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ANALYSIS OF THE METHODS AND MEANS FOR MEASURING DENSITY OF OIL PRODUCTS

Current methods and means for measuring density of oil products are systemized and analyzed, their advantages and disadvantages are indicated.

A new improved classification of methods and means for measuring density of oil products is elaborated. It is based on four main classification criteria: the method; form of the method realization; means of the method realization; design features.

The choice of the most perspective and accurate method for controlling the quality of oil products under pre-defined conditions is substantiated. It is the ultrasonic method, which in spite of minor drawbacks (the necessity to pump out air from the pulps as air bubbles have considerable influence on the absorption of ultrasound; high cost), has a lot of advantages over other methods, namely: inertia-free and contactless measurements; absence of movable parts in the flow, of pressure losses in the pipelines; the possibility of application for measuring density of contaminated and aggressive mediums.

Keywords: *density, oil products, measuring methods, densitometer.*

Density is the main among the physicochemical parameters that determine properties and characterize the composition of oil products. Norms of density are regulated by “Euro 5” standard [1, 2]. Density determination is one of the most labor-consuming measuring processes. It is rather difficult to determine this parameter while controlling oil products during the processes of their manufacture, transportation and use, especially under the conditions of fast-running technological processes. Instruments intended for density measurements are referred to as densitometers.

Density is the content of a substance mass in the unit volume, occupied by this substance. It strongly depends on the temperature and reduces as the temperature grows [3 – 5]:

$$\rho_{t1}=\rho_{t2}[1-\beta(t_1-t_2)]=\rho_{t2}(1-\beta\Delta t),$$

where ρ_{t1} and ρ_{t2} – density of the medium under operating temperature t_1 and under temperature t_2 respectively, kg / m^3; β - coefficient of the cubical thermal expansion of a substance in Δt temperature interval.

The role and significance of densitometers are growing from year to year [4]. Development of technologies changes the requirements to densitometers: bulky and unreliable devices are replaced by densitometers, compatible with other products of microelectronics. Main requirements to the instruments, designed for density measurements, are as follows: high precision, unambiguity of readings, fast response, low cost, multifunctionality, operability in extreme operating conditions, reliability and durability.

Measuring density of oil products is of current importance: by the oil product density we can estimate its composition and quality, presence of additives in it, etc. The existing methods and means for measuring density of oil products have a number of drawbacks and, therefore, there is a necessity to analyze them and to choose the method that is the most relevant and perspective for further investigation.

Aim of the work is to estimate advantages and disadvantages of current methods and means for measuring density of oil products as well as to substantiate the choice of the most perspective and accurate method for controlling quality of oil products under definite conditions.

To achieve the aim, the following tasks should be solved:

- to review the literary sources on this topic, to systemize and analyze the existing methods and means for measuring density of oil products, to identify their advantages and disadvantages;
- to elaborate a new improved classification of the methods and means for measuring density of oil products;

- to substantiate choice of the most perspective and precise method for controlling quality of oil products under definite conditions.

Analysis of the methods and means

After analyzing the existing methods and means for measuring density of oil products [3 – 19] and already available classification [20], a new improved classification has been elaborated (Fig. 1), which is based on the four main classification criteria, namely: the method, the form of the method realization, means for the method realization, design features.

Thus, according to the method the following densitometers are distinguished: float-weight, volume-weight, hydrostatic, hydrodynamic, vibration, radioisotope, optical, capacitive and acoustic densitometers.

According to the type of realization there are pyrometric and hydrostatic methods; volumetric, piezometric, adsorption, dilatometric and pycnometric; jet, fast-response, differential and pneumometric; centrifugal, turbine, jet and power-based methods; beta, gamma and alpha methods; amplitude and frequency methods, fast-response and impedance and fast response-impedance; polarimetric, calorimetric, nephelometric and refractometric; capacitive methods for measuring density of oil products.

