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# RADIOFREQUENCY MEASUREMENT OF LIQUEFIED PETROLEM GAS MASS IN A RESERVOIR

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**Abstract:** Design principles and operation of radiofrequency (RF) sensor for measurement of liquefied petroleum gas (LPG) mass in a reservoir are considered. Designed and tested measuring system containing RF mass sensor provides LPG counting by mass with error not more than ± 0,5 % under real storage conditions in reservoirs is described.

**Keywords**: liquefied petroleum gas, mass, reservoir, measurement, radiofrequency

## 1. INTRODUCTION

Liquefied petroleum gas (LPG) is mixture of propane and butane where little quantity of methane, ethane and other components are present [1,2].

LPG is widely used as a fuel in thermal units of municipal, industrial and agricultural objects and also as a motor fuel. Highly accurate measurement of LPG technological parameters, in particular of its mass is very important under LPG storage in reservoirs.

LPG density depends on its composition and temperature. Because of data absence on LPG density it is not possible to provide highly accurate LPG counting by mass using traditional measurement methods (applying level measurement).

One of reasons is caused by the fact that there exists rather big vertical temperature gradient in a reservoir under operation of pump-compressor installations. So it is not possible to take into account LPG density and mass in every layer along the height of a reservoir.

Traditional method for mass measurement of LPG contained in a reservoir includes level measurement, calculation of volume by calibration table and calculation of mass by multiplication of volume and density. If exact value of density is unknown then additional errors appear.

Diagrams for the dependence of density of propane and butane on temperature are shown in Fig. 1.

Modeling results of error of LPG mass measurement versus temperature for measuring system containing level sensor tuned for propane mass measurement are shown in Fig. 2: errors of propane mass and butane mass without and with temperature correction - 0,26 % per 1 ºC (correction by temperature for propane).

Such measuring system can measure mass of propane with error near 1 % while data on butane mass are decreased up to – 15 %.

If averaged tuning values of density and temperature corrections for propane and butane are chosen then measurement errors can be decreased. However they are still rather high.

In fact even under optimal temperature correction error of density calculation can change at low temperatures within the range - 6 ÷ + 6 % and at high temperatures within the range - 8 ÷ + 8 % if LPG composition is changed.

Coefficient of temperature correction for calculation of propane density is - 0,26 % per 1 ºC; therefore accurate data on LPG temperature are needed.

If error of temperature measurement or temperature gradient in a reservoir is 2-4 ºC then it results in additional density calculation error 0,5-1 %.

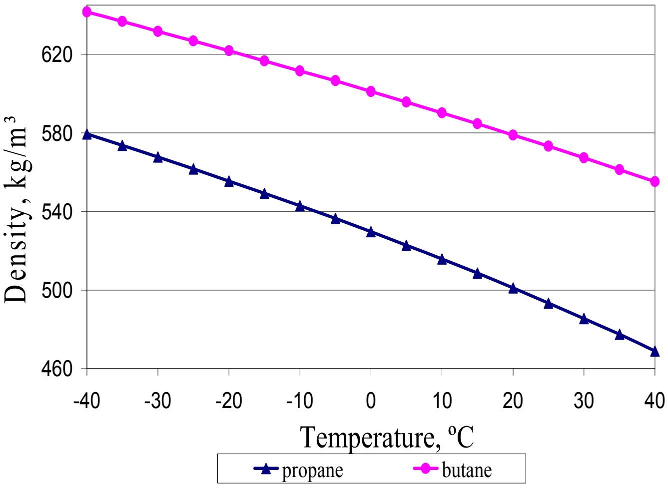

Fig. 1. Density of propane and butane versus temperature.

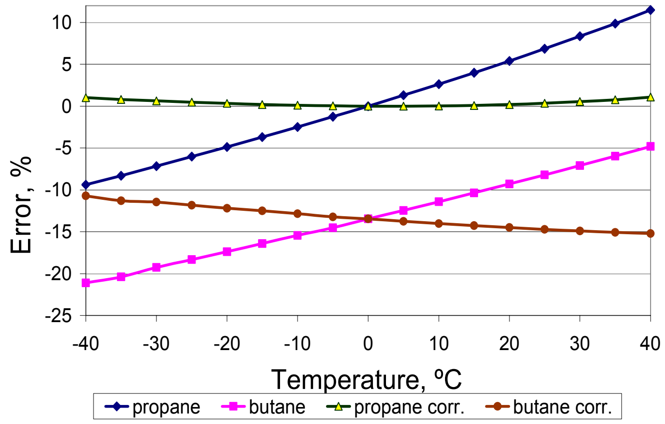

Fig. 2. Error of LPG mass measurement versus temperature.

