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MATHEMATICAL MODEL OF NATURAL GAS HUMIDITY ANALYZER

There had been suggested the mathematical model for two-channel gas humidity analyzer, as well as methodology for determination of specific molar absorptivity indexes of natural gas and water vapor. There had been carried out the experimental tests to check the received results of relative humidity.

Key words: *relative humidity, water vapor, dry gas, wave length, pressure, temperature, absorption index, transmission coefficient, specific molar absorptivity, density.*

Introduction

Humidity measurements and control in gas environment are urgent for both modern science and its use in economy, and play a considerable role in the process of assuring quality parameters of high-tech processes. Analyzing the humidity of process gases, the most informative parameters which directly determine the quantity of water in the specified volume is absolute or relative humidity which directly determines the consumer characteristics of gases.

Humidity control can be divided into three groups according to technical processes, namely: during gas dehumidification in the field; on the gas processing plant; during the accounting of commercial gas.

Among analyzers used for laboratory analysis of gas humidity only a few are able to work in the churn out mode. Information-measuring condensation systems, which implement the direct method of measurements of the dew point temperature, are considered to be the most perspective. In this method, in order to get the reliable measuring results, the water must attain equilibrium in the analyzed gas and in the sensor. That is why such measurements take a lot of time. And the other methods have the same drawback. Furthermore the admixtures of the natural gas such as methanol are water-soluble and the dew point temperature of such solutions may considerably differ from its value for pure water. If in a multicomponent medium (natural gas is just the very medium), the temperature of dew point of any component is higher than the temperature of dew point of the water vapor, the analyzer then may take it for a true value [1-5].

Basing on the above, the analyzer of gas humidity must comply with the following main requirements:

– Fast response to avoid transferring a huge amount of non-standard gas;

– Avoiding influence of corrosive admixtures as well as distortion of measuring results because of influence of alcohol compounds;

– Low errors and high repeatability of measuring results;

– Built-in means to check the reliability of indicators readings without the need to demount the field block and cease the process that enables fast elimination of disputes between the supplier and customer in questionable situations.

Recently there has been a progress in creating IR LEDs and photodiodes applicable in spectral analyzers of gas humidity. Such analyzers meet the above mentioned requirements and most fully realize wireless advantages. The use of IR range to measure gas humidity is reasonable on conditions that gas pressure and temperature are registered.

The purpose of this work is to develop the mathematical model for infrared analyzer of gas humidity that complies the above requirements.

Results and materials of the research

The absorption spectroscopy method is based on the effect of selective absorption of radiation by polyatomic molecules when this radiation passes through the medium. The absorption causes the weakening of radiation is described by the Beer–Lambert–Bouguer law

$$I(\nu) = I_0 e^{-K(\nu)Cd}, \quad (1)$$

where $K(\nu)$ – the molar absorptivity factor, a function of ν frequency; C – concentration of substance under control; d – the depth of gas layer, through which a light beam intensity $I(\nu)$ travels.

The relative humidity cited in the paper [6] considering the standard conditions of pressure $P_{(s)}$ and temperature $T_{(s)}$, as well as operating conditions of pressure P and temperature T may be calculated as

$$\phi = \frac{\left(\mu_{d.p.} P_{(s)} TZ \cdot ln\frac{I_0(\nu)}{I(\nu)} - dK^{d.p.}(\nu) T_{(s)} P \rho_{d.p.\cdot(s)}\right)\mu_{w.v.}}{\left(\mu_{d.p.} K^{w.v.}(\nu)\ \rho_{w.v.(s)} - \mu_{w.v.} K^{d.p.}(\nu) \rho_{d.p.(s)}\right) dT_{(s)} P_{w.v.\max}}, \quad (2)$$

where $K^{d.p.}(\nu)$ and $K^{w.v.}(\nu)$ - specific molar factors of absorptivity of dry natural gas and water vapor at ν frequency correspondingly; $\mu_{.dp.}$ and $\mu_{w.v.}$ – molecular weights of dry natural gas and water vapor correspondingly; $\rho_{d.p.(s)}$, $\rho_{w.v.(s)}$ – density of dry part and density of water vapor under standard conditions correspondingly.

The natural gas is a gas mixture, which besides mixture of carbohydrates (C_nH_{2n+2}) and water vapor may contain nitrogen, carbon dioxide, hydrogen sulfide, oxygen, hydrogen, argon, helium, etc. It means that the density of the mixture and molecular weight correspondingly can vary under the standard conditions. That is why it is necessary to carry out the additional measurements. Such measurements can be performed by both direct (real-time measurements of density) and indirect methods (determination of density as a function of pressure and temperature). All these factors complicate the process of gas humidity measuring [7].

