METHOD OF TRANSPORTING LIQUEFIED GASES, IN PARTICULAR LNG, AT A TEMPERATURE BELOW SATURATION TEMPERATURE

In proposed method of liquefied gases (primarily LNG) transportation the liquefied gas is cooled prior to its loading into tanks of carrying vessel (e.g. a ship, an automobile, a railcar) to temperature which is lower, than saturation temperature at design pressure in tanks during the transportation. During the transportation heat inflow from the environment is absorbed by free increasing of liquefied gas temperature from subcooled liquid to saturated liquid state. Liquefied gas is not boiled off (as it would otherwise be the case for absorption of heat inflow) so it is not necessary to use reliquefaction plant on board of the carrying vessel or to dispose of boil-off gas. Seagoing ships transport large mass of liquefied gas so difference between liquefied gas temperature at the beginning of the transportation and saturation temperature will be relatively small. For example for LNG tanker having volume of tanks 150,000 m³ its value is 4.5 °C.
1. Technical Field.
IPC B63J 99/00, CIOL 3/00, F25J 1/00, F17C

This invention relates to field of transport of liquefied gases by sea- and river going ships, automobiles and railway transport. Invention is mainly intended for use on seagoing ships which carry large quantities of liquefied gases for long distances.

2. Background Art.

Presently three methods of liquefied gases transportation are known:
- at the ambient temperature and corresponding saturation pressure;
- at the pressure slightly exceeding atmospheric and corresponding saturation temperature;
- at the pressure considerably higher than atmospheric and corresponding saturation temperature (known as combined method of liquefied gases transportation).

First method of liquefied gases transportation is most economical since it does not require refrigeration. However tanks of such liquefied gas carrying ships are too heavy. Tanks of such ships are designed to withstand high pressure (up to 1.75 MPa) so they have spherical or cylindrical form. Tanks of such form inefficiently utilize volume of the ship's hull. Method yields extremely poor results for gases which have temperature of critical point lower than ambient temperature.

Second method requires presence of expensive and complicated refrigeration equipment on board the ship (gas reliquefaction plant) and high consumption of energy for running the reliquefaction plant. Alternatively gas, which is
boiled off as a result of heat inflow from the environment, is not recondensed but released into the atmosphere or burned as a fuel in the ship's engine. The method is economically justified for large ship and long distance of transportation. Majority of LNG tankers utilize such method.

Third (combined) method of liquefied gases transportation also requires use of heavy tanks (but not as heavy as for first method) and refrigeration plant (but of lower cooling capacity than what is required for second method).

3. Disclosure of Invention.

In proposed method of liquefied gases transportation the liquefied gas is cooled prior to its loading into tanks of carrying vessel (e.g. a ship, an automobile, a railcar) to temperature which is lower than saturation temperature at designed pressure in tanks during the transportation. The name of such state of the matter in thermodynamics is subcooled liquid as opposed to saturated liquid in traditional method of liquefied gases transportation. During the transportation heat inflow from the environment is absorbed by free increasing of liquefied gas temperature from subcooled liquid to saturated liquid state. Liquefied gas is not boiled off (as it would otherwise be the case for absorption of heat inflow) so it is not necessary to use reliquefaction plant on board of the carrying vessel or to dispose of boil-off gas.

4. Brief Description of Drawings.

Not applicable.

5. Best Mode for Carrying Out the Invention.

Best results can be obtained from application of the invention to seagoing LNG tankers.

Presently LNG is transported by sea in tankers at atmospheric pressure, boil-off gas is either burnt in tanker's main engine or condensed in onboard reli-
quefaction plant and then returned into tanks. 90% of existing fleet utilize former solution, while majority of newbuildings - the latter. Burning of boil-off gas imply using of steam turbine for vessel's propulsion which characterized by low fuel efficiency. Reduction in quantity of LNG delivered to the port of destination is another shortcoming. Fitting the tanker with reliquefaction plant solves these two problems but the plant is quite expensive - about 10% of vessel's construction cost.