## 2. RADIOFREQUENCY SENSOR AND ITS LOCATION IN A RESERVOIR

Radiofrequency (RF) method and measuring devices were designed for highly accurate measurement of technological parameters of LPG contained in reservoirs [2-4].

Design principles and operation of radiofrequency sensor (Fig. 3) for highly accurate measurement of LPG mass in a reservoir are considered.

Fig. 3. Radiofrequency sensor.

Radiofrequency sensor contains coaxial resonator (cylindrical capacitor) filled in by a monitored substance, six temperature sensors evenly located along the length of the radiofrequency sensor and microprocessor.

Location of these sensors (coaxial resonator and 6 temperature sensors) in a reservoir is shown in Fig. 4.

Here $H$ – LPG level, $L_1$ – length of radiofrequency sensor; $L$ – distance between the edge of hatch and the bottom of a reservoir; $X_0 = L - L_1$ – distance between the bottom and lower end of the sensor; $L_0$ – LPG level under 100 % filling in of a volume; $h$ – level of monitored liquid filling in the sensor; $t_1$, $t_2$, $t_3$, $t_4$, $t_5$, $t_6$ – location points of temperature sensors.

One more temperature sensor is present in the electronic unit. It is needed for determination of temperature $t_7$ used for correction of instrument errors of electronic transducer while it is not used in calculations applied for mass determination and is not shown in Fig. 4.

Designed measuring system containing radiofrequency sensor provides LPG counting with inaccuracy not more than ± 1 % under the following conditions:

– range of LPG density change is from 470 кг/м$^3$ to 640 kg/m$^3$;
– range of temperature change is from - 50 ºC to + 60 ºC;
– gradient of temperature in a reservoir can reach ± 5 ºC;
– a reservoir is vertical and cylindrical one (dependence of volume on level is close to linear).

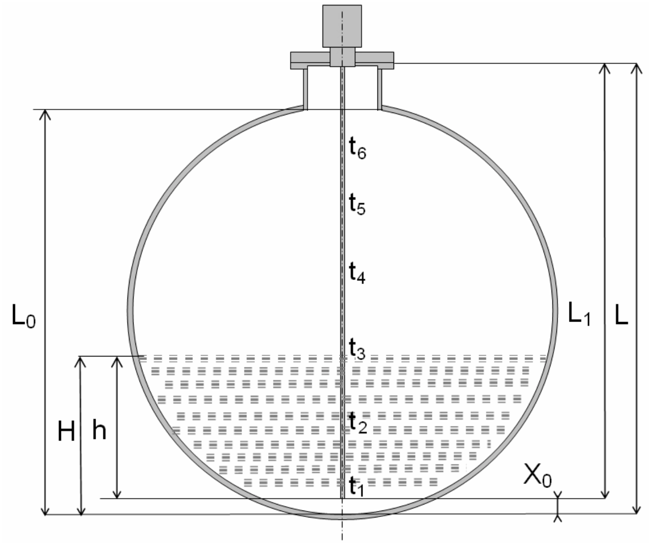

Fig. 4. Location of the sensors in a reservoir.

Signals from measuring system coming to PC and indicators contain data on LPG total mass in a reservoir and temperature at six points along the height of a reservoir.

## 3. MEASUREMENT OF LPG MASS INDEPENDENTLY FROM LPG COMPOSITION

Radiofrequency measuring method and devices are suggested for highly accurate determination of LPG technological parameters [3-5]. Features and operation of RF LPG mass sensor are considered in the paper.

Data on LPG total mass and temperature for six measuring points in different values of filling level are come from the measuring system to PC and indicators.