The paper suggests a humidity analyzer to overcome the listed drawbacks. The analyzer which contains two equivalent channels: the first is the measuring channel tuned to a operating (ν_1) wave length; the other one – to the (ν_2) reference wave length.

The output intensity of the measuring channel according to [6] can be determined as

$$I(\nu_1) = I_0(\nu_1) e^{-d\left(K^{w.p.}(\nu_1) C_{w.v.} + K^{d.p.}(\nu_1) C_{d.p.}\right)} = I_0 e^{-d\left(K^{w.v.}(\nu_1)\frac{\rho_{w.v.}}{\mu_{w.v.}} + K^{d.p.}(\nu_1)\frac{\rho_{d.p.}}{\mu_{d.p.}}\right)}. \quad (3)$$

The output intensity of the reference channel is determined as

$$I(\nu_2) = I_0(\nu_2) e^{-d\left(K_2^{w.v.}(\nu_2) C_{w.v.} + K_2^{d.p.}(\nu_2) C_{d.p.}\right)} = I_0 e^{-d\left(K_2^{w.p}(\nu_2)\frac{\rho_{w.p.}}{\mu_{w.p.}} + K_2^{d.p.}(\nu_2)\frac{\rho_{d.p.}}{\mu_{d.p.}}\right)}, \quad (4)$$

where $K^{d.p.}(\nu_1)$ and $K^{w.v.}(\nu_1)$, $K^{d.p.}(\nu_2)$ and $K^{w.v.}(\nu_2)$ – the specific molar factors of absorptivity of dry natural gas and water vapor of the measuring and reference channels correspondingly; $\mu_{d.p.}$ and $\mu_{w.v.}$ – molecular weights of dry natural gas and water vapor correspondingly.

The density of the real natural gas considering the Z compressibility factor is determined by the formula

$$\phi = \frac{\mu_{w.v.} P_s TZ \cdot \left(K^{d.p.}(\nu_1) ln\frac{I(\nu_2)}{I_0(\nu_2)} - K^{d.p.}(\nu_2) ln\frac{I(\nu_1)}{I_0(\nu_1)}\right)}{dT_s P_{w.v.(\max)}\left(K^{d.p.}(\nu_1) K^{w.v}(\nu_2) - K^{w.v}(\nu_1) K^{d.p.}(\nu_2)\right)\rho_{w.v.(s)}}. \quad (5)$$

The conversion equation (5) enables to determine the relative humidity of the gas, considering neither density of gas mixture nor its molecular weight or pressure, which significantly simplifies

the measuring processes.

Fig. 1 shows the structure of two-channel humidity analyzer. The sensor consists of body 1, optical schemes for inputting radiation from measuring and reference channels 2,7, LEDs 3 and 6, which emit monochromatic light of the proper frequency, optical schemes for radiation outputting from measuring and reference channels 4, 9 and photo detectors 5, 8.

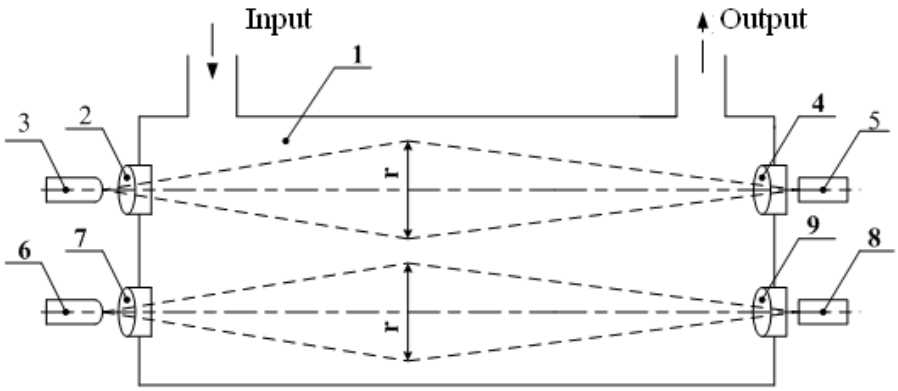

Fig. 1. Optical scheme for two-channel gas humidity analyzer

The body of the analyzer is a tube, the diameter of which depends on the overall dimensions of the optical system providing the optimal parameters of the light flux.

To select the dimensional specifications of the sensor as well as the parameters of the optron system in order to provide the necessary sensitivity and measuring accuracy of gas humidity one should carry out the experiments in the laboratory environment. In view of this the paper suggests the methodology for determination of the specific molar factors of absorptivity of dry natural gas and water vapor and develops the device for the research of gas humidity analyzer characteristics, structured scheme of which is presented in fig.2.