An alternative way to absorb heat inflow into vessel's tanks is to cool LNG below its saturation temperature at atmospheric pressure. During the voyage temperature of LNG will be rising gradually and will reach saturation temperature upon arrival to the port of destination. As far as inventors aware such solution was never discussed for LNG transportation. Probable reason for this is that pioneers of LNG industry copied solutions used by XIX century scientists for storing relatively small quantities of liquefied gases at atmospheric pressure. Large quantity of LNG carried by tanker enables using its enormous heat capacity to absorb heat inflow. Corresponding increase of LNG temperature will be 4.5 °C for typical 20 days voyage of 150'000 m³ tanker.

In proposed method of LNG transportation by sea LNG is cooled prior to its loading into tanker to temperature which is lower than saturation temperature at atmospheric pressure. During the voyage heat inflow is absorbed by LNG gradual heating to saturation temperature. LNG is not boiled off so it is not necessary to use reliquefaction plant on board of the ship.

Subcooling of LNG is done by shore based liquefaction plant which uses cheaper electricity than ship based reliquefaction plant. Moreover powerful shore based plants use more efficient thermal schemes (AP-X, c 3-MR, cascade), than ships based (N₂). For this reason shore based plants consume per kJ of withdrawn heat not more than 70% of mechanical power required to drive ships based plant. Due to economy of scale capital expenses per kW of withdrawn heat also favor shore based plant (one typical shore based liquefaction plant pro-
duce quantity of LNG which can be transported by 16 constantly operating tank-
ers).

Tanker carries large quantity of LNG so level of subcooling from saturation point will be small. For example daily boil-off on 150'000 m³ capacity LNG tanker which carry its cargo at 0.103 MPa is 0.15 % or 94.9·10³ kg. Heat of vaporization is 509.9 kJ/kg, so heat inflow is 48.39·10⁶ kJ/day. Mass of LNG in vessel's tanks is 63.27·10⁶ kg, isobaric heat capacity of liquid methane is 3.424 kJ/kg, so subcooling by 0.22 °C is sufficient to compensate daily heat inflow. Basis duration of the voyage 20 days subcooling of LNG required to absorb heat inflow is 4.5 °C.

Because of subcooling temperature drop between environment and LNG will increase which will result in corresponding increase of heat inflow. Temperature drop between environment (15 °C) and LNG at saturation temperature (at atmospheric pressure) is 176 °C. Because of subcooling average increase in temperature drop will be 2.3 °C i.e. 1.3 %.

Methane vapor in ship's tanks above LNG surface will arrive to thermodynamic equilibrium with liquid. Temperature of subcooled LNG is lower than its saturation temperature at atmospheric pressure so pressure of methane vapor above the surface of subcooled LNG will be lower than atmospheric. For this reason after completion of loading it is necessary to mix methane vapor in tanks with inert gas (e.g. nitrogen). Content of each component should be selected on the basis of equality of sum of partial pressures to atmospheric pressure. In the course of the voyage temperature of LNG in tanks will be rising and partial pressure of methane in the mixture of gases will be rising correspondingly. Excessive part of the gases mixture from tanks should be released into atmosphere or burnt in the ship's propulsion plant.

In case of methane subcooling 4.5 °C partial pressure of its saturated vapor will be equal to 0.070 MPa and partial pressure of nitrogen - 0.033 MPa. Basis
volume of gas equal to 5% of liquid required mass of nitrogen is \(7.2 \times 10^3\) kg which is relatively minor figure.