RF sensor represents coaxial resonator that is coaxial capacitor or a section of coaxial TEM transmission line filled in by a monitored substance. Electrical capacitance of the sensor (or its change) is proportional to level of LPG liquid phase and its dielectric permittivity. LPG vapor phase contributes also to the change of the electrical capacitance proportional to LPG vapor density and the length of the vapor-located sensor's part. In addition LPG temperature is measured in six points, temperature sensors are placed evenly along the sensor length from minimal to maximal values of reservoir filling.

LPG are dielectrics, their dielectric permittivity depends on LPG composition and temperature. Dielectric permittivity of LPG is proportional to its density [6]. Therefore electrical capacitance of RF sensor is proportional to the result of multiplication of level and density; RF sensor is really the device for LPG mass measurement.

Diagrams for temperature dependencies of dielectric permittivity for propane (line 1) and butane (line 2) are presented in Fig. 5. Modeling results for temperature error of LPG mass measurement in measuring system with RF sensor tuned for propane mass measurement are in Fig. 6: line 1 – error of propane mass measurement without temperature correction; line 2 – error of butane mass measurement without temperature correction; line 3 – error of propane mass measurement with temperature correction + 0,06 % per 1 ºC; line 4 – error of butane mass measurement with temperature correction + 0,06 % per 1 ºC (correction by temperature for propane).

In order to do diagrams in Fig. 6 values of dielectric permittivity are reduced to density value for propane at temperature 0 ºC through multiplication by coefficient *K* that allows to present dielectric permittivity by density; it is used for tuning to a maximum if needed:

$$K = \rho_{l0}/(\varepsilon_{l0}-1), \qquad (1)$$

where $\rho_{l0}$ = 0,5297 g/cm$^3$ is density of propane at 0 ºC; $\varepsilon_{l0}$ = 1,7148 is dielectric permittivity of propane at 0 ºC; according to initial tuning *K* = 0,5297/(1-1,7148) = 0,7410.

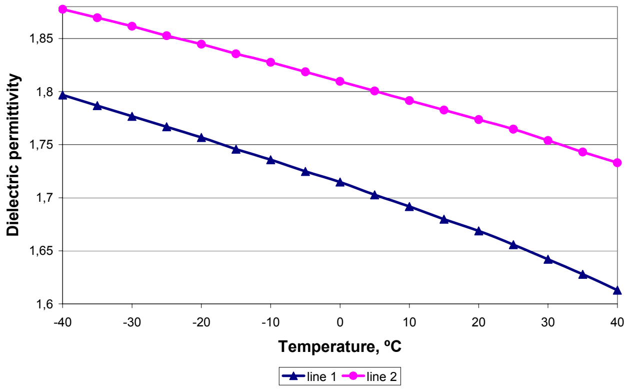

Fig. 5. Temperature dependence of dielectric permittivity for propane (line 1) and butane (line 2).

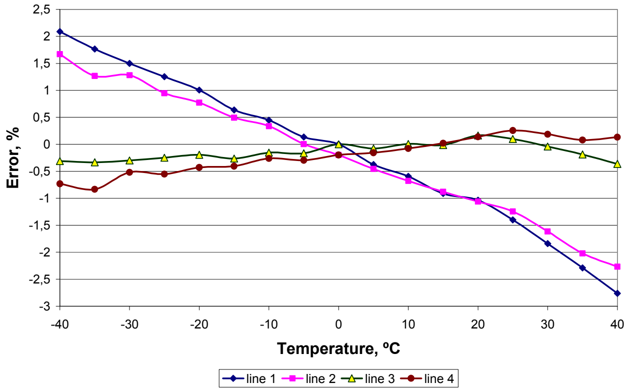

Fig. 6. Temperature error of LPG mass measurement for measuring system with RF sensor tuned for propane.

Error of mass measurement for each temperature are calculated as a difference between scaled increase values of dielectric permittivity (related to density of sensor operating) and real density (reference data); this difference is divided by $\rho_{l0}$ = 0,5297 g/cm$^3$ (density of propane at 0 ºC) and multiplied by 100 %. Such measuring system can measure mass of propane with error not more than ± 0,5 % (line 3) and mass of butane with error not more 1 % (being tuned for propane, without taking into account errors because of inaccurate recalculation of calibration table).