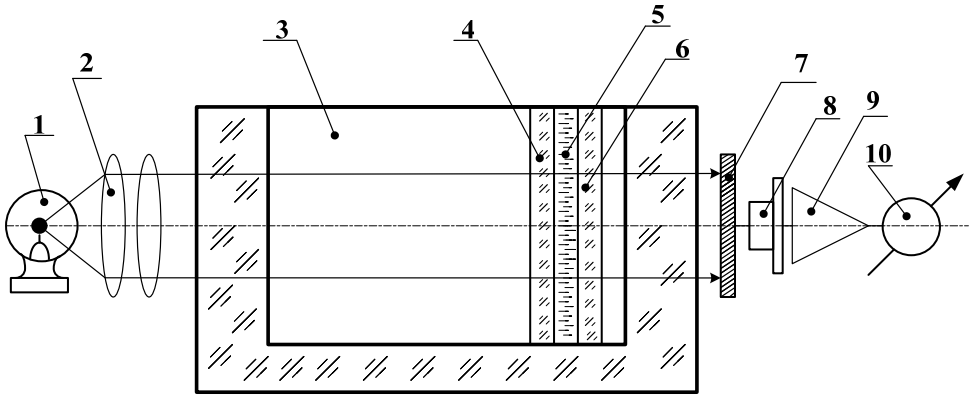

Fig. 2. Structure scheme of the device for the research of gas humidity analyzer characteristics

The scheme of the device contains the incandescent lamp 1, optical system to form a parallel light flux 2, cell 3 which houses the slide plates 4 and 6 inside, between which the liquid to be researched is contained 5, monochromatic filter 7, photo detector 8, signal amplifier 9, indicator 10.

The light flux from the incandescent lamp 1, with the help of the optical scheme 2 is directed to the system of slide plates 4, 6 and travelling through the layer of liquid 5 due to which the weakening of the flux takes place. Then the weakened light beam passes the monochromatic filter 7, which singles out the spectral component from the flux with a thick absorption line of the liquid. The beam, formed on the filter output enters the photodetector 8. The light flux being a parameter function of weakening of the damp gas is converted into the electrical signal and shall be fed to the

repeated measuring converter. The conversion function of this transformation is described as

$$U = \Phi_e \tau_{ose} \tau_c \tau_м \tau_{si} \tau_{osf} S K_{PA}, \quad (6)$$

where Φ_e – source light flux; τ_{ose}, τ_{osf} – transmission coefficients of the optical system of the measuring converter and photodetetor channel correspondingly; τ_{ose}, τ_{osf} - transmission coefficients of the optical system of the analyzer and photodetector device correspondingly; τ_c – transmission coefficient of the cell and slide plates; $\tau_м$ – transmission coefficient of the liquid; τ_{si} – transmission coefficient of the filter of spectral interval selection; S – integral sensitivity of photodetector device; K_{PA} – transmission coefficient of the preamplifier.

To carry out the researches a distilled water and white spirit as a carbonic like compound were used. The water and white spirit ware placed between the slide plates. The depth of the layer was measured by the microscope and made up 0,01 mm. The diameter of the photodetector chip was known as 0,3 mm. It made possible to calculate the volume and mass of the liquids between the plates, which made up $7{,}065*10^{-7}$ g for water and $5{,}581*10^{-7}$ g for white spirit. The set of slide plates enabled gradual increase of the mass of the studied liquids. Such an approach made possible to receive the experimental dependencies of light transmission from mass for water and white spirit, as well as to determine the $T(\nu)$ transmission coefficient of the water and white spirit. At that the transmission coefficient was determined as a relation of the intensity of the light passed through the cell with the liquid to the intensity of the light flux passed through the cell without liquid

$$T(\nu) = \frac{I(\nu)}{I_0(\nu)} \cdot 100\%$$

It means that determination of $T(\nu)$ is reduced to the measurements of $I_0(\nu)$ and $I(\nu)$. The determined transmission coefficients of the water will correspond to the transmission coefficients of the water vapor $\overset{w.v.}{T}(\nu)$ in the determined volume, and the determined transmission coefficient of the white spirit will correspond to the transmission coefficient of the dry natural gas $\overset{d.p.}{T}(\nu)$ in the determined volume. At that the losses for reflection from the cell windows and slide plates on the way of the monochromatic beam are considered.

The researches were held in the monochromatic light on the wave length from 1 to 1,5 μm, which made possible to determine the maximal and minimal sensitivity to water. Thus, it was determined that LED of the reference channel must operate on the wave length of 1,33 μm, and the measuring one – on 1,45 μm.