Application of the method to LNG-tanker with capacity 150'000 m\(^3\) with reliquefaction plant will produce following results:

- cost of power for maintaining LNG in liquid state during ocean transportation will decrease by \(0.43 \times 10^6\) US $ per year;

- for a ship which do not use reliquefaction plant, at the commencement of ballast passage it will be necessary to leave LNG heel in tanks in order to keep them cold till the end of the ballast passage. This will increase fuel expenses for ship's propulsion plant by \(0.64 \times 10^6\) US $ per year but will decrease fuel expenses for reliquefaction plant by \(0.67 \times 10^6\) US $ per year;

- cost of additional energy required for LNG subcooling before its loading on the tanker amount to \(0.06 \times 10^6\) US $ per year;

- all above will reduce operational expenses by \(0.40 \times 10^6\) US $ per year

- capital expenses because of increasing of capacity of shore based liquefaction plant will amount to \(3.4 \times 10^6\) US $ but on or before the stage of ship's construction there is a possibility to save \(20 \times 10^6\) US $ for ship's reliquefaction plant which will become redundant.

For ships with reliquefaction plant application of the method on or before the stage of vessel's construction will reduce both operational and capital expenses. Application of the method to existing ships is not justified.

For the same LNG-tanker without reliquefaction plant results will be as follows:

- fuel expenses will be reduced by \(0.64 \times 10^6\) US $ per year due to use of heavy fuel oil instead of boil-off natural gas in the vessel's propulsion plant;

- cost of additional energy required for LNG subcooling before its loading on the tanker amount to \(0.06 \times 10^6\) US $ per year;

- capital expenses arising because of increase in capacity of shore based liquefaction plant \(3.4 \times 10^6\) US $.
Thus for LNG tanker without reliquefaction plant basis return on investment 7% annually period of depreciation of innovation will be 10 years.

LNG subcooling implies use of heavy fuel oil for vessel's propulsion. For LNG tanker without reliquefaction plant there is a possibility to replace steam turbine (with 30% thermal efficiency) with slow speed diesel (with thermal efficiency 50%). For existing tankers feasibility of such replacement should be decided on case to case basis. For new tankers replacement of steam turbine with slow speed diesel will be always feasible because all new vessels with reliquefaction plants (which also make it possible to use heavy fuel oil for propulsion) are fitted with diesels, not with steam turbines.

6. **Industrial Applicability.**

This invention can be applied on sea- and river going ships, automobiles and railcars which transport liquefied gases. Primary industry where invention may find application is seagoing ships (LNG tankers) which carry large quantities (50,000-250,000 m³) of LNG for long distances (1,000-10,000 nautical miles).
Method of liquefied gases (primarily LNG) transportation at the temperature below saturation temperature, which consist in cooling liquefied gas before transportation to the temperature which is lower than saturation temperature at the transportation pressure, which differs by not maintaining temperature of the liquefied gas during the transportation constant by way of the gas partial boil off or using refrigeration plant, while in proposed method heat inflow from environment during transportation is compensated by free increasing of the liquefied gas temperature from its temperature in the beginning transportation to the saturation temperature.
Method of transporting liquefied gases, in particular LNG, at a temperature below saturation temperature which consist of following steps:

(i) Subcooling liquefied gas before transportation to the temperature which is lower than saturation temperature at the atmospheric pressure. Degree of subcooling (i.e. difference between latter and former temperatures) is determined by following condition: heat inflow from environment into vehicle's tanks is compensated by free increasing of the liquefied gas temperature from its temperature in the subcooled state at the beginning of the transportation to the saturation temperature in the end of the transportation.

(ii) Pumping subcooled liquefied gas into tanks of transport vehicle.

(iii) Adding inert gas (e.g. nitrogen) into space of tanks which is not filled by liquefied gas. Sum of partial pressures of inert gas and vapor of liquefied gas in this space must be equal to atmospheric pressure.

(iv) Transporting liquefied gas in the vehicle to the destination.

(v) Pumping liquefied gas from tanks of transport vehicle into receiving tanks at the destination.
## A. CLASSIFICATION OF SUBJECT MATTER

**INV.** F17C5/Q2

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F17C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

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