RADIOFREQUENCY MEASUREMENT
OF LIQUEFIED PETROLEUM GAS QUANTITY

[(1)]*Alexander Sovlukov,* [(2)]*Victor Tereshin*

[(1)] Institute of Control Sciences, Moscow, Russia
[(2)] Technosensor Co., St.- Petersburg, Russia

Abstract – Measurement of liquefied petroleum gas quantitative parameters are considered. Radiofrequency measurement method is proposed providing highly accurate determination of level (gas-liquid interface position), density and mass of liquid and gaseous phases, total mass. Three RF-sensors (two level sensors, gas dielectric permittivity sensor) are contained in the designed RF devices. Informative parameters (resonant frequencies of electromagnetic oscillations) of these RF sensors are jointly processed providing the needed data. Experimental procedures are described and measurement results are presented.

Keywords: liquefied petroleum gas, measurement, quantity, radiofrequency

1. INTRODUCTION

Consumption of liquefied petroleum gases (propane, butane and their mixtures) is increasingly used as fuel in thermal aggregates of municipal, industrial and agricultural objects. Liquefied petroleum gas (LPG) becomes also more popular as motor fuel. There are now many cars with LPG tanks, a lot of companies began serial production of dual fuel motor vehicles. Growing demand on LPG put the problem of highly accurate quantity determination of LPG stored in various reservoirs. Existent measuring devices for LPG storage determination don't provide needed degree of reliability and accuracy under long-term exploitation conditions.

In this paper are considered radiofrequency (RF) techniques that provide highly accurate LPG quantity measurement. Measurement results don't depend on physical state of liquefied gas and represent total mass of LPG in a tank.

2. EXISTENT PROBLEMS TO BE SOLVED UNDER LPG QUANTITY MEASUREMENT

The following factors should be taken into account under highly accurate measurement of LPG storage in reservoirs: change of gaseous phase density that depends on LPG composition and temperature; LPG level and density change under its boiling; LPG liquid phase density change depending on its composition and temperature; possibility of sensor contamination because of water presence in LPG;

lack of liquid "mirror" under LPG boiling (because of this reason known sensors based only on level determination of a liquid surface are not operable). Let's consider these factors in more detail.

2.1. Change of vapor phase and density versus LPG composition and temperature

Density of LPG gaseous state depends on temperature, pressure and composition of propane and butane in their mixture. It is shown that under LPG mass measurement ignoring of gaseous phase mass can result in additional measurement error up to 3 – 7 %. Here may be also added error because of change of pressure under gas pumping. So for highly accurate LPG mass measurement there is a need to have a measuring channel for gas density measurement in order to do correction because of its change.

2.2. Change of LPG level and density under boiling

Problem of LPG boiling is not properly studied up to now. It was assumed that boiling is not significant and therefore it should not be taken into account. However our study showed that existent intensive boiling (5 – 10 % increase of level) takes place at the end LPG pumping process, under smoothing of gaseous phase pressure and pressure drop because of any reason; duration of such boiling is several minutes. Weaker boiling (level increase up to 1 – 3 %) takes place after intensive boiling as evanescent process, under gas sampling by compressor, mixing of liquefied gases with different temperatures and under changes of temperature; this process may be during several ours. Boiling process may have random character (spectral density and intensity change at wide limits). Therefore suggestion of adequate mathematical model of the process and design of effective high-speed digital filter are very difficult problems.

It is shown in the paper that determination of LPG liquid phase density can provide effective solution of this problem. This density if decreased proportionally to level and volume increase under boiling. Accordingly measuring density LPG mass may be calculated correctly. In Fig.1,*a* and Fig.1,*b* are shown as examples data for LPG level and mass change accordingly during a shown period of daily time (~ 13:00 −14:30); these data were received using the suggested devices. These figures correspond to the stage of LPG repumping. As it is seen at the end of pumping process there