Coefficient of temperature correction for density calculation is + 0,06 % per 1 ºC; error of temperature measurement or temperature gradient in a reservoir up to 2-4 ºC is admitted; it results in additional error of density calculation 0,12-0,24 %.

Increase of sensor capacitance is related to LPG parameters so:

$$C_s=C_l\times[(\varepsilon_l-1)\times h_1+(\varepsilon_g-1)\times(L_1-h_1)], \qquad (2)$$

where $C_l$ is sensor electrical capacitance per 1 m in vacuum, $C_l$ = 47 pF); $h_1$ is level of LPG liquid phase, filling in the sensor; $L_1$ is sensor length; $\varepsilon_l$ is dielectric permittivity of LPG liquid phase; $\varepsilon_g$ is dielectric permittivity of LPG vapor phase.

Output parameter of the sensor *D* is data on LPG mass:

$$D = K\times(L_0-X_0)\times C_s\times(1+T_s\times t_7)/(C_l\times\rho_0) + X_0, \qquad (3)$$

where $T_s$ is coefficient of temperature correction for density; $T_s$ = 0,0006 for LPG; $t_7$ is LPG temperature (ºC), the sensor provides temperature measurement in six points, temperature $t_7$ is used according to initial tuning); $\rho_0$ is density of LPG liquid phase at temperature 0 ºC (tuning is done for LPG kind); it is chosen $\rho_0$ = 0,5297 g/cm$^3$ according to initial tuning (that is propane density at temperature 0 ºC), this parameter can be changed periodically, be introduced as tuning for LPG kind from PC (however it may not be done, it is additional option); $C_l$ is electrical capacitance per 1 m in vacuum, $C_l$ = 47 pF/m; $X_0$ is the height of sensor location (distance from bottom of a reservoir to lower end of the sensor), mm; $L_0$ is level under filling in by volume on 100 % (maximal level), mm; *K* is tuning coefficient.

Parameter *D* has dimension of level, mm; it is needed for the ability to use calibration table and to show data on level. Parameter *D* can be several percents different as compared with a right value of level (proportionally to the ratio of a right value of density to $\rho_0$).

Volume *V* of LPG as function $F_{grad}$ of parameter *D* is calculated by calibration table: $V=F_{grad}(D)$. Mass *M* of LPG is calculated so: $M=V\times\rho_0$.

## 4. TEMPERATURE MEASUREMENT

Temperature is measured in six points along the height of a reservoir; temperature sensors are located evenly along the length of RF sensor from minimal to maximal values of filling in a reservoir.

Points of temperature measurement are related to LPG level at 5 %, 23 %, 41 %, 59 %, 77 % и 95 % of its maximal value (if other requirements for position of these points are absent). It gives ability to have accurate data on temperature of LPG liquid and vapor phases. Sensors located lower than a current level of filling in, measure temperature of liquid phase while Sensors located above a current level of filling in, measure temperature of vapor phase.

Locations of the sensors are monitored (in liquid or in vapor phases) for calculations and averaged temperature values of liquid and vapor phases are calculated. Data from sensors that can be at the interface between LPG liquid and vapor phases are rejected.

In order to exclude errors there is used the following condition: sensor N 7 (the lowest one) is used only for measurement of liquid temperature, sensor N 2 (the uppermost one) is used only for measurement of vapor temperature. Sensor N 1 is placed on the plate of electronic unit and is not used for measurement of temperature. Temperature of LPG liquid (averaged value) and vapor phase is designated as $t_7$ and $t_2$ correspondingly.

## 5. ERRORS BECAUSE OF INACCURATE RECALCULATION OF CALIBRATION TABLE

Additional error can appear at calculations of LPG volume and mass by the relationships $V=F_{\text{grad}}(D)$ and $M=V\times\rho_0$ correspondingly. It is caused by the fact that parameter $D$ is not equal to real value of level for LPG liquid phase. If real density is $\rho_0$ (LPG density at temperature 0 ºC) then parameter $D$ is equal to real value of level. In other cases parameter $D$ may be several percents different from real value of level (proportionally to the ratio of real value of density to $\rho_0$).

