{zb} = 408** Weight of „carousel": $P_{carousel}$ = abt. 40 **P_{zb}** + $P_{carousel}$ = 448
ρ_s = 7.801 [t/m³] - density of X-80 HS steel		
Volume of steel tank/ Volume of pipe turns in one „carousel" [m³]	$V_{zb} = \frac{4}{3}\pi r^3 + \pi r^2 H$ **V_{zb} = 21.0 ÷ 31.2**	**V_{zb} = 325**
Weight of compressed gas in cargo tank [t]	$P_{gas} = V_{zb} * \rho_{spr.\ gas}$ $\rho_{spr.\ gas}$ = 0.22 [t/m³] - mean CNG density	
	P_{gas} = 4.6 ÷ 6.9	**P_{gas} = 72**
Gas weight/cylinder weight ratio	**$\eta = P_{gas}/P_{zb}$ = 0.23**	**$\eta = P_{gas}/P_{zb}$ = 0.18**
Weight of gas in all cargo tanks on the considered ships *),**) [t]	**$P_{wg} = P_{gazu} * n_{zb}$** **$P_{wg}$ = 4.9 * 1296 = 6350**	**$P_{wg} = P_{gazu} * n_{zb}$** **$P_{wg}$ = 72 * 108 = 7776**
Weight of all cargo tanks on the considered ships *),**) [t]	**$P_{wzb} = P_{zb} * n_{zb}$** **$P_{wzb}$ = 20.2 * 1296 = 26131**	**$P_{wzb} = P_{zb} * n_{zb}$** **$P_{wzb}$ = 408 * 108 = 44064**
Estimated compression ratio	*) $\frac{V_2}{V_1} = \frac{6226000}{27631} \cong \frac{230}{1}$	**) $\frac{V_2}{V_1} = \frac{9339000}{35176} \cong \frac{270}{1}$

*), **) - the main design parameters of the ships - as given in Tab. 1.
V_2 – natural gas volume (ship load-carrying capacity),
V_1 – compressed gas volume in cargo tanks (for the „Coselle" tank: equal to abt. 325.7 m³; for the gas cylinder: abt. 21.32 m³, at h = 24.4 m)

Parameters of compressed natural gas and gas cargo tanks

The greatest difficulty in CNG shipping is associated with an excessively large tank mass / shipped CNG mass ratio. As compared with LNG technology, load-carrying capacity of CNG ships is from two to three times lower. Therefore in every CNG transport technology above described attempts are undertaken to increase volume of transported gas in relation to weight of cargo tanks by improving materials used to production of the tanks (e.g. application of non-metallic composites, higher strength steel) or increasing the mass/volume ratio of gas by searching for optimum parameters in pressure-temperature relation.

To assess volume of a cargo tank and gas to be contained in it, appropriate calculations were performed; its results are presented in Tab. 2. Out of the presented design solutions of cargo tanks the two types have been selected for further analysis: the cylindrical steel tank according to the EnerSea-Votrans' concept and the steel tank in the form of thin – walled pipes according to the Coselle's concept.

As results from the preliminary calculations, despite the greater weight of the cargo tanks according to the Coselle concept its pressure and temeperature parameters of compressed gas result in the greater gas compression ratio, that makes it possible to transport the greater amount of gas.

CHARACTERISTICS OF TRANSPORT TECHNOLOGY OF GAS IN THE FORM OF HYDRATES

By using NGH (natural gas hydrate) ships natural gas in the form of hydrates can be transported in the conditions of the low temeperature T = –20 °C and atmospheric pressure.

Gas hydrate is a substance consisted of frozen water particles which form cage structures (pellets) in the condition of elevated pressure and/or lowered temeperature, in which gas particles are kept.

To form hydrates, presence of water or its vapour (in equilibrium state) and hydrate building gases as well as an appropriate range of pressure and temperature is necessary.

The conditions for forming hydrates during their production and transportation are presented in Fig. 5.