takes place non-significant level increase due to boiling caused by compressor functioning. It takes place also strong level increase (up to 9 cm) due to LPG boiling under decrease of vapor pressure (at equaling pressure with it of empty tank) (Fig.1,*a*). LPG density is decreased under boiling that results in level and volume increase. However LPG mass measured by the suggested devices is not changed under such pumping (Fig.1,*b*). It follows from taking into account LPG density and vapor mass in the suggested techniques. Similar behavior of LPG level, volume and mass is observed under other technological operations (filling in of a reservoir; filling in a reservoir and simultaneous LPG pick up from a reservoir for balloons and car tank filling in, etc.).
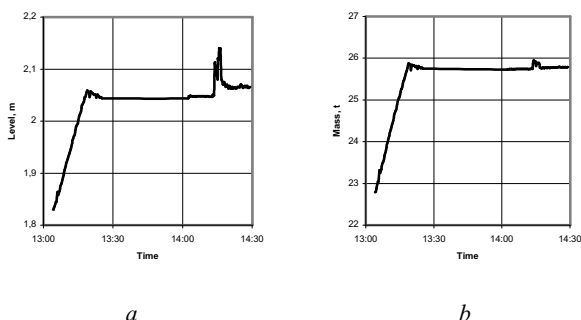

a   *b*

Fig. 1. Change of LPG level (*a*) and mass (*b*)
during repumping

2.3. *Change of LPG liquid phase density versus composition and temperature*

Density of LPG liquid phase is dependent on temperature; such a dependence is shown in Fig.2 for propane (line *1*) and butane (line *2*). Errors caused by absence of taking into account of such density changes can have considerable values (up to ± 15%). They depend on both temperature and LPG composition (relative content of propane and butane).
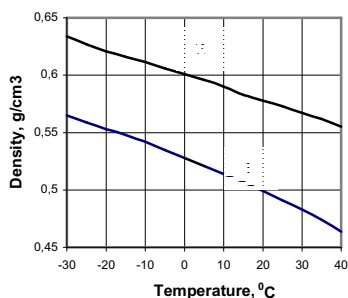

Fig. 2. Density of propane (line *1*) and butane (line *2*)
versus temperature

2.4. *Change of LPG vapor mass versus temperature*

Vapor density of LPG depends on temperature, pressure and composition (relationship between propane and butane). In Fig.3 is presented dependence of vapor mass/liquid phase of LPG on temperature for propane (line *1*) and butane (line *2*). It follows that ignoring of vapor mass results in

additional error within 3÷7%. Also should be added error resulted from pressure change under LPG repumping.
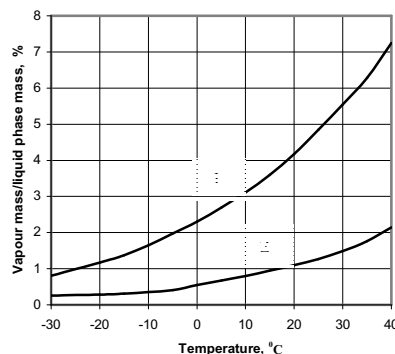

Fig. 3. Change of vapor mass/liquid phase mass versus
temperature for propane (line *1*) and butane (line *2*)

In order to measure LPG mass accurately there should be foreseen measuring channel for determination of vapor density in LPG mass meter. Using it appropriate correction of error because of change of vapor density can be realized.

3. LPG MASS RF MEASUREMENT METHOD

3.1. *Measurement principles*

The suggested radiofrequency measurement method is operable under real conditions of LPG storage in a tank. Based on RF/microwave measurement techniques many technological parameters are known as effectively measured [1–3].

According to the considered here RF method there are conducted simultaneously three measurements: two RF level (gas-liquid interface position) measurements and RF measurement of gaseous-phase dielectric permittivity. This method may be realized using both capacitance sensors and sensors on the base of TEM-transmission line sections. Capacitance sensor may serve as element of resonator, while its resonant frequency f_r is used as informative parameter. Section of TEM-line with various end loads may be excited as RF-resonator itself; its resonant frequency may also serve as informative parameter of such a sensor. Besides, in this case as informative parameters may be used also other parameters, in particular phase shift of sounding and reflected RF electromagnetic waves propagated along TEM-transmission line (coaxial, two-wire, et al.), etc.

Not restricting generality of the suggested measurement method it is considered in the paper using capacitance sensors. In this case it is possible to use equivalent electric capacitances characterizing appropriate capacitive RF sensors.