Fig.3 shows the experimental dependencies of the transmission coefficient as a function of the liquid mass through which a light flux passed.

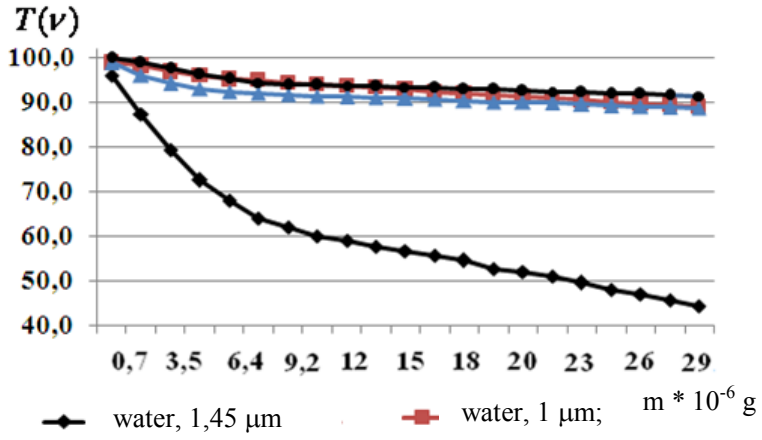

Fig. 3 Experimental dependencies of the transmission coefficient from liquid mass

The experimentally received transmission coefficients enabled the determination of the specific molar absoptivities, which made up 1710 $\frac{l}{cm \cdot mol}$ for water, 29 $\frac{l}{cm \cdot mol}$ for white spirit on the wave length of 1,45 μm; they made up 18,1 $\frac{l}{cm \cdot mol}$ for water, and 23,6 $\frac{l}{cm \cdot mol}$ for white spirit on the wave length of 1,33 μm. And proceeding from the acceptable and possible masses of water vapor and gas, the basic distance of light path of the analyzer was 0,5 m.

Fig.4 shows the dependency of the relative gas humidity received from the expression 5.

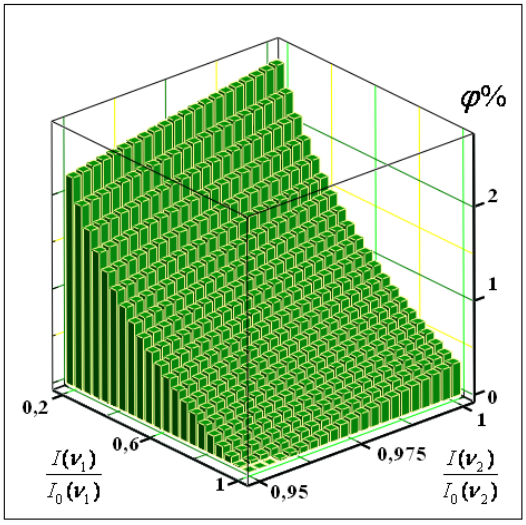

Fig. 4. The dependency of relative humidity

The researches have shown that the influence of the reference channel on the measuring results is insignificant, but occurs. That enables increasing measuring accuracy, as two-channel system in contrast to the one-channel does not require any additional measurements of gas pressure and its molecular weight. Besides, the usage of the additional channel allows to eliminate the influence of corrosive admixtures. The absolute error of relative humidity measuring makes up 0,5 %.

The verification of the results of relative humidity received on the basis of (5) and data of the water vapor concentration according to Fig.3 and Fig.4 has been made relative to the expression, which uses the value of the dew point temperature in [8, 9]. The maximal deviation of the calculated values of the relative humidity from the values calculated by the expressions given in [8, 9] does not exceed 8%.

Conclusions

Results of the researches enable to make the following conclusions:

1. There had been suggested the mathematical model of two-channel gas humidity analyzer, which in contrast to one-channel one does not require any additional measurements of gas pressure and molecular weight.

2. The had been suggested the methodic for the determination of specific molar absoptivity of dry natural gas and water vapor, as well as the experimental device to study the characteristics of gas humidity analyzer.

3. There had been conducted the experimental researches on the determination of maximal sensitivity in close IR range, chosen the wave length of 1,45 μm for the measuring channel and 1,33 μm for the reference channel.

4. There had been made the verification of the received values of the relative humidity according

to the expression (5) relative to the level based on the value of the dew-point temperature in [8,9]. The maximal deviation does not exceed 8%.

The results received allow to make a conclusion that the use of two-channel system enable to improve the metrological characteristics of infra-red analyzer.

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