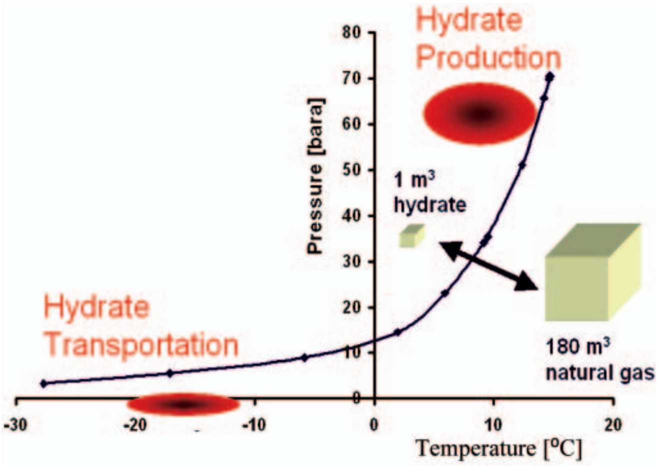


Fig. 5. Conditions for forming hydrates during their production and transportation

Transport chain of gas in the form of hydrates

Transport of natural gas by using NGH ships can be split into the following phases, Fig. 6:

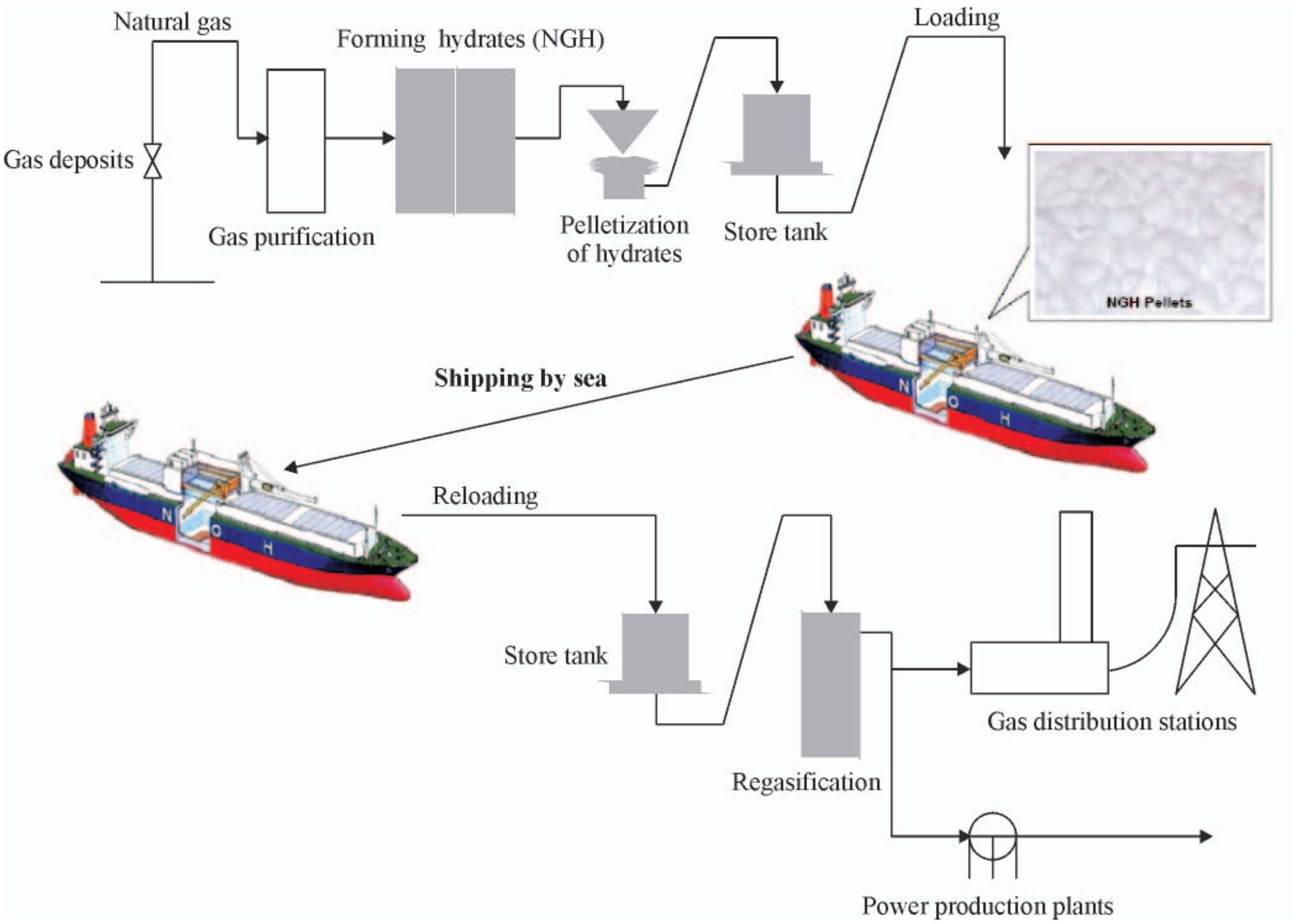


Fig. 6. NGH transport chain (the author's elaboration based on [7])

- mining
- production of NGH in the form of hydrate pulp or granulates
- preparation to transport and loading into ship
- reloading and regasification – gas recovery
- delivery to gas provider.

Design concepts of NGH carriers

As for many years the transport technology of gas in the form of hydrates by using NGH carriers has been still under study there are no built ships of such a type.

Design concepts of NGH carriers are under elaboration in a few countries, namely: Japan, Norway, USA and Great Britain. Scientific research centres operating in the countries, i.e.: *Mississippi State University* (MSU), *Mitsui Engineering & Shipbulding Co. Ltd.* (MES) or *Norwegian University of Science and Technology* (NTNU) conduct research projects on the storing and transporting of natural gas in the form of hydrates.

In 2001 the first design concept of such ship was elaborated, Fig. 7, and as results from a long-term feasibility plan, the end of the pilotage project is scheduled on the year 2009.

The NGH ship design concept resembles a traditional cargo ship in design, such as tanker or bulk carrier. The ship's hull is characterized by double side and bottom plating and subdivision into 12 holds whose tanks are insulated to prevent ice forming outside. Loading operation of the hydrate would be carried out by using the piping system leading to the tanks. During voyage the heat transferred to the cargo through tank walls would locally result in a decomposition of the hydrate into gas and ice. The so released gas could be utilized as a fuel for propelling main engine.