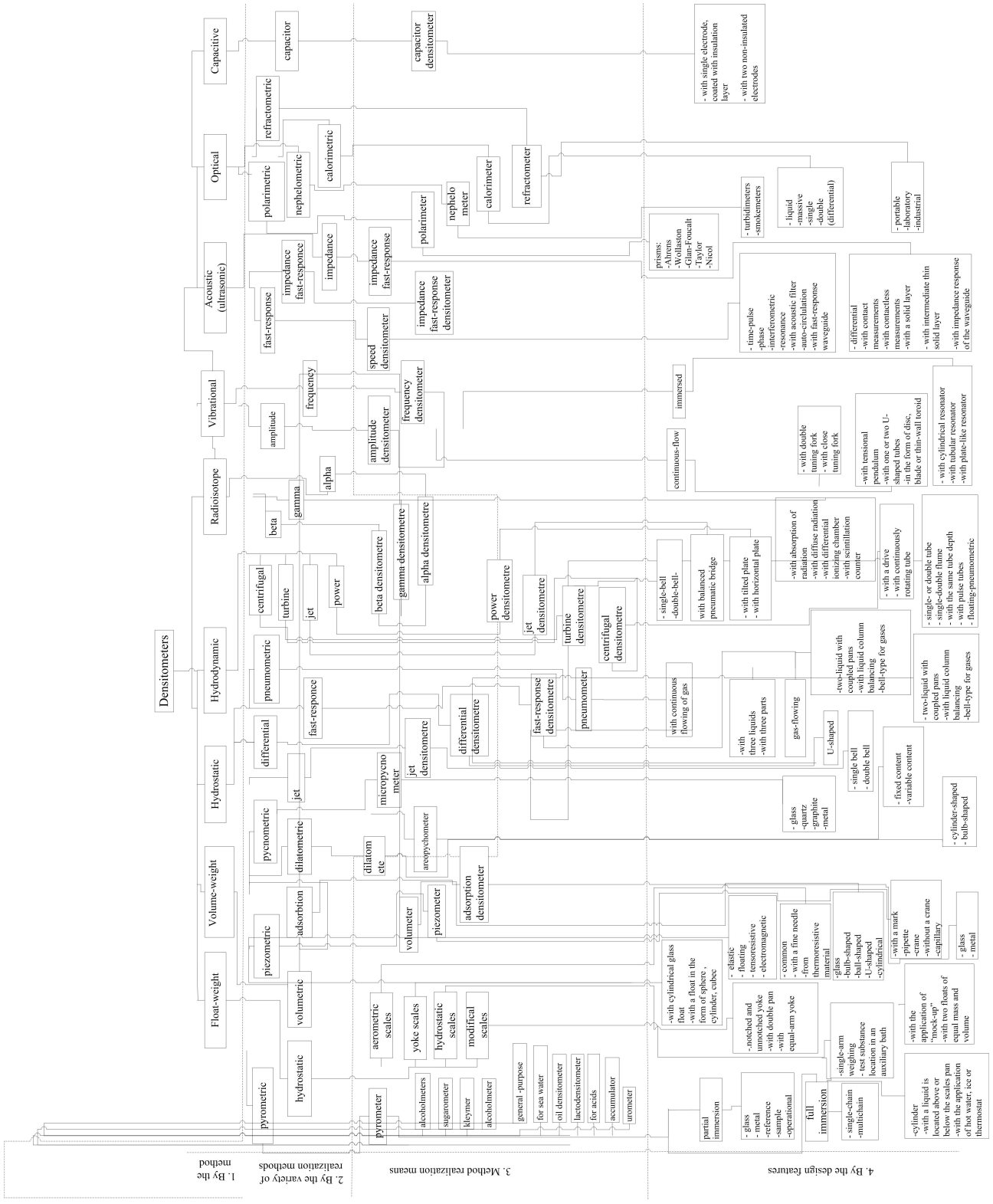

Fig. 1. Classification of the methods and means for measuring density of oil products

For each method realization corresponding density measuring means are used. Let us consider each of them in detail.

Float-weight method for measuring density of oil products

Float-weight method is based on Archimedes' principle. In accordance with this method buoyancy force acting on the float, immersed in the test liquid, is measured and then the liquid density is calculated on the basis of the relationship [3 – 5]:

$$F(x) = \rho_0 g \int_{h-x}^{h} S(x)dx + \rho g \int_{0}^{x} S(x)dx,$$

where ρ_0 - density of the medium above the liquid; g – acceleration of free fall ; ρ - density of the liquid, where the lower part of the float is immersed; S – sectional area of the float.