Besides of the first level measurement by equivalent electric capacitance C_{e1}, the second one is done through determination of equivalent capacitance C_{e2} for determination of LPG mass in a tank. Density of LPG gaseous phase is determined by measurement of dielectric permittivity ε_g. It is found through measurement of appropriate equivalent electric capacitance C_{e3} that is

located at the upper part of a tank filled in by LPG gaseous phase.

The first capacitive or TEM-line level sensor (Fig.4) provides determination of level z of liquefied gas I the whole range of its measurement: from zero value up to the full filling in (in this case $z = l$, where l is the height of a tank).
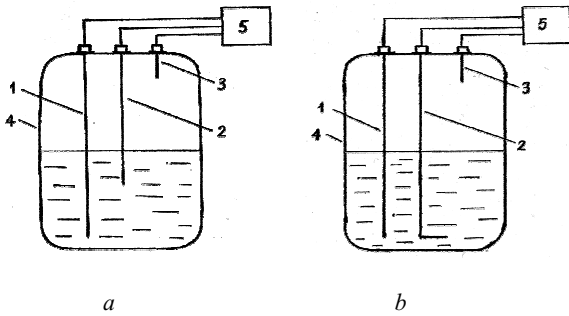

Fig. 4. Schemes of LPG mass measuring devices
1 – first level sensor, 2 – second level sensor, 3 – sensor of gas density, 4 – tank, 5 – electronic unit

Then for the first measuring channel (sensor *1*) there is the following expression for its equivalent capacitance C_{e1}:

$$C_{e1} = z\varepsilon_l C_0 + (l-z)\varepsilon_g C_0 \qquad (1)$$

Here ε_l and ε_g are relative dielectric permittivities of LPG liquid and gaseous phases accordingly; C_0 is capacitance per unit length.

Equivalent capacitance C_{e2} of the sensor *2* is determined under second capacitive RF measurement of level z. In this case measurement range is decreased (Fig.4,*a*) or is increased (Fig.4,*b*) from below on the value l of level change (that is measurement range). The capacitance C_{e2} can be expressed so:

$$C_{e2} = (z \pm l_0)\varepsilon_l C_0 + (l-z)\varepsilon_g C_0 \qquad (2)$$

Here signs "+" and "-" correspond to the increase and the decrease of the length of sensor *2* at the second measurement. The increase of measurement range by lengthening of sensor *2* may be realized through addition of horizontal section with length l_0 at the lower sensor end. This section is also filled in by a monitored substance at once on its whole length under a tank filling in.

There can be practical tasks characterized by presence of non-measured known value of level $\varDelta l$ from below that is not more than $0,05L$ (L is a tank height). Then this value should be taken into account under determination of the degree h of tank filling in: $h = z + \varDelta l$. Here zero point corresponds to the lower end of the first sensor that is placed at the distance $\varDelta l$ from a tank bottom.

It is received from formulas (1) and (2):

$$\varepsilon_g = \pm \frac{C_{e2} - C_{e1}}{l_0 C_0} \qquad (3)$$

In (3) the sign "−" corresponds to the decreased level range under its second measurement (by sensor *2*). In this case $C_{e1} > C_{e2}$. The sign "+" is related to the increased level range under its second measurement; for this case $C_{e1} < C_{e2}$.

Dielectric permittivity of gas (vapor) phase may be determined by measuring equivalent capacitance C_{e3} by sensor *2*:

$$\varepsilon_g = \frac{C_{e3}}{C_{e3_0}} \qquad (4)$$

Here C_{e30} is initial (at $\varepsilon_g = 1$) value of C_{e3}.

For the scheme of measuring device in Fig.4,*a* it follows from (1) and (2):

$$z = \frac{C_{e1} - \varepsilon_g l C_0}{(\varepsilon_l - \varepsilon_g)C_0} = \frac{\dfrac{C_{e1}}{l C_0}\dfrac{C_{e30}}{C_{e3}} - 1}{\dfrac{\varepsilon_l}{\varepsilon_g} - 1} l \qquad (5)$$

Dielectric permittivities ε_l and ε_g in (5) are expressed by the formulas (3) and (4) correspondently.