For vertical cylindrical reservoir it doesn't result in appearance of additional error. The reason is that as more or less is volume relative to its real value calculated by the formula $V=F_{\text{grad}}(D)$ then equally proportionally is decreased or increased mass value calculated by the formula $M=V\times\rho_0$ as value of $\rho_0$ is not equal to real value of density. For horizontally placed reservoir additional errors will appear.

## 6. ACCURACY INCREASE OF LPG COUNTING

In order to increase accuracy of LPG counting via application of RF sensor the following development of algorithms and software are undertaken.

For each reservoir a kind of LPG is introduced from PC to controller manually as one of three variants: G1 – pure propane; G2 – mixture with 50 % of propane and 50 % of butane; G3 – pure butane. In this case any 3 kinds for any substances may be chosen; their descriptions are stored in controller in the table form and may be edited by a user.

Calculation of mass is done not by simplified formulas for expression of D, V and M presented above, but by full algorithms that provide calculation of LPG vapor phase density (taking into account composition and temperature of vapor), vapor mass, liquid mass, liquid level and LPG mass in a reservoir.

RF sensor of LPG mass operating by developed algorithm provides LPG counting by mass with total error not more than ± 0,5-0,75 % under the following conditions: range of LPG density change from 470 kg/m$^3$ to 640 kg/m$^3$; range of temperature change from - 40 ºC to +50 ºC or more; LPG composition is set by one of three variants; gradient of temperature in a reservoir may reach ± 5 ºC; a reservoir is vertical and cylindrical one (dependence of volume on level is close to linear).

## 7. CALCULATION OF LPG DENSITY

Application of 3 tuning variants and availability of data on LPG temperature give ability to calculate density and mass of vapor phase, density, mass and level of LPG liquid phase rather accurately. It is important for management of LPG counting.

Vapor mass at high temperatures may have very big value (up to 5 % of LPG liquid phase mass under entire filling in a reservoir) and is unsupplied rest of LPG in a reservoir. In addition to it LPG vapor is trade stock; under filling in of a reservoir vapor is condensed and may add up to 5 % to a volume of liquid in a reservoir.

Exact value of LPG liquid phase level is important to know in order to make commands for alarm signaling and blockage of equipment operation under overfilling of a reservoir.

### *7.1. Density calculation for LPG liquid phase*

For each of 3 variants of tunings temperature dependencies of density are determined (see Table 1). The table is composed with discrete temperature gap 1 ºC.

The table may be edited by a user for more exact assignment of variants for properties of monitored substances. Reference data on physical properties of monitored substances are used for composition of the table.

The following table is introduced into the controller's memory:

Table 1

| Temperature ºC | Density of propane vapors, kg/m$^3$ | Density of vapor mixture (propane in liquid 50%), kg/m$^3$ | Density of butane vapors, kg/m$^3$ |
|---|---|---|---|
| -40 | 579,4 | 610,45 | 641,5 |
| -35 | 573,7 | 605,2 | 636,7 |
| -30 | 567,7 | 599,7 | 631,7 |
| -25 | 561,6 | 594,2 | 626,8 |
| -20 | 555,5 | 588,65 | 621,8 |
| -15 | 549,3 | 582,95 | 616,6 |
| -10 | 542,9 | 577,2 | 611,5 |
| -5 | 536,4 | 571,5 | 606,6 |
| 0 | 529,7 | 565,35 | 601 |
| 5 | 522,8 | 559,25 | 595,7 |
| 10 | 515,8 | 553 | 590,2 |
| 15 | 508,6 | 546,6 | 584,6 |
| 20 | 501,1 | 540 | 578,9 |
| 25 | 493,4 | 533,3 | 573,2 |
| 30 | 485,5 | 526,4 | 567,3 |
| 35 | 477,5 | 519,4 | 561,3 |
| 40 | 468,9 | 512,05 | 555,2 |

### *7.2. Density calculation for LPG vapor phase*

Composition of LPG liquid and vapor phases are very different but the cases when a single component – propane or butane is present in a reservoir.

Elasticity of saturated LPG vapor is increased while temperature is increased.

According to Dalton low total pressure of mixture vapors is the sum of partial pressures of vapor in a mixture: $p_i = r_i \times p$ where $p_i$ is partial vapor pressure of a component; $r_i$ is molar part of a component in vapor phase; $p$ is total pressure.