Float-weight densitometers are made with partially immersed or fully immersed float [5, 7]. In the instruments of the first type the depth of immersion of the float with definite shape and constant mass serves as a measure of the oil product density [4, 6]. In densitometers of the second type the depth of the float immersion is practically constant and, therefore, buoyancy force, acting on the float and proportional to the oil product density, is measured.

According to the method realization form, among the float-weight densitometers pyrometric and hydrostatic densitometers could be distinguished. Facilities, realizing the pyrometric method, are termed pyrometers. They include alcoholmeters, saccharimeters, glue-meters, hydrometers, oleometers, lactodensimeters, urometers and the like. For realization of the float-weight method the following facilities are used: hydrometric scales (common scales with a fine needle, made of a heat-resistant material), modified scales (with the application of a "mock-up" or of two floats having equal mass and volume), hydrostatic scales (a notched or unnotched yoke with a double-cup, equal-arm balance) and yoke scales (with cylindrical glass float, with a float in the form of a sphere, cylinder, ball; elastic, floating, piezoresistive, electromagnetic) [3, 5, 7].

Areometric balance is a metal or glass areometer of a constant volume with an additional plate (pan), fixed to the bottom of its body. On the middle part of the rod a scale is applied or a single circular mark. Density measurement with areometric balance is described in [5 – 7].

Measurement error is about ± 1 kg / m^3. Higher precision can be provided by improved scales with a rod, made of a thin needle (with the diameter of 0,2 – 0,3 mm) [5, 8].

Advantages of hydrometers include the possibility to obtain higher measurement precision due to the use of a rod, made of a fine needle, and the possibility to be used under high temperatures [4 – 8].

A drawback consists in the necessity to select weights of the required mass for three-time weighing and to use an additional layer of oil.

Modified scales are equipped with a simple additional device [4, 7], while cylinder support is made of any material and positioned so that balance pan could move freely up and down. More accurate results could be obtained using scales positioned so that liquid is below the scales [8]. Operating principle of the modified scales is described in [3 – 5].

Advantages of modified scales are as follows: the possibility to obtain better measurement results due to the liquid location under the scales; regulation of the bath temperature by adding of a small amount of hot water, ice or a thermostat.

A minor disadvantage is the use of baths with large water volumes.

For measuring density of liquids and solid bodies yoke scales are widely used [6]. They are simple in design and convenient for servicing by instruments.

Their essential advantage is a comparatively small amount of substance required for measurements. Measurement error is ± (0,05-0,1)%. Calculations of errors and readings of yoke densitometers are presented in [4, 6].

Among the producers of densitometers, operating principle of which is based on the float-weight method, there are such well-known companies as JSC «Geotron» (Russia), a group of companies «ATOM» (Russia), Chi-da-vin-chi Ventures (Nigeria), TOBIAS Associates (US).

Volumetric-weight method for measuring density of oil products

According to the volumetric-weight method, a certain constant volume of a medium is weighed and then density of this medium is calculated by the relation [4]:

$$\Delta G = 0{,}25\pi d^2(\pi R + 2L)(\rho - \rho_0)g,$$

where d – inner diameter of the pipe; R – the pipe bending radius; ρ_0 - initial value of the substance density; ρ - current value of the substance density.

Change in the weight corresponds to the substance density change [6 – 9].

In this method readings do not depend on the properties of the medium (surface tension, viscosity, presence of solid particles, etc.) and the controlled flow parameters (velocity of passing through the sensing element, pressure and flow rate pulsation, etc.).

This method for measuring density of oil products is realized by volume-weight densitometers. According to the form of its realization they are divided into volumeters, piezometric, adsorption, pycnometric and dilatometric densitometers.

Accordingly, for realization of the above techniques for measuring density of oil products the following facilities are used: volumeters (glass, bulb-shaped, spherical, U-shaped, cylindrical), piezometers (with a mark, pipette-type, crane densitometers, without a crane, capillary), adsorption densitometers (metal, glass), areopycnometers (of constant or variable content) and micropycnometers (glass, quartz, graphite, metal), dilatometers (cylindrical, bulb-shaped).

There is a variety of pycnometers and their application is determined by the type of the liquid under study, its amount as well as the required measurement precision [7, 8].

Measurement error reduction to ±0,0001% is provided by a differential pycnometric method, based on the application of two pycnometers with capillary neck and having, if possible, equal volumes. Operating principle of such pycnometer is described in [7].

