Detection of Trace Concentration of Explosives on Human Fingers and Documents Using Ion Mobility Spectroscopy

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***Abstract*-The sampling unit of the device, based on ion mobility spectroscopy technique, for detection of ultra-small concentration of substances on human fingers and documents, is described. The vapor pressure of some substances is subtle; so the heating of an examined surface is a must for efficient detection of these substances. In the present work it was shown (by the thermal transfer investigation) that more efficient method of surface heating consists of the using of the impulse gas-discharge lamp in comparison with the use of a heated air flow or heat transfer from the warm body by thermal conductivity. However the heating of the human fingers by the irradiation of the gas-discharge lamp is not effective because of a small concentration of the melamine (pigment of the black or brown color) in the skin of the human palm. Therefore in this work the combination of the two methods is used: irradiation of the gas-discharge lamp heats grid and a grid heat the surface of the finger that is pressed to a grid. The system will be effective for the control of admission to public events and providing anti-terrorist measures [1-3].**

Keywords- Ion Mobility Spectrometry; Explosives; Human Fingers; Documents; Personnel Portal Sampling

I. INTRODUCTION

The presence of residual molecules in the air is usually determined using highly sensitive gas analyzers such as ion mobility spectrometers which are suitable for detecting trace amount of explosives and other compounds [4-6]. Concentration of molecules detected material in the sample gas determines the sensitivity of such devices. However, one of the areas of practical interest is to detect trace amounts of material on the surface.

Heating of surface [7-10] enhances vaporization and increases the concentration of molecules in the gas sample, and increases the sensitivity of the instrument with the direct study of the gas near the surface. Heating of the surface can be heated stream of gas directed at the surface, the transfer of heat from the heated body to the surface by conduction through the air gap or by direct contact, radiative way directional flow of infrared or other material analyzed surface absorbed radiation.

The momentum of heated normal flow of air is low enough due to the low heat capacity of air. In addition, the gas stream carries food from the surface of the evaporation zone study or very dilute gas near the surface. Use to heat flow over the surface of the heat of the gas, such as water vapor, greatly complicates the design, followed by condensation on the surface, has limitations in the detection in environments with high humidity.

Consider the example of the heating surface of the plastic (typical example - polystyrene) normal flow of air. Suppose there are five seconds to warm up the surface area of 0,001m^2 from a room temperature of 20 ℃ to 70 ℃. The depth of penetration of the thermal front in polystyrene for 5s will be $0.8*10^{-3}$m. For heating, this layer to 50 ℃ required about 60J heat. Let the air flow, which transfers this power initially heated to 200 ℃. Further, it is cooled to 50 ℃ as a result of the interaction with the surface with a requirement of 300*10-6m^3 hot air. During the same time, the analyzer only gets 25*10-6m^3 (regular flow 5*10-6m^3/s), heating the air will carry more than 90% of the molecules evaporated from the surface. For metal surfaces even more pessimistic assessment because of the high conductivity of the material surface. Use a strongly heated air to lead to overheating and damage of the analyzed surface.

The heating of the transfer of heat from the heated body to the surface by conduction through the air gap has a lower efficiency because of the low thermal conductivity of air. Transfer heat energy 60J to the surface 0,001m^2 air gap1 mm is available when the heater temperature at 500 ℃ above the temperature of the heated surface. Together with the structural problems in the implementation of this method of heating the limitations arise personal safety, the possibility of overheating of the analyzed surface, the combustion of dust on the surface of the heater.

The radiative heating does not cause significant disturbance of air near the surface being analyzed. In addition, the radiative heating can be performed remotely. Using the mechanism of surface heating by radiation, for the conditions listed in the previous example, the heat radiating surface will need a temperature of up to 400 ℃, which obviously has significant

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limitations related to the case of heating by conduction of the air gap. The effectiveness of surface radiative heating can be significantly improved by using a pulsed mode [11].

II. THE SURFACE HEATING

The objective of this part of the development was to analyze available on the national market pulsed discharge lamp (Fig. 1). This study is presented because of the relatively short life of these lamps (especially at high pulse power mode). The impulse, lamp IFK-120, is a traditional element in national developments. The following are its specifications.

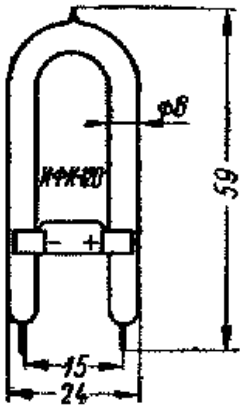

Fig. 1 The lamp IFK-120

The peculiarity of the lamp is small in size at a sufficiently high energy flare. Operating voltage is low. It is designed for portable handheld flash and alarms. The container is made of glass. Strips of silver paste deposits on the surface of the tube present ignition electrode. The body of the luminous part is U - shaped. Dimensions of the luminous parts are: diameter of 5 x 23 x 30 (10^{-3}*m).