According to Raul low partial pressure of a mixture component is determined by elasticity of vapor for this component at some temperature and its molar part in the liquid phase: $p_i = x_i \times p_i`$ where $p_i$ is partial vapor pressure of a component; $x_i$ is molar part of a component in liquid phase; $p_i`$ is elasticity of vapor for pure component at the same temperature.

In order to calculate density of LPG liquid phase, at first partial pressure for each component $p_i$ dependent on its part $x_i$ in the liquid phase is calculated using reference data on pressure of propane and butane at different values of $p_i`$ for each value of temperature.

After that density of each component in the mixture is calculated at normal conditions (2,019 kg/m$^3$ for propane, 2,703 kg/m$^3$ for butane). Density of the mixture is determined as the sum of densities for all the components in the mixture.

The following table is introduced into the controller's memory:

Table 2

| Temperature, ºC | Density of propane vapors, kg/m$^3$ | Density of vapor mixture (propane in liquid 50%), kg/m$^3$ | Density of butane vapors, kg/m$^3$ |
|---|---|---|---|
| -50 | 1,23159 | 0,723915 | 0,21624 |
| -45 | 1,79691 | 1,060635 | 0,32436 |
| -40 | 2,30166 | 1,36707 | 0,43248 |
| -35 | 2,88717 | 1,713885 | 0,5406 |
| -30 | 3,49287 | 2,097825 | 0,70278 |
| -25 | 4,19952 | 2,572785 | 0,94605 |
| -20 | 5,00712 | 3,12525 | 1,24338 |
| -15 | 5,95605 | 3,759192 | 1,562334 |
| -10 | 7,04631 | 4,620573 | 2,194836 |
| -5 | 8,35866 | 5,498394 | 2,638128 |
| 0 | 9,73158 | 6,447045 | 3,16251 |
| 5 | 11,22564 | 7,518435 | 3,81123 |
| 10 | 13,04274 | 8,785133 | 4,527525 |
| 15 | 14,96079 | 10,1915 | 5,422218 |
| 20 | 17,08074 | 12,05427 | 7,0278 |
| 25 | 19,52373 | 14,08937 | 8,655006 |
| 30 | 22,06767 | 15,99384 | 9,92001 |
| 35 | 24,85389 | 18,04919 | 11,24448 |
| 40 | 28,18524 | 20,64875 | 13,11225 |
| 45 | 31,41564 | 23,07485 | 14,73405 |
| 50 | 35,02965 | 25,96305 | 16,89645 |

For each of 3 variants of tunings temperature dependencies for vapor density are determined (see Table 2). The table is composed with discrete temperature gap 1 ºC. For example vapor density is 14,09 kg/m$^3$ for the mixture of liquid LPG with 50 % of propane and 50 % of butane at the temperature + 25 ºC. This vapor density is received as a result of calculations taking into account propane density 9,76 kg/m$^3$ and butane density 4,33 kg/m$^3$ in the mixture. The table may be edited by a user for more exact assignment of variants for properties of monitored substances.

## 8. CALCULATION OF LPG LEVEL, VOLUME AND MASS

Increase of sensor electrical capacitance is related to LPG parameters by formula (2). Dielectric permittivity $\varepsilon_l$ of liquid phase and и dielectric permittivity пара $\varepsilon_g$ of vapor phase are calculated so:

$$\varepsilon_l = 1 + \rho_l / [K \times (1 + T_s \times t_7)] \tag{4}$$

$$\varepsilon_g = 1 + \rho_g / [K \times (1 + T_s \times t_2)], \tag{5}$$

where $t_7$ is temperature of liquid; $t_2$ is temperature of vapor; $T_s$ is coefficient of temperature correction for density; $T_s$ = 0,0006 is for LPG; $K$ is tuning coefficient that is used for recalculation of dielectric permittivity to density and for tuning to a maximum if needed (see (1)).

Level $h_1$ of RF sensor filling in is found from (2). Liquid level in a reservoir is $H = h_1 + X_0$ where $X_0$ is the height of sensor location (distance from the bottom of a reservoir to lower end of the sensor), mm.

