Measurement of Inductance of Liquefied Natural Gas

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***Abstract*–The peculiarities of application of various means of measuring gas mass are being considered. We study the dependence of the inductance of a gas cylinder from the quantity of liquefied gas in the tank and the ambient temperature. The results of experiments are presented. The scheme of device for determining the amount of liquefied gas in the** cylinder **has been proposed.**

I. Introduction

For the past several years the world has witnessed a trend towards fuel-based liquefied natural gas. Natural gas is an important component of the world energy supply, one of the cleanest, safest and most useful of all energy sources. Natural gas vehicle (NGV) fuel is a unique combination of environmental, economic and technical advantages [1]. A massive shift to liquefied petroleum gas (LPG) is due to the following reasons.

- The prospect of the world's natural gas reserves.
- The depletion of traditional energy source – oil.
- Lower cost of liquefied natural gas compared with fuel oil based.
- High energy and economic characteristics of liquefied natural gas.
- Environmentally, natural gas is the cleanest form of fossil fuel. (During combustion gas produces on average five times less harmful emissions compared to other fuels).

The transition to natural gas in the first place refers to such fields as transport [2], heating system and gas stoves in homes, boilers and CHP, furnaces for various purposes and number of chemical plants, that is region that affect the widest layers of the population and largely determine the economic and environmental situation. This requires continuous improvement of technology of production of natural gas, preparation and transportation of liquefied gas, storage and distribution of liquefied natural gas.

Therefore, fuel-based liquefied natural gas is the fuel of the future. This determines the necessity and urgency of scientific and technical developments in this field. It is obvious that a massive shift to LPG requires improvement of methods and means of quantity control and fuel consumption to optimize the operation of the relevant systems, ranging from trucks to complex technological equipment of chemical plants in three main areas [3], [4], [5].

- Providing a convenient visual monitoring of fuel consumption.
- Control of gas leakages during the leakage of gas reservoirs and the prevention of situations relating to possible explosions, poisoning the environment, as well as for unauthorized access to pipelines to steal fuel.
- Development of automatic regulators of fuel consumption to ensure a more efficient operation and reduce the amount of harmful emissions with the use of possibilities of modern computer technology.

Today in Russia the innovation vector in the use of natural gas fuel is maintained at all levels; plans for the introduction of gas fuel for transport are confirmed by the government's policy [1].

II. Target setting

There is a comparative analysis of existing methods of measuring the mass of light oil in reservoirs and ensuring the necessary measurement accuracy in [3]. The direct method of static measurements based on the measurement of the total weight of product in shipping containers and based at the weigh-in with weights. The most common indirect methods are static measurements based on the measurement of density and volume of product in the tank. Indirect methods measure the level of fluid volume is determined in accordance with the calibration tables of the tank, calculated mass of the product as the product of volume per density. When the analysis considers errors associated with thermal expansion tanks. Precision measurements of the mass of liquefied gas are dependent on the accuracy of liquid level measurement, accuracy of calibration charts and the accuracy of the density measurement. For automated measurement of level uses level sensors: float, microwave, radio frequency, electroacoustics, ultrasonic, servo, mooring, hydrostatic, laser [3], [4], [5].

Currently existing methods and devices for control and measurement based on the measurement of the weight and the float principle, does not allow provide high accuracy and reliability in different climatic conditions and wide temperature ranges, during the autonomous operation of mobile devices in the conditions of shaking and vibration. In addition, the introduction of sensors in a tank of gas violates its original strength that is unsafe in high pressure and provides ease of maintenance, including work associated with calibration of instruments [6], [7], [8], [9].

In the methods based on the use of RF sensors is the electrical capacitance measurement, filled in a controlled substance and is arranged vertically inside the tank with liquefied gas, and the temperature measurement of liquid and gas phases inside the tank using sensors located uniformly

ISSN 2305-7254

along the length of the sensor inside the tank [10]. The disadvantage of this device is the placement of sensors inside a gas cylinder, which complicates their installation and maintenance – inspection, repair and replacement, and to perform these works required the depressurization of the container, thus there is the harmful factor in the form of gas.