The appropriate formula for the scheme in Fig.4,*b* can be written similarly.

Dependencies of equivalent capacitances C_{e1} and C_{e2} on LPG level z for the measuring scheme in Fig.4,*a* are illustrated in Fig.5,*a* (lines 1 and 2 correspondently). The length decrease of sensor *2* at the second level measurement is designated as l_0. In Fig.5,*b* are shown dependencies of $C_{e1}(z)$ and C_{e2}(z) for the measuring scheme in Fig.4,*b* (appropriate lines *1* and *2*). Here effective increase l_0 of level z range at its second measurement due to the horizontal section of sensor *2* is shown by dotted line. A current level z and appropriate values of $C_{e1}(z)$ and $C_{e2}(z)$ are also shown in Fig.5,*a* and Fig.5,*b* by the dotted lines.
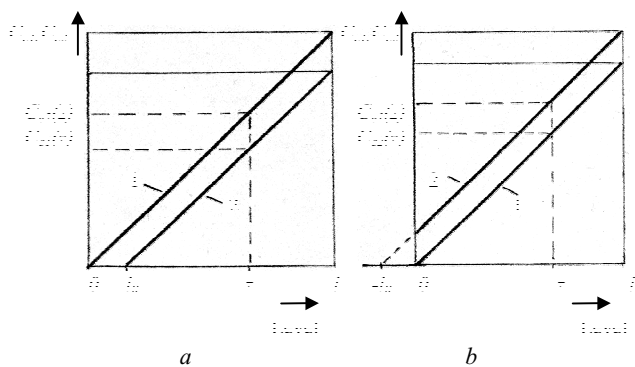

Fig. 5. Equivalent capacitances
versus LPG level

3.2. Operation regimes

There should be considered regimes for operation of measuring devices. For the scheme in Fig.4,*b* it is clear that the appropriate measuring device has both level sensors operable in the whole level range. However it is not so for the scheme in Fig.4,*a*. Sensor *2* here is operable only if LPG level is higher than the lower sensor end. If LPG level is less than lower end position of sensor *2* then level value z is

chosen as its measure in a tank that corresponds to nominal value C_{e2n} of equivalent capacitance C_{e2} for the previously calculated value ε_{ln} of permittivity ε_l. If such data concerning ε_{ln} is absent then it is taken known value of ε_l at nominal temperature.

Increase of capacitance C_{e2} may be due to both change of vapor pressure (not more than 4 pF for sensors in experiments) and tank filling in by LPG (up to 100 pF).

The value 6 pF of C_{e2} increase is chosen as the measure of liquid or vapor presence at the sensor lower end: 1) if this condition is satisfied then LPG level is considered as higher of this lower end; relationships (1)–(5) are used for determination of LPG quantitative parameters; 2) in the opposite case previously calculated value of ε_l is used; error caused by change of ε_l is not significant because LPG level is not more than 30% of its range, volume is not more than $15 \div 20\%$; 3) constant value of ε_l at nominal temperature is used under the first switching on the measuring device; this value differs significantly from ε_g; so, for propane-butane mixture $\varepsilon_{ln} = 1,7$ at the temperature 20^0C; this value of ε_{ln} is substituted into (5) for determination of level z.

3.3. RF measuring channels

In Fig.6 is shown scheme of RF measuring channel that is similar for sensors *1*, *2* and *3*. Such an RF sensor is the element of autogenerator *1* determining its frequency. Besides of RF sensor oscillation circuit includes inductance *2*. Hard mutual position of sensor inner conductor *3* and outer conductor (tube) *4* is provided by several dielectric (in particular made from teflon disks) supports; in the figure are shown only two such supports *5* and *6*. They have through holes for free liquid movement. For instance these stubs can be positioned at the distance of 0,7 m each from the other like in real devices.