Volume $V$ of liquid phase is calculated by calibration table as a function of level (there is value of volume for each value of level in table that is determined through check filling out liquid from the reservoir or calculations using geometry of the reservoir): $V = F_{\text{grad}}(H)$. Mass of LPG liquid phase is calculated so: $M_l = V \times \rho_l$. Mass of LPG vapor phase is calculated so: $M_g = (V_0 - V) \times \rho_g$. Total mass of LPG in a reservoir is $M = M_l + M_g$.

## 9. PRACTICAL RESULTS

It is assumed that problems of accurate LPG counting in reservoirs are caused by the absence of true data on LPG density. In fact even under accurate determination of LPG density it is not always possible to provide true LPG counting. Process of filling in of railway cisterns from reservoirs of gas-filling stations is considered as example.

Data come through interface RS-485 from sensors to spark-protection units where monitored parameters are calculated; data from these units through adapter RS-485 – USB come to PC and are viewed as graphics, tables and are transferred to distant (client) computers.

In fact LPG pumping was done from reservoirs N 8 and N 9 via compressor. At 10.22 pouring out reservoir N 8 was started. At 11.40 it was started pouring out reservoir N 9. Up to 13.00 it was flow from reservoir N 9 into reservoir

N 8 in addition to the pouring. At 15.02 the pouring was over. Visually according to pouring trends LPG quantity in other reservoirs was changed insignificantly. Really it was flow of LPG to other reservoirs. Totally + 4050 kg of LPG flowed. Part of the liquid became as the vapor. LPG is heated under operation of a compressor and vapor mass is increased. Vapor mass is increased by + 2861 kg. Final value of LPG mass change is -153848 kg taking into account flow of liquid. Measurement accuracy may be checked via weighing of railway cisterns.

## 10. ON GRADIENT OF TEMPERATURE

Diagrams of temperature change in the reservoir N 9 per 24 hours are shown in Fig. 7.

Since 0.00 to 11.40 liquid LPG was in the reservoir. All the temperature sensors were in the liquid. Since 15.00 all the temperature sensors were in the vapor. Temperature sensor T1 was near the bottom of the reservoir, sensor T2 was at the filling level 20 %, sensor T3 was at the filling level 40 %, sensor T4 was at the filling level 60 %, sensor T5 ws at the filling level 80 %.

When LPG pumping was over then temperature in the reservoir was increased and reached a maximal value near 17.00. Simultaneously temperatures at the lower and upper parts of the reservoir were - 13 ºC and - 3 ºC correspondingly. Gradient of temperature along the height of the reservoir was 10 ºC LPG vapors. Averaging of temperatures took place at 22.00 when condensation of LPG vapors stopped.

Not less interest has gradient of temperature for LPG liquid phase. At 0.00 temperature at the lower part of the reservoir was - 20,8 ºC, at the upper part it was - 18,8 ºC. Such change of temperatures along the height of the reservoir was gradually decreased, at 5.00 in the morning temperatures became equal. The reason is that condensation of LPG vapors took place while upper layers of the liquid were heated.

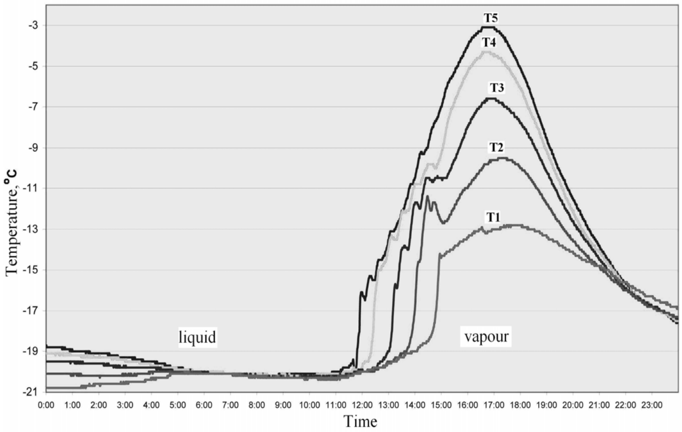

Fig. 7. Temperature trends in the reservoir N 9.

## 11. CONCLUSION

Designed and tested measuring system with RF sensor provides LPG counting by mass with error not more than ± 0,5 % under real conditions of LPG storage in reservoirs.

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