Areopycnometers are a type of pycnometers. They are used for measuring density of liquids in small volumes (e.g., for blood tests). Unlike a conventional areometer, readings of the areopycnometer scale grow from bottom to top [4, 6].

Various designs of non-standard pycnometers are described in [3, 5, 7].

Advantages of pycnometers include the possibility to obtain higher measurement precision due to application of small-volume pycnometers. The bigger the volume of a pycnometer for liquids and gases, the lower the relative weighing error, but at the same time the higher the error caused by non-uniform temperature throughout the entire mass of the liquid (gas).

Dilatometers are calibrated cylindrical or bulb-shaped vessels, having a narrow neck with a circular mark. The vessel is filled with test liquid of a known mass and its volume is determined by measuring the height of the level relative to the mark, using a cathetometer. The density to be found is determined by the formula given in [4, 6, 8].

Piezometers are intended for studying the dependence of density on pressure and temperature. Piezometers could be of constant and variable volume. Piezometers of the first type measure the test liquid mass, which is a variable value and depends on pressure and temperature while the definite volume of a piezometer remains constant. In piezometers of the second type the test liquid mass is constant while its volume varies depending on temperature and pressure variations. Density under different temperatures is determined from the relationship, described in [9]. Constant-volume piezometers are used for gases and vapors, which under room temperature are in a liquid state.

Measurement error of such instruments is ±0, 2% [8]. In variable-volume piezometers measurements of test liquid with the known mass could be registered by various means, described in [3 – 7]. Main drawback of this piezometer is the mercury contact with the liquid, which limits its application in terms of temperature range.

Densitometers, the operating principle of which is based on volume-weight method, also include adsorption devices. As a rule, these densitometers are used for measuring density of vapor. Circuit of the given densitometer and its basic components are given in [7]. Error of adsorption densitometers is ±0,1%.

Volumeters could be designed for solids and gases. Measuring cylinders, burettes, microburettes, beakers are the simplest volumeters. Their operating principle is described in [9].

Advantages of liquid volumeters include simple and fast density measurements. Under field conditions they are indispensible for studying porous and fine-grained substances. However, they are much less accurate than pycnometers. It should be noted that the larger the test body volume, the higher measurement precision is [10].

Main advantages of the volume-weight method and densitometers, based on it, are as follows: the possibility to be used for pulps, suspensions, contaminated, viscous and volatile substances; readings do not depend on properties of the liquid and its flow rate; measurements could be performed under increased pressure (25 kgf / sm^2 ≈ 2,5 MPa); constant cross-section of the measuring portion of the device, which prevents deposition of solid particles contained in the flow; high sensitivity and small error (from 100 to 2000 kg / m^3). Application range of the volume-weight densitometers is limited by impermissibility of gas particles presence in the liquid.

Producers of densitometers, operating principle of which is based on volume-weight method, are such companies as Spectro (US), Euro Sistem Srl (Italy), Dexter King Ventures Ltd (Nigeria).

Hydrostatic method for measuring density of oil products

Hydrostatic method is based on measuring pressure differential of the liquid column at the throttling element at a constant height and the oil product density determination. [3, 8].

Operating principle of hydrostatic densitometers is based on finding pressure p in the substance at distance H from its surface by the expression given in [8].

In hydrostatic densitometers pressure of the liquid column is usually measured using an indirect method of continuous blowing of inert gas (air) (its pressure is proportional to the pressure of the liquid column) through the substance (piezometric densitometers) [4, 8].

The following main types of hydrostatic densitometers are distinguished: differential and jet densitometers (with direct measurement of the liquid column pressure), fast-response (with indirect liquid column pressure measurement) and pneumometers (with continuous blowing of gas).

Operating principle of pneumometers is based on measuring the pressure, required for a gas bubble detachment from the edge of the tube, immersed vertically in the test liquid [9, 10].

In differential densitometers two U-shaped tubes of equal diameter are used. One of the tubes is filled with test liquid, having density ρ, and the second tube – with control liquid of a known density ρ_c. Simultaneously, a certain pressure differential is created. Error of these densitometers is ± 0,2% [9].

For measuring density of gases jet densitometers are widely used. Their operating principle is based on the gas density dependence on the rate of its outflow from the opening [10]. Measurement error of jet densitometers is determined by their design and is about ±1%. Operating principle of jet densitometers is described in [11].