Methods based on the pressure measurement, cannot fairly judge the weight of the remaining liquefied gas in the tank. The pressure in the cylinder depends on the mixture composition, physical specifications of the mixture and the ambient temperature. The pressure drops in the expenditure of gas. Under reduced pressure the liquefied gas begins to evaporate (boil) and the pressure increases again, but if the pressure is too increased, the gas is liquefied and the pressure drops. The gas being evaporated is cooled and takes the necessary heat from the environment. When the gas is heated back to ambient temperature, the pressure is restored. Therefore, only pressure to accurately determine the amount of liquefied gas is impossible [11], [12].

In the methods based on the use of ultrasonic means for measuring the pressure is performed to register the passage of acoustic waves in the gas medium of the container and the container body, and by the magnitude of the difference in time of arrival of signals judge the gas pressure [7]. The advantage of this method is the contactless pressure control of gas cylinders. The drawback of the methods and devices is the dependence by changing the position of the gas cylinder, from vibrations and accelerations in the vertical direction, which virtually eliminates the possibility of using these inventions on a moving vehicle.

In addition, as a rule, devices that are used to display fuel consumption, placed directly on the cylinder, which leads to the need of direct human contact with the tank (for example, you need to stop the car, open the trunk, etc.).

In this regard, the task was to find parameters which can be used to control the amount and flow rate of the liquefied gas, without violating the integrity of the tank regardless of factors such as shaking, vibration, humidity, chance of electrical sparks, etc.

The authors hypothesized that as such the parameter may be the inductance of the tank with liquefied gas.

The essence of the proposed approach is to measure the inductance of the tank with liquefied natural gas as its consumption (or leakage). For this purpose the tank is equipped with a special winding (without violating its integrity and design). After that liquefied natural gas can be considered as the "core" of the coil [13].

III. Inductance of liquefied natural gas

With the aim of testing the hypothesis measured the inductance of the portable gas cylinder (made of metal) containing 450 g of a mixture of butane (20%) and propane (80%). The cylinder was placed a coil of several turns of copper wire (wire PEV-2 in diameter of 0.14 mm) and thus, the container represents an inductor. The inductance measurement was carried out with the gas combustion in the burner that is installed on the cylinder. The measurement was taken with a digital RLC meter E7-8. Over time, as the combustion gas, the inductance decreased, though slightly, but it is noticeable. Thus, was observed a clear dependence of the inductance on the mass of the gas.

In the time interval 16:30 – 16:48 inductance is linearly decreased from 1.356 H to 1.347 H. This experiment was conducted on a small time interval (18 minutes). Schedule of change of inductance is shown in Fig. 1.

The next stage was the investigation of the dependence of the inductance of the mass of liquefied gas to a more significant interval of time to identify the behavior curve of the inductance on the mass of liquefied gas when burned. Fifty minutes later the areas where the inductance is not practically changed was discovered. Then a linear dependence restored again, etc. In this case, when touching the cylinder was felt that the temperature of the cylinder is much lower environment. So the next stage was to identify and study the temperature dependence.

IV. Temperature and inductance

The temperature change of the cylinder is easily explained, as the combustion gas remaining inside the cylinder, the gas expands and when the gas expansion work is being performed at the expense of its internal energy. A measure of change in internal energy is temperature. In other words, the gas expands, its thermal energy is distributed over a larger volume. Because it requires energy, it results in lowering the temperature of the cylinder.

Thus, the total temperature of the cylinder is the sum of ambient temperature and temperature due to the release of gas from a cylinder. To study the impact on the cylinder temperature of the environment, full gas cylinder, with a wound coil was placed in the refrigerator. After a while, the cylinder can be removed that is connected to the inductance meter and left to warm up naturally to room temperature. This time the gas is not being used.

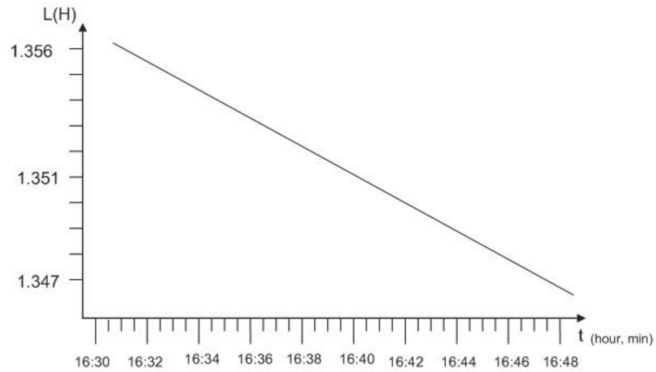

Fig. 1. The change in the inductance of the gas cylinder over time during combustion of gas

The change in inductance was measured with an interval 10^{-3} H. For 4 hours 05 minutes the cylinder is heated from 7.6 °C to 24.1 °C. The inductance increased from 1.621 H to 1.639 H, i.e., with increasing temperature of cylinder inductance also increases.