According to the preliminary design of NGH ship each of its 12 tanks was fitted with a mechanical self-reloading device similar to those used to reloading operations on bulk carriers. The necessity of installing such devices in every cargo tank of NGH ship contributes to a very high cost of such ship.

Transport of gas in the form of hydrates is another alternative in relation to LNG transport technology and has many advantages, a.o. such as:
- CNH is easy for storing and safe in transporting
- low transport requirements as to temperature and pressure (T = –20 °C, at atmospheric pressure)
- low investment and operational costs – inexpensive in production and delivery
- high transported hydrate mass /tank mass ratio
- lower risk of possible explosion due to cristalline structure
- ecological – not dangerous to the environment
- possible conversion of existing ships, e.g. oil tankers
- adjustment of gas deposit resources and quality of transported gas to receiver's needs
- lower requirements as to thermal insulation of cargo tanks.

However the following is disadvantegous:
- hydrate contains abt.10% of water
- small gas volume relative to cubature
- profitable only for ships of VLCC size
- necessity of regasification.

Like in CNG transport technology, only short-range shipping up to 3000 Mm is profitable. When properties of the gas in LNG and NGH form are taken into account, size of the fleet of NGH ships should be almost four times greater as compared with that of LNG ships (under the assumption that LNG contains 600 m^3 of natural gas and NGH about150 m^3 of it). Therefore load-carrying capacity of NGH ships must be at least four times greater than that of LNG ships at the same transported quantity of natural gas, that detrimentally influences cost of NGH shipping by sea.