More reliable results are provided by a two-bell densitometer, composed of two single-bell devices, located in one housing [9, 11]. One of the bells is intended for operation with air and the other – with test gas. Shape, weight and volume of the bells are the same. Due to equal size of the

bells and gas outflowing time, relative density estimation is reduced to the bell displacement measurements [4, 8].

Advantages of the two-bell densitometer include more simple, faster measurements and absence of the necessity to measure time and perform re-calculation for the dry state; verificarion and setting of the device are also simplified [5 – 10]. When measuring density of small samples of liquid, a drop test is used. It is based on the following principle: speed of a droplet of liquid, falling into another liquid of smaller density, not mixed with it, increases with increasing density of the test liquid [9 – 11].

Special attention should be paid to the strictly vertical installation of the cylinder. The droplet falling time is measured by a timer with the error of ± (0,1-0,2) sec. Measurements are performed 5 – 6 times and average value is determined. Drop-test could provide density measurement with the error of ± (0.001 – 0,05)% [5 – 7].

Application of such hydrostatic fast-response densitometers has a number of limitations [3 – 9]:

- measurement range in one liquid is small: differences in the densities of a droplet and a substance should not exceed 0,05 g / sm^3. Therefore, for studying a group of different liquids many control liquids have to be prepared and tested;
- it could be problematic to find a substance that would satisfy the above requirements and had density, sufficiently close to that of a test substance;
- in order to reduce convection currents, strictly constant temperature should be maintained.

Fast-response densitometers are rather convenient for rapid systematic density measurements of small amounts of a liquid (e.g. in medicine for blood tests).

Among the manufacturers of hydrostatic densitometers there are such companies as Markbiz Nigeria (Nigeria), Cole Mills Limited (US), Motormonitor s. c. Jaroslaw Labich, Piotr Jukaszewski (Poland).

Vibration method for measuring density of oil products

Vibration method consists in measuring frequency of natural vibrations of a resonator in the self-vibration mode and subsequent calculation of the substance density, which depends on the resonator vibrations, by the following expression [3, 9]:

$$f = \frac{\lambda^2}{2\pi}\sqrt{\frac{EI}{ml^3}},$$

where λ - a constant that depends on the tube fastening conditions; E – elasticity modulus of the tube material; I – inertia moment of the tube cross-section; m and l – mass and length of the tube.

Operating principle of vibration densitometers is based on the relationship between the parameters of elastic vibrations entering the tube (vessel) with test substance or a body, placed in it, on the one hand, and density of the substance on the other hand.

Vibration densitometers could be divided into the following facilities used for this method implementation [12, 13]:

1) amplitude densitometers, where amplitude of the resonator vibrations under its constant resonance frequency is used as a measure of density. Change of the density causes deviation from the resonance and the respective amplitude change. As resonator vibration amplitude is determined not only by its parameters, but by a number of other factors (pulse power, liquid flow rate), measurement precision of this group is limited [12].

2) frequency densitometers, which measure frequency of the resonator natural vibrations, which is functionally related to the substance density. Resonator together with the drive (excitation system) and feedback system creates an electromechanical generator. Frequency measurement depends only on the resonator parameters (shape, dimensions, elasticity modulus and mass of the resonator and of the substance, contained in it) and does not depend on the amplitude. Frequency densitometers have

better metrological characteristics than amplitude densitometers and are more convenient in output signal processing, i.e. they are superior as to their design and performance indicators.

Equality, presented in [13], is a calibration characteristic of vibration densitometers with tubular resonators. Typically, calibration characteristic is linearized in the measured density range, linearity error being determined by the scale width and linearization method. Sometimes vibration densitometers are delivered with a specialized electronic attachment that linearizes calibration characteristic [8].

Tubes, cylinders or plates, fixed on stationary bases, are used as sensing elements of vibration densitometers. They are set into self-vibration mode by the excitation system [9].

Among main advantages, which determine increasing application of frequency densitometers, we should mention high precision, sensitivity and reliability, direct conversion of the sought-for density into output frequency signal, the possibility to be used under high pressures for wide range of controlled mediums (gases, substances).

At the same time densitometers have certain disadvantages, which include limited permissible flow rate of the fluid, determined by cross-section area of the flow channel, non-linearity of the scale, the necessity for special facilities to compensate the influence of temperature and pressure on the resonator parameters [5, 7, 13].