Thus, to determine the flow rate of the liquefied gas is not the only measurement of inductance, it is necessary to know the temperature of the cylinder, which significantly depends on the ambient temperature and the gas flow.

Fig. 2 shows a graph of the dependence of inductance on temperature. Dependence is almost linear.

To determine the dependence of the inductance of the mass of gas in the tank and temperature following a pilot study was conducted.

Full gas cylinder with a coil was put on electronic digital scale, connected to a portable meter inductance, and between the container and the paper winding frame was placed a temperature sensor, connected to the portable electronic digital temperature meter. The burner was installed on the cylinder.

Photos of the experiment are shown in Fig. 3. The gross weight of the cylinder is 631 g. Liquefied natural gas weighs 450 g. The burner weighs 210 g. Weight of coil paper frame was 276 g. The initial total weight of the container, coil and burners was 1117 g. The study was conducted in the following way.

The measurements were carried out for 4 hours 15 minutes. Fig. 4 shows the obtained graphs of the time dependency of the temperature (curve 1), the mass of the cylinder (curve 2), inductance (curve 3).

After we lit the fire and started the gas flow, simultaneously and continuously, down to empty the cylinder regularly at certain intervals of time was measured by mass (weight).

Since the gas during combustion is consumed continuously, the mass of gas decreases monotonically and the dependence is close to linear dependence (curve 2).

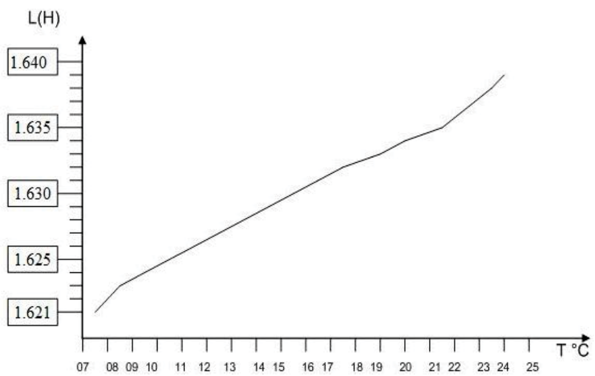

Fig. 2. Dependence of the inductance of the full cylinder from temperature

The temperature of the cylinder consists of two components – the ambient temperature and the temperature due to the release of gas. The dependence of the temperature (curve 1) initially decreases, reaches a minimum and then begins to grow. In the first stage, the gas escapes under high pressure, which ensures the reduction of temperature of the cylinder.

Fig. 3. Photo of the experiment

As gas flow, temperature reaches a minimum, then, in connection with the emptying of the cylinder and decreasing pressure, the external component of temperature begins to "dominate" and the curve goes up.

The value of inductance (curve 3) decreases with decreasing gas mass, as its consumption. The curve has a nonlinear character associated with the effect of temperature on the inductance of the cylinder.

The ambient temperature is "trying to raise" the curve 3, and the temperature due to releasing gas “attempts to keep it cold" thus lower curve 3. Hence, such a "fancy" curve 3.

And in the time interval 16:30-16:50 the dependence is linear, which corresponds to the dependencies shown in Fig. 1. From the analysis of the dependencies in Fig. 4 it is easy to see that the curve of inductance has sections parallel to the time axis. If an indication of the mass of gas in the cylinder only inductance, the same inductance value will correspond to different values of the mass. To account for this ambiguity, it is necessary for each mass value to be matched by a pair of numbers – the value of the inductance and the temperature of the cylinder.

V. Practical implementation

Presented in the paper allow us to conclude the following. Consumption of liquefied gas in the cylinder can be measured by mapping the mass of gas two parameters, inductance and temperature of the cylinder.