Output signals of all the sensors are jointly processed in electronic unit of the measuring device according to the above relationships for determination of LPG quantity.
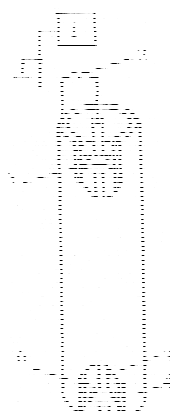

Fig. 6. RF measuring channel
1 – autogenerator, *2* – inductance, *3* – inner conductor,
4 – metal tube, *5* and *6* – dielectric supports

The received results are also true for realization of the method on the base of TEM-line sections. Equivalent

capacitances C_{e1} and C_{e2} of two coaxial level sensors (measuring channels) with different length are measured. Length l of one of them is equal to the tank height; the other is shortened at the lower end on the value l_0 not more than $0,35\ l$ or has the length l with additional section at the lower end that is perpendicular to the basic section (it is also filled in by a monitored liquid). The third coaxial capacitive sensor used for gas permittivity measurement is placed fully in gas phase near the reservoir cover and has the length not more than $0.3l$. Its equivalent capacitance C_{e3} is also measured.

As it is noted above capacitive RF sensor *2* for the second level measurement has the length that is not more than $0,35l$ shorter at the lower end as compared with the length l of the sensor *1*. It is not desirable to have sensor *2* shorter because appropriately level range is decreased; oppositely, the value of l_0 (difference between lengths of sensors *1* and *2*) is decreased at higher values of this sensor length that results in increasing of error at calculations of ε_l according to the formula (3).

The following causes choice of the length of sensor *3* not more than $0,3l$. Its lower end should not to reach real maximal level z_{max} of tank filling in. Practically $z_{max} = 0,7 \div 0.85$ of the value of level range. Choice of real maximal level z_{max} is determined by requirements of safe exploitation of LPG tanks.

Examples of experimental data characterizing output characteristics of measuring channels versus time are presented in Fig.7. Each output characteristic is frequency f of appropriate autogenerator. Here lines *1*, *2* and *3* correspond to the first, the second (shortened) level sensors and the third sensor (placed in vapor phase). These data are received for the stage of LPG repumping for a shown period of daily time ($\sim 13{:}00 - 14{:}30$) and are related with the data in Fig.1. Experimental data (Fig.1,*b*) received with the measuring device characterize measured LPG mass at this technological stage.
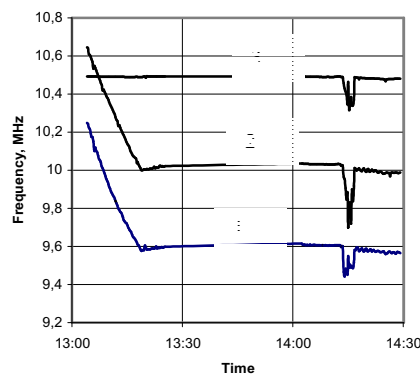

Fig.7. Output characteristics of measuring channels

Volumes of liquid V_l and gaseous V_g phases in it can be found knowing geometric form of a tank. So if cross-section S of a vertical cylindrical tank is constant then $V_l = zS$; $V_g = V_0 - V_l$ where V_0 is volume of a tank. Such a consideration is only true if precise interface exists between liquid and gaseous phases of monitored substance.

3.4. Determination of LPG mass

Mass M of a liquefied gas in a tank is the best characteristic of its quantity. For non-polar dielectric substances including LPG is true Clausius-Mossotti relationship between a substance (liquid, gas) density and its dielectric permittivity [4,5]:

$$\frac{\varepsilon - 1}{\varepsilon + 2}\frac{\mu}{\rho} = \frac{4\pi}{3}N\alpha \qquad (6)$$

In this formula ε is dielectric permittivity of a substance, μ is its molar mass, ρ is density of a substance, α is molar polarizability, N is Avogadro's number.

Based on the use of RF-transmission line techniques and this relationship mass of cryogenic substances in spacecraft tanks can be also accurately determined [5].

It follows from (6)

$$\rho = \frac{1}{A}\frac{\varepsilon - 1}{\varepsilon + 2} \qquad (7)$$

Here $A = 4\pi N\alpha/3\mu$ is the value constant for each substance.