Vibration densitometers are produced by the following companies: JSC «Geotron» (Russia), a group of companies «ATOM» (Russia), «Chi-da-vin-chi Ventures» (Nigeria), TOBIAS Associates (US).

Radioisotope method for measuring density of oil products

Radioisotope method consists in measuring attenuation of penetrating radiation as it passes through the test substance with subsequent calculation of its density [12]. During the photoabsorption and Compton scattering rays with the energy below 1 MeV are considered.

Radioisotope method of density measurement and devices, based on it, are used for continuous measurements. Radioisotope densitometers are noncontact devices (sensitive element is not located in the movable test medium) and they are expedient to be used for measuring density of aggressive and highly-viscous mediums, pulps and substances, which are under high pressure or have high temperature in big-diameter pipelines, but only in the cases when other above-mentioned densitometers cannot be used [3 – 5, 9 - 11].

In radioisotope densitometers three types of nuclear radiation are used: alpha, beta and gamma. Alpha rays have small mean free path of particles and are used, therefore, in densitometers for gases [13]. Beta- and gamma-rays are used in densitometers for liquids and solids. Beta-radiation is a flow of electrons or positrons that are released by atom nuclei and move with the speed, close to the speed of light. Gamma-radiation is electromagnetic vibrations of a very small wavelength – below $4 \cdot 10^{-11}$m. Gamma-rays are characterized by higher penetrating power as compared to beta-particles.

As gamma-rays pass through a substance, their intensity is weakening (radiation energy is transformed into other forms of energy). Measurement of a substance density in pipelines and reservoirs, using gamma-radiation, could be realized by two techniques, described in [9 – 12].

An important advantage of these densitometers is the possibility of controlling substance density in hard-to-reach places. A drawback of radioisotope densitometers is dependence of the readings on physical properties of the test fluid, which requires individual calibration with respect to the type of substance.

Radioisotope densitometers are produced by such companies as «ATOM» (Russia), «Spectro» (US), «Euro Sistem Srl» (Italy), group of the company «Motormonitor s. c. Jaroslaw Labich, Piotr Jukaszewski» (Poland).

Optical method for measuring density of oil products

Optical method for measuring density of oil products consists in light capture by a moving medium (the effect of Fizeau – Fresnel) or in light scattering by moving particles (Doppler effect) [13].

According to the method implementation technique, polarimetric, calorimetric, nephelometric and refractometric densitometers are distinguished.

Facilities, used for this method implementation, are divided into polarimeters, calorimeters, nephelometers and refractometers [12, 14].

Polarimeter is a device designed for measuring rotation angle of the plane of polarization, caused by optical activity of transparent mediums, solutions and liquids [13, 14]. In a broad sense, polarimeter is a device that measures parameters of a partially polarized radiation (in this sense Stocks vector parameters, polarization degree, parameters of polarization ellipse of the partially polarized radiation could be measured). It is used for studying structure and properties of a substance in the laboratories of food, chemical and other branches of industry and science for determining concentration of solutions of optically active substances (such as sugar, glucose, protein) by rotation angle of the polarization plane [8, 10, 13]. It also allows observing and measuring residual stresses in the glass. According to the design features, Ahrens prism, Wollaston prism, a prism of Glan-Foucault, Taylor prism and Nicol prism are distinguished.

Calorimeter is a device for measuring the amount of heat emitted or absorbed in any physical, chemical or biological process [10 – 12]. Modern calorimeters operate in the temperature range from 0.1 to 3500 ^{o}C and allow measuring the amount of heat with the accuracy of 01 – 10%. There are various calorimeters and their types are determined by the nature and duration of the process under study, temperature range in which measurements are performed and the required precision. By the design features, calorimeters are classified as liquid, mass, single, double (differential) calorimeters.

Nephelometer is an optical device for measuring the degree of turbidity in liquids and gases by their light scattering intensity [14, 16]. The nephelometer operation is based on comparing the intensity of two light fluxes: one from scattering a suspension and the other – from a reference substance (e.g., dim glass). Nephelometers are divided into turbidimeters and smokemeters. They are used for studying disperse systems [17].

Refractometer is a device that measures light refractive index in a medium [17, 18]. There is a wide variety of refractometer types having different designs and technical data. They are intended for solving various research, production and technological problems. Refractometers could be portable, laboratory, industrial.