To move to the practical implementation of the proposed method it is necessary to solve many applied problems. Will present a preliminary list and define some of the stages in the solution of these problems.

Despite the fact that the range of applications of liquefied gas is extremely wide (household appliances, vehicles,

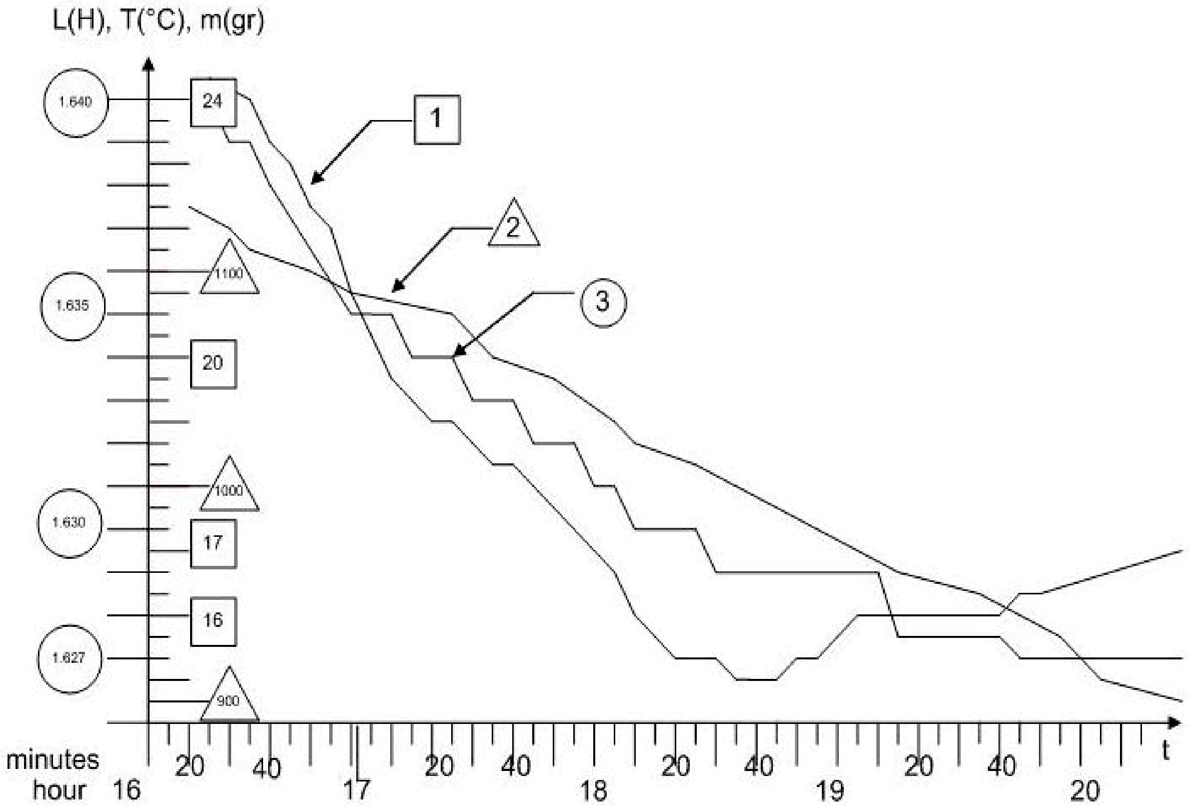

Fig. 4. The time dependence of the temperature (1), the mass of the gas cylinder (2) and inductance (3)

chemical manufacturing, military, etc.), you can specify three basic stages that are common to all applications character associated with the effect of temperature on the inductance of the cylinder.

A. Design

At this stage, in each case, it is necessary to solve a number of technical issues.

- To pick up a container of optimum (from the point of view of inductance) winding, namely, the number of turns, wire diameter, type of winding, the material of the frame, the location of the coil on the cylinder (in the middle, closer to the bottom, throughout its length, etc.).
- Determine how you will measure the parameters. You can use ready devices. On the market there are a large number of portable digital measurer inductance and temperature. It is possible to develop an original device, for example, sew up tables in ROM, received after calibration of the cylinder, and the current values of inductance and temperature to use as the addresses to which the recorded weight of gas, etc.
- In case of sharp fluctuations of external temperature it is necessary to have a device that can switch from one table derived during calibration, on the other. For example, the micro – computer on a single chip, flash memory, etc. Special conditions it is advisable to place the cylinder in a kind of outer shell (thermos) to exclude the effects of changes in ambient temperature.