Therefore it can be written the following formulas for densities of liquid ρ_l and gaseous ρ_g phases:

$$\rho_l = \frac{1}{A}\frac{\varepsilon_l - 1}{\varepsilon_l + 2} \qquad (8)$$

$$\rho_g = \frac{1}{A}\frac{\varepsilon_g - 1}{\varepsilon_g + 2} \qquad (9)$$

Knowing these densities it can be determined appropriate mass values of liquid and gaseous phases:

$$M_l = \rho_l V_l \qquad (10)$$

$$M_g = \rho_g V_g \qquad (11)$$

It is known that for mixtures of gases, liquefied gases in particular propane-butane mixtures it is true with high accuracy the following relationship [4]:

$$\rho_m = \frac{3}{4\pi N}\frac{\sum_i n_i\mu_i}{\sum_i n_i\alpha_i}\frac{\varepsilon_m - 1}{\varepsilon_m + 2} \qquad (12)$$

Here ρ_m and ε_m are density and dielectric permittivity of a mixture, n_i is the number of i-th kind molecules per volume unit, α_i is molar polarizability for a molecule of i-th kind, μ_i is molar mass for a molecule of i-th kind.

For each kind of mixture the value

$$A_m = \frac{3}{4\pi N}\frac{\sum_i n_i\mu_i}{\sum_i n_i\alpha_i} \qquad (13)$$

is constant.

It follows from relationships (12) and (13) the following formula for a mixture of substances:

$$\rho_m = A_m\frac{\varepsilon_m - 1}{\varepsilon_m + 2} \qquad (14)$$

This relationship is true with high accuracy for any phase state of mixture including liquefied gases. Therefore using (14) it can be found total mass of a mixture similarly to (10) and (11). Knowing V_l, V_g, ρ_l and ρ_g may be determined mass M_l of liquid phase, mass M_g of gaseous phase and total mass $M = M_l + M_g$ of LPG in a tank.

Shown in Fig. 1,*b* examples of experimental data received with the measuring RF device characterize measured LPG mass at the stage of LPG repumping. The data received at various technological stages characterize highly accurate determination of LPG quantitative parameters. Error of level (gas-liquid interface position), volume and mass determination is not more than ± 0,5 % as related to appropriate measuring ranges.

4. CONCLUSION

The proposed method and realized experimental installations provide highly accurate determination of LPG quantitative parameters. The following data are determined: level (gas-liquid interface position), volume and mass of LPG phases, LPG total mass, density of liquid and gaseous phases.

Such techniques may be effectively used in LPG storage bases of gas-filling stations, vehicle LPG-filling stations. Using them processes of gas pumping from reservoirs into various tanks can be also accurately monitored. Similar approaches can also be used to measure quantitative parameters of other liquefied gases.

REFERENCES

[1]   V.A. Viktorov, B.V. Lunkin, A.S. Sovlukov, "High frequency method for measuring of nonelectrical quantitires", *Nauka Publ.*, Moscow, 1978 (in Russian).

[2]   E. Nyfors, P. Vainikainen, "Industrial microwave sensors", *Artech House*, Norwood, MA, 1989.

[3]   V.A. Viktorov, B.V. Lunkin, A.S. Sovlukov, "Microwave measurements of technological processes parameters", *Energoatomizdat Publ.*, Moscow, 1989 (in Russian).

[4]   C.C. Luo, R.C. Miller, "Densities and dielectric constants for some LPG components and mixtures at cryogenic and standard temperatures", *Cryogenics,* vol. 21, pp. 85-93, 1981.

[5]   B.N. Petrov, V.A. Viktorov, N.A. Kriksunova, B.V. Lunkin, A.S. Sovlukov, "Measurement of storage of media in tanks on spacecraft", *Acta Astronautica*, Vol. 3, pp. 449-458, 1976.

Authors: 1) Prof. Sovlukov A. S., Institute of Control Sciences, 65, Profsoyuznaya str., Moscow, 117997, Russia
Phone/Fax: +7 095 369 3702, E-mail: sovlas@ipu.rssi.ru
2) Dr. Tereshin V. I., Technosensor Co., 2, Blagodatnaya str., St.-Petersburg, 196128, Russia
Phone: + 7 812 911 1531, E-mail: technosensor@yandex.ru