OPERATIONAL COSTS OF DIFFERENT NATURAL GAS TRANSPORT TECHNOLOGIES

The two following factors decide on which technology of gas transport by sea would be the most profitable:
- load-carrying capacity of ship
- transport range (distance).

Size of gas carriers as well as their whole fleet and especially volumetric capacity of their cargo tanks would first of all depend on:
- direction of import
- quantity of imported gas
- land infrastructure, i.e.: gas receiving terminal and gas piping network

whereas their operational costs would be dependent on:
- location of natural gas import source, i.e. choice of transport route
- fuel cost (depending a.o. on current fuel price, specific fuel consumption, ship speed etc)

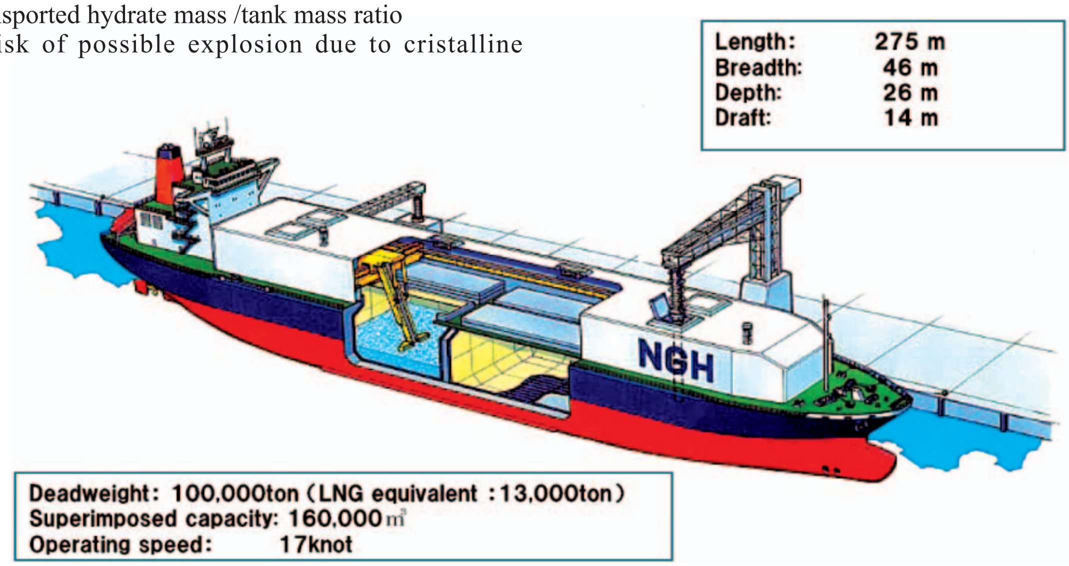


Fig. 7. *NGH ship design concept [7]*

- size of ship and kind of its propulsion system (it mainly concerns LNG ships)
- type and number of applied cargo tanks as well as design parameters of ship hull
- personnel cost – freight rate (long-term one)
- additional expenditures.

Moreover for calculations of the operational costs the following should be assumed:
- period of active operation of ship
- period of ship stand-by in ports during each round voyage of the ship
- number of ships angaged on a given route– depending on their load-carrying capacity and speed, as well as for LNG ships - on a gas cargo quantity evapourized during voyage.

Summing up, operational costs depend on many above mentionad factors. Knowledge of all the parameters makes it possible to perform optimization investigations to select the best variant of gas carrier together with appropriate gas transport technology, regarding gas delivery cost minimization.

Determination of exact operational cost is usually difficult and complicated because of lack of reliable data, as well as due to commercial secret policy from the side of firms competing on the market.

In Fig. 8, on the basis of literature sources and available knowledge, a comparison of component costs of LNG and CNG transport technologies is presented, and in Tab. 3 – a comparison between costs of LNG and NGH transport technologies.