B. Calibration gas cylinder

This is a very important step necessary for setting in correspondence to each value of the current mass of gas in the tank of the pair of measured parameters.

- It is installed on the cylinder coil the inductance device of the gas flow and a temperature sensor connected to the electronic thermometer.
- The cylinder is placed on scales, and winding connects to the meter inductance.
- It is exposed the ambient temperature. The temperature is determined by the scope of the container. For example, for cars it can be a range from -50 ^{o}C to +50 ^{o}C.
- Turn on the device the gas flow, for example the burner will run until complete emptying of the container.
- The calibration is executed.

Then the cylinder is refilled, or taken another similar a full tank. Change the ambient temperature and produce re-measurement of parameters. The step change in temperature is determined by the specific conditions and requirements for accuracy. This procedure can be lengthy, but it is done one time for the commercially available standard cylinders.

C. Commissioning tests

Vital steps in commissioning any system are following.

- Prepared the test plan.
- Is placed in your tank with a coil, mounted measuring.
- Performed regular system operation in the test plan.
- Compile a list of non-compliances.
- Comments are removed, fatal count, etc. Is a document, signed by the authorized persons, the readiness for operation.

VI. Device for Determining Quantities of Liquefied Gas in the Cylinder

Fig. 5 shows a diagram of the proposed device for determining the amount of liquefied gas in the cylinder [14].

In the device for determining the amount of liquefied gas in the cylinder inductance coil 2 is put on the container 1 with liquefied gas and electrically insulated from the cylinder 1. The findings of the inductor connected to the module inputs of the meter inductance 3.

A set of N temperature sensors 4_1, 4_2, ..., 4_N are installed on the gas cylinder 1, and on separate lines of the sensors are connected to respective inputs of the module temperature meter 6.

The computing unit 5 comprises a module temperature meter 6, the temperature equalization module 7, a calculation module 8, the comparison module 10, memory module 12 and transfer module 15.

The outputs of the module temperature meter 6 are connected to the module inputs equalization temperature 7 whose outputs are connected to first inputs of the calculation module 8, the second inputs of which are connected to the outputs of the module of the meter inductance 3.

The outputs of the calculation module 8 are connected to the indicator 9 and the first input of the comparison module 10. The second and third inputs of the comparison module 10 are inputs 13 and 14 to set the mass of gas, and the output of the comparison module 10 is connected with the indicator of remaining gas 11. Outputs module meter inductance 3, module temperature meter 6, the temperature equalization module 7, calculation module 8 and comparison module 10 are connected to corresponding inputs of the memory module 12 and module 15 of the exchange. The outputs of the transfer module 15 are external bus exchange device 16. Temperature sensors placed on the surface of the cylinder, as at the ends of the cylinder and around the circumference of the cylinder near the inductors. The number of sensors N and their location depends on the operating conditions and the location of the gas cylinder.

For example, if the container is placed in the trunk of the car, the temperature of all points of the cylinder are practically the same. Or, if the container is located under the truck, the temperature of the external and internal sides and ends of the cylinder may vary due to the impact of the external environment – heat from the sun, cooling from wind, snow or rain.

Therefore, for calculations of the mass of gas is averaging the temperature of the cylinder.

The results of the calculations are displayed on the indicator, which may be digital, dial, or made in the form of scale led. In addition, the device entered the alarm device dual mode mass of the gas, which informs about approaching to a minimum of liquefied natural gas ("flashing" lamp mode signaling) or the amount of gas less than the minimum (lamp indicator is lit continuously).

In addition, the device has entered the memory module and the exchange module, which can be used to calibrate the device and control its operation. Presented in the paper allow us to conclude the following. Consumption of liquefied gas in the cylinder can be measured by mapping the mass of gas two parameters, inductance and temperature of the cylinder. Based on the research developed and tested a circuit device for determining the amount of liquefied gas in the cylinder. For the practical use of the proposed method of measurement of the flow of liquefied gas it is necessary to conduct additional studies of the effect on the inductance of a gas cylinder other factors, such as atmospheric pressure, humidity, etc.