Densitometers with operating principle, based on the optical method, are produced by such companies as «Spectro» (US), «Euro Sistem Srl» (Italy), «Dexter King Ventures Ltd» (Nigeria).

Capacitive method for measuring density of oil products

Capacitive method is based on measuring capacitance of the capacitor formed by an electrode, immersed in the medium, and by the controlled medium [8, 10, 13].

Parameter of the material, characterizing the ability of the material to create a capacitance, is termed dielectric permeability. It indicates the degree of capacitance increase, when the given material is placed between the capacitor plates without changing the capacitor dimensions, as compared to the vacuum [13, 17]. Writing expressions, which determine resistance and capacitance of the isolation area, and multiplying the right and the left sides, we obtain [18]:

$$R = \frac{\rho}{l}, \qquad C = \varepsilon_0 \varepsilon \frac{}{l},$$

wherefrom

$$CR = \varepsilon_0 \varepsilon \rho .$$

where C and R – resistance and capacitance of the isolation areas; ε_0 – electric constant; ε – dielectric permeability; l – reduced length of the capacitor; ρ – density of the medium.

From the the expression it is evident that the capacitance does not depend on the dimensions and shape of the capacitor and depends solely on ε and ρ.

Densitometers of this type could be used for measuring both electrically non-conductive and conductive liquids. They are suitable for density measurements under wide range of pressures and temperatures of aggressive and non-aggressive mediums. Their readings depend on dielectric permeability of the medium that may change with the temperature. Application of compensational capacities enables significant reduction of this influence but cannot exclude it completely [11, 13]. Electronic circuit of capacitive densitometers is rather complex, which limits their application range.

For liquid electrically conductive mediums primary transducers with a single electrode, coated with an insulation layer, are used. The controlled medium plays the role of the second electrode.

For measuring the level of non-conductive mediums a primary transducer with two non-insulated electrodes is used. [10, 12,16].

Capacitive densitometers have the following advantages: simplicity, convenience of mounting and maintenance, reliability and potentially high precision (there are capacitive densitometers with the main error not exceeding 0.1 – 0.2%). Capacitive densitometers are widely used in industry. Their disadvantages include high sensitivity to changes in the electrical properties of fluids, caused by changes in their composition, temperature, etc., electrically conductive film that appears on the sensor elements due to chemical activity of the liquid, condensation of its vapor, sticking of the liqiod itself to the contact elements.

Among the producers of capacitive densitometers there are such well-known companies as JSC «Geotron» (Russia), the group of companies «ATOM» (Russia), Chi-da-vin-chi Ventures (Nigeria), TOBIAS Associates (US).

Ultrasonic (acoustic) method for measuring density of oil products

Ultrasonic method is based on measuring flow rate of a liquid or gas using ultrasound. [6, 8, 13].

High-frequency sound vibrations (20 KHz and higher), created by electroacoustic vibrator (emitter), pass through the medium and are registered by a receiver, located at the distance D from the emitter.

Application of ultrasound for measuring density of a substance is a new and perspective trend in the development of densitometers.

Ultrasonic (acoustic) method for measuring density of a substance and devices, based on it, are usually used for continuous measurements. By the type of realization, acoustic densitometers are divided into impedance, fast-response and impedance-fast response densitometers. Operating principle of these devices is described in [8, 10, 14].

Acoustic densitometers are devices, where output signal of measuring information depends on acoustic properties of the substance analyzed.

Velocity of propagation of longitudinal acoustic vibrations in a substance is given by [15]:

$$C = \sqrt{K / \rho} = \sqrt{1/ \chi\rho},$$

where K - bulk compression modulus, Pa; χ - compression ratio, м^2/N.

From the expression it is evident that density of the test substance could be estimated by the speed of sound [13, 14].

Propagation of ultrasonic waves in any medium is accompanied by the sound energy absorption, which is characterized by absorption coefficient α. Intensity of ultrasound, when it passes distance *d,* decreases according to the exponential law:

$$I = I_0 e^{-2\alpha d},$$

where I_0 - initial ultrasound intensity, W / m^2.