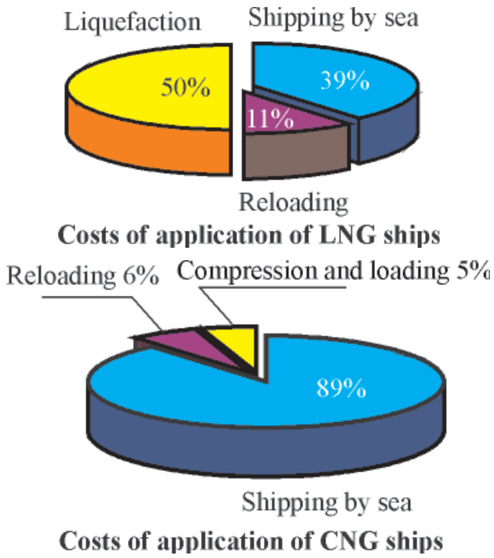


Fig. 8. *Comparison of component costs of application of CNG and LNG ships [3]*

As results from an economic analysis performed in 2002, the costs of the NHG transport chain are lower by 12% in relation to those of LNG transport chain. Shipping costs are similar, but the option of NGH transport technology is more expensive by 2% only, like the difference of their regasification costs which amounts to 1% only, Tab. 3, acc. [5].

CONCLUSIONS

– Fast growing demand on natural gas and its limited resources will cause increasing prices, therefore new, better solutions of natural gas transport technology should be searched for economical and ecological reasons. Limited possible application of piping systems to its transportation forced to an extent the development of mass transport technologies of natural gas in the liquid or compressed form.
– Long-range transport of liquified gas is (despite its complexity and high cost) the most profitable transport method, whereas CNG and NGH transport technologies are the best for transportation of medium and small amounts of gas over short distances, up to 3000 Mm. Therefore economic merits of the two transport alternatives should be taken into consideration in planning natural gas transport to Poland, especially in the case of its delivery from Norway. Expected delivery distance (from Barents Sea to Swinoujscie) equal to abt. 2600 km indicates large possible savings in investment cost, mainly for transport operation.
– As above mentioned, transport of gas in the form of hydrates is still in the research phase hence its practical application would be a more distant alternative. For the time being, it could be considered a potential, future alternative of gas delivery to Poland.
– Research on development of design and production technology of ships intended for natural gas shipping are currently carried out in the Department of Ocean Engineering and Design of Sea-going Ships, West-Pomeranian University of Technology, ZUT in the frame of the research project No. 507-09-022-9718/7, titled: *„METAN – Research on development natural gas shipping with special attention paid to the state of transported gas, optimum size of ship, type of power plant as well as logistic and technolgical problems"*.

NOMENCLATURE

B – ship breadth [m]
D – outer diameter of cylinders or pipe turn [m]
D_{max} – maximum ship displacement [t]
DWT – ship deadweight [t]
h – height of cylindrical tanks [m]
H – ship hull depth [m]

Tab. 3. *Costs of transport chain based on NGH or LNG technology, acc. [5]*

Transport chain	LNG [%] mln $ ([%])	NGH [%] mln $ ([%])	Difference mln $ ([%])
Production	1144 (55%)	992 (54%)	152 (13%)
Shipping by sea with the use of ships	660 (32%)	628 (34%)	32 (5%)
Regasification	285 (13%)	218 (12%)	57 (24%)
Total	2089 (100%)	1838 (100%)	**251 (12%)**

Note: Calculations were perfromed under the assumption that the yearly amount of gas transported in the delivery range of abt. 6000 km is equal to 11320000 m^3.

l − length of turn of pipes acc. to Coselle technology [m]
L_{pp} − ship length b.p. [m]
M_{SP} − light ship mass [t]
n_{zb} − number fo cargo cylinders / number of carousels with pipe turns [pieces]
r − cylindrical tank diameter [m]
t − cylindrical tank wall thickness [m]
T_{max} − maximum ship draught [m]
V − ship speed [m/s]
$V_{Ł}$ − load-carrying capacity of ship [m^3]
V_1 − volume of compressed gas in cargo tanks [m^3]
V_2 − volume of natural gas [m^3]
$\rho_{spr.gas}$ − density of compressed natural gas [t/m^3]

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