VII. Conclusion

Presented in the article allow to draw the following conclusion. Consumption of liquefied gas in the cylinder can be measured by mapping the mass of gas two parameters, inductance and temperature of the cylinder. Based on the research developed and tested a circuit device for determining the amount of liquefied gas in the cylinder. For the practical use of the proposed method of measurement of the flow of liquefied gas it is necessary to conduct additional studies of the effect on the inductance of a gas cylinder other factors, such as atmospheric pressure, humidity, cylinder material etc.

More in-depth theoretical studies of the influence of the factors considered in the article on inductance are also required.

Another possible direction of that work is design and development of the reliable data collecting software for the gas level measurements that can be used in the complex, dynamic, highly distributed and diverse cyber-physical systems as automotive vehicles that can have advantages of proposed technique. In that case it is possible to use architecture proposed in [15].

Acknowledgment

Authors acknowledge support from the MEPhI Academic Excellence Project (Contract No. 02.a03.21.0005).

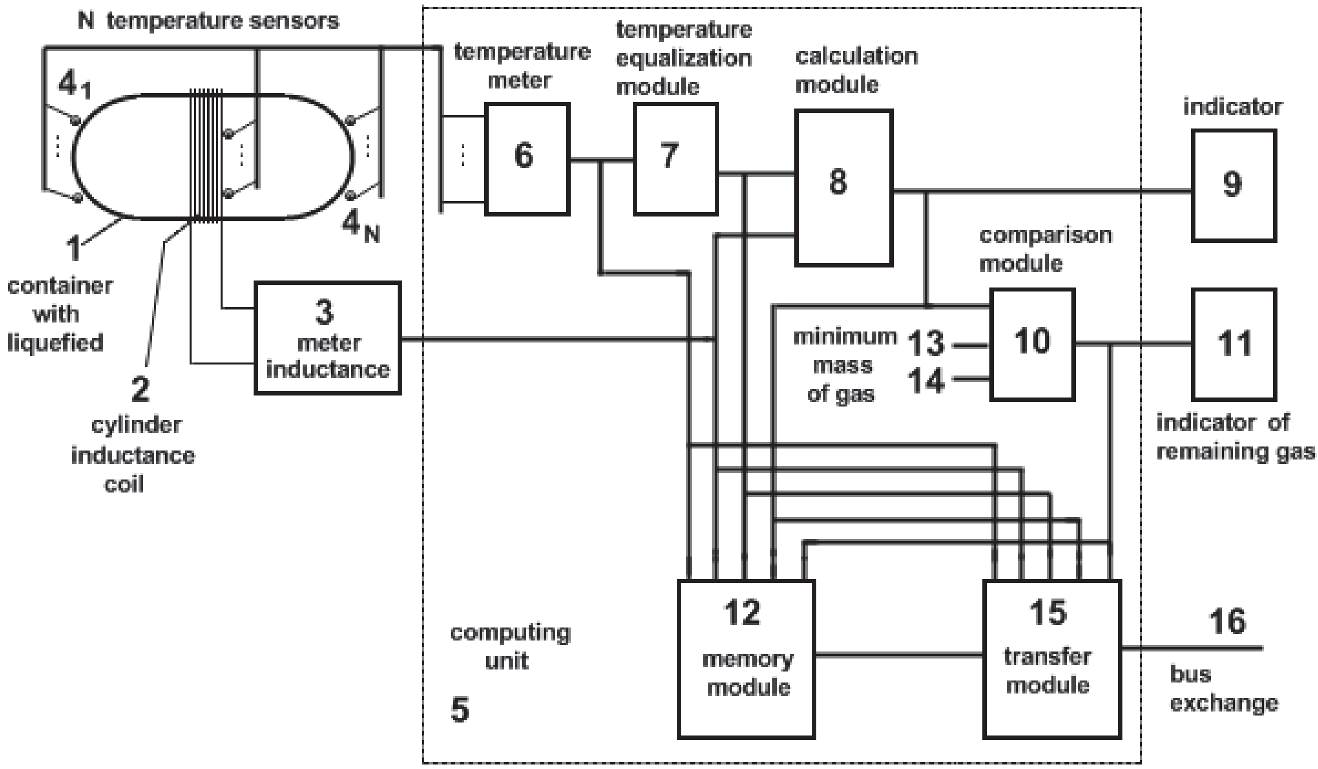

Fig. 5. Diagram of the device for determining the amount of liquefied gas in the cylinder