Fast-response ultrasonic densitometers are designed, primarily, for homogeneous substances, binary solutions, mixtures of substances and gases [14, 16]. Among them the following types of densitometers could be mentioned. Time-pulse densitometer is based on measuring changes of time of ultrasonic vibration propagation in the controlled medium, depending on its density change. Operating principle of the phase densitometer consists in measuring the phase of ultrasonic vibrations (continuous or amplitude-modulated), which passed through the medium [15, 17]. Interferometric densitometer is based on measuring the wavelength of ultrasonic vibrations by the acoustic resonance of the medium column of the given height, when an integral number of half-waves fit in it. Characteristic feature of the resonance densitometer consists in the following: in the layer of substance between two plane-parallel surfaces, one of which is adjacent to the emitter connected with a broadband electric generator and the other is a reflector, a stationary wave is created [18]. Densitometers with acoustic filter use the effect of ultrasonic pulse spectrum change, when the pulse is propagating in the controlled liquid through the solid layer, located in it. In auto-circulation densitometers a value is determined, which is reverse to the time of ultrasonic pulses propagation in the medium. This value is auto-circulation frequency in the electro-acoustic closed-loop system [17, 19]. Densitometer with a fast-response waveguide is based on the effect of the change of ultrasonic vibration propagation rate along the solid layer due to the density of the liquid, which collides with this layer. As a solid layer, a wall of the pipeline or of the reservoir with the controlled liquid is typically used. Operating principle of fast-response densitometers is described in detail in [6, 8, 10, 14].

Impedance densitometers measure density of homogeneous solid and gaseous substances, binary solutions and mixtures of liquids and gases. [17, 20]. Application of these densitometers is based on the known (or pre-determined) relationship between resistance and density of the substance. One of the circuits of impedance densitometers [19] is based on determining equivalent resistance of radiation of piezoelement with known area. If contact with the medium is impermissible [17], a receiver is placed in the intermediate acoustic line and ultrasonic vibrations of the emitter are transmitted to the medium and to the receiver via this line.

The differential densitometer is a type of impedance densitometers. It measures the difference between the acoustic pressures, created by identical emitters in the controlled medium, and by the auxiliary medium with known resistance [19 – 20]. Densitometer with impedance response of the waveguide is based on the exponential attenuation of the Lamb ultrasonic wave in the solid layer (the waveguide), which is in contact with the controlled medium. Ultrasonic densitometers, based on the absorption of sound energy and sound propagation rate, are actively developed. Operating principle of impedance densitometers is considered in detail in [5 – 8, 11 – 18].

Among the above-mentioned impedance densitometers, devices with an intermediate layer and impedance response of the waveguide have the highest sensitivity.

Impedance fast response densitometers, which combine the above-described types of impedance and fast-response measuring methods, are perspective due to the possibility to be used for a wide variety of products and contactless measurements [17, 19].

Other circuits of ultrasonic densitometers and their elements are presented in [6 – 8, 18 – 20]. Depending on the circuit and design of densitometers, their reduced error varies from т ±1,5 to ±3 %.

The following advantages of acoustic (ultrasonic) densitometers facilitate their application: high sensitivity; the possibility to be used for measuring density of contaminated and aggressive

mediums; inertia-free and contactless measurements; absence of movable parts in the flow; absence of pressure losses in the pipelines, etc. [17 – 20].

Ultrasonic method has some minor disadvantages: the necessity to drain air from the pulps as air bubbles have significant influence on the absorption of ultrasound; high cost of ultrasonic densitometers.

Among the producers of densitometers with operating principle, based on the ultrasonic method, there are such well-known companies as «Markbiz Nigeria» (Nigeria), «Cole Mills Limited» (US), JSC «Geotron» (Russia), «TOBIAS Associates» (US).

Conclusion

The existing methods and means for measuring density of oil products have been systemized and analyzed. Their advantages and disadvantages have been determined.

A new, improved classification of methods and means for measuring density of oil products has been elaborated. It is based on four main classification criteria, namely: method; method realization form; method realization means; design features.

The choice of the most perspective and accurate method for controlling quality of oil products in pre-defined conditions is substantiated. This is the ultrasonic method, which in spite of having minor drawbacks (the necessity of draining water from the pulps as air bubbles have a significant influence on ultrasound absorption; high cost), has a lot of advantages over other methods. The advantages include: inertia-free and contactless measurements; absence of movable parts in the flow and of pressure losses in the pipelines; the possibility of application for measuring density of contaminated and aggressive mediums.

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