References

[1] E.E. Avtaikina,"Innovations in gas industry. Gas engine fuel – an innovative direction for the Russian economy", NovaInfo.Ru, no. 26, 2014. pp. 79-81, Web: http://novainfo.ru/archive/26.

[2] V.I. Erokhov, *LPG cars (design, calculation, diagnostics). Textbook for high schools.* M.: Hotline, 2012.

[3] V.I. Tereshin and A.S. Sovlukov, "Comparative analysis of existing methods of mass measurement of light petroleum products in tanks", *III-rd International Metrological Conference "Urgent Matters of Measurements of Flow Rate and Amount of Liquids and Gases",* 2-4 Sep. 2015, Kazan, Russia. – Kazan: publishing house the World without borders, 2015, pp. 72-78.

[4] N. Rozhkov, "Metering devices: which to choose?", *Russian Gas*, no. 3, 2014, pp. 50-53.

[5] S.A. Zolotarevsky, "On the applicability of different methods of flow measurement for commercial accounting of gas", *Electronic journal of energy service company "Ecological systems"* No. 5, 2007, Web: http://esco.co.ua/journal/2007_5/art54.htm.

[6] T.M. Mustafin and A.S. Burkov, "Gas cylinder pressure monitoring method", Patent RU №2548059 C1. Application RU 2013153745/28, 05.12.2013. Published 10.04.2015, bull. No. 10. IPC G06L11/06.

[7] P.P. Kremlevsky, *Flow meters and counters number of substances: Reference book:* Book 2 // Under total Ed. E A. Shornikov, SPb.: Polytechnica, 2004.

[8] N.V. Christoforova and A.G. Kolmogorov, *Technical measurements and instruments,* Angarsk: AGTA, 2008.

[9] A.S. Sovlukov and V.I. Tereshin, "Method to determine mass of liquefied hydrocarbon gas in reservoir", Patent RU 2506545 C1. Application RU 2012132133/28, 27.07.2012. Published 10.02.2014, bull. No. 4. IPC G01F23/26, G01F1/64.

[10] V.I. Tereshin and A.S. Sovlukov, "Improving the accuracy of measuring of mass of oil when using RF sensors", *IV-th International Metrological Conference "Urgent Matters of Measurements of Flow Rate and Amount of Liquids and Gases",* 7-9 Sep. 2016, Kazan, Russia. – Kazan: publishing house the World without borders, 2016, pp. 70-75.

[11] B.V. Skvortsov , S.A. Borminskij, V.A. Solntseva and D.I. Blinov, "Method to measure mass of liquid in reservoir", Patent RU 2497085 C2. Application RU 2011147442/28, 22.11.2011. Published 27.10.2013. bull. No. 30. IPC G01F1/76.

[12] V. Arnstejn and I.M. Shel'dal', "Method and device for measuring flow rate of wet gas and determination of gas characteristics", Patent RU 2498230 C2. Application RU 2011125651/28, 14.12.2009, Published 10.11.2013, bull. No. 31. IPC G01F1/74.

[13] V.S. Fomenko and V.A. Shurygin, "Method and device for measuring liquefied gas in balloon", Patent RU 2010179 C1. Application SU 19925049189/10, 12.05.1992. Published 30.03.1994. IPC G01F23/26.

[14] V.A. Shurygin and I.M. Yadykin, "A device for determining quantities of liquefied gas in the cylinder". Patent RU 161814 U1, Application RU 2015157224/28, 29.12.2015, Published 10.05.2016, bull. No. 13. IPC G01F 23/26.

[15] D.A. Liman, A.A. Dyumin, L.I. Shustova, I.V. Chugunkov, "The Log Data Collection Service for Cloud Robotics", *in Proc. of 11th Int. Conf. on Application of Information and Communication Technologies*, 20-22 Sep. 2017, Moscow, Russia