Durable heat-resistant glass form balloon lamp IFK-120, close foreign analogue, is borosilicate glass Pyrex. Spectral characteristics of light transmission materials used for containers of pulsed gas discharge lamps (Fig. 2).

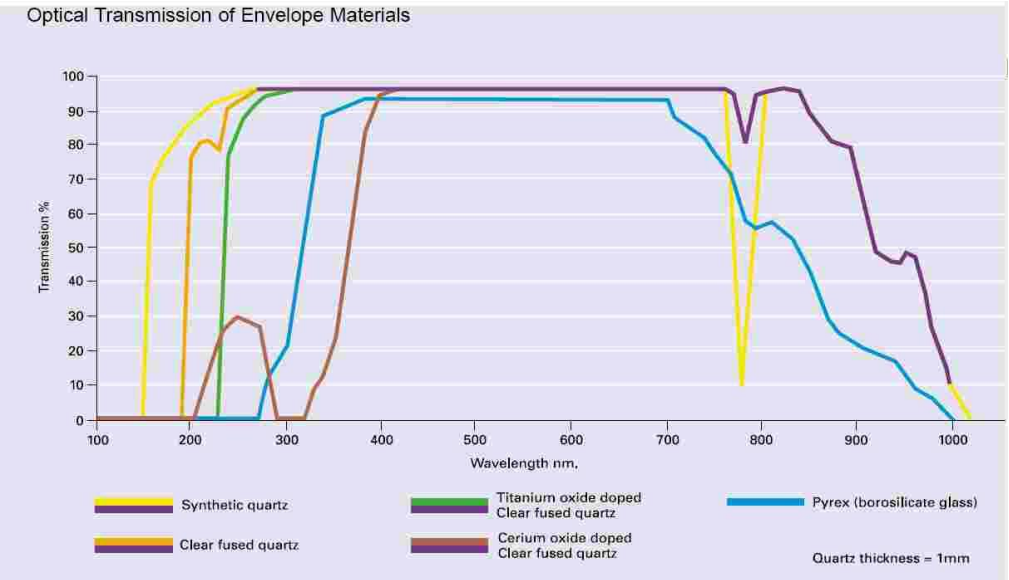

Fig. 2 The transmission spectra of cylinder gas discharge lamps

The container should be transparent in the spectral range of light produced by a lamp. The material should be stable in air and in relation to the gas that fills the tube. The lamp operates at high temperatures, and large pulse pressure drops inside the container.

Borosilicate glass is cheap enough tech stuff. It is a general practice for lamps operating at relatively low average power, when it is possible to ensure adequate cooling of the cylinder. The energy of single pulses can be high. In the high power pulse glass is subjected to thermal, mechanical treatment, and in the material tank cracks, leading to the destruction of the lamp. Cylinders of more expensive lamps consist of quartz glass, which provides increased mechanical and thermal stability, as well as transparency for light emission in the near ultraviolet region. Although the physics of the processes occurring in the plasma

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is rather complicated, and further shows the basic model, which explains some of the dynamic properties of the lamp pulse and steady-state level. The structure of the gas discharge in the lamp is presented in Fig. 3.

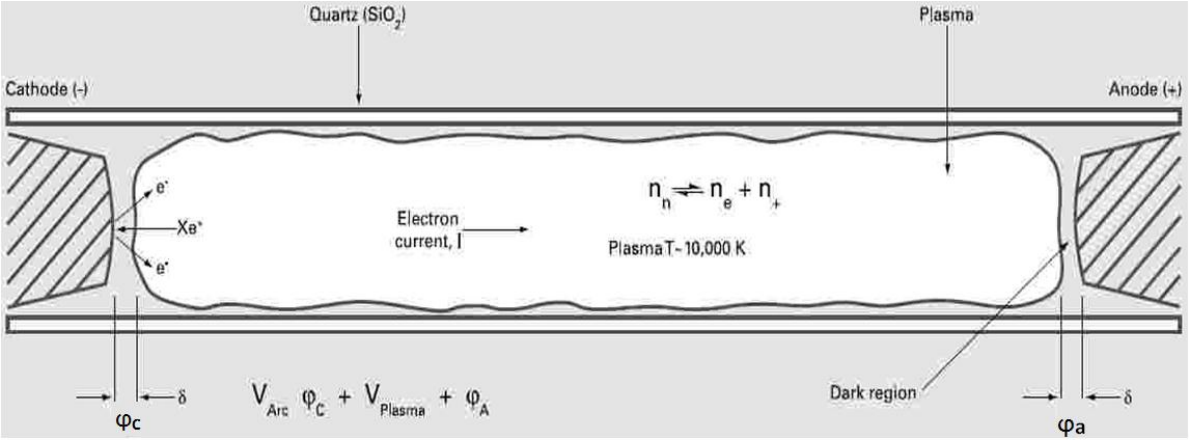

Fig. 3 The cathode dark area and the dynamics of gas-discharge plasma

The plasma has the most heat in comparison with other states of matter (solid, liquid, gaseous). In the center of the plasma temperature of the gas-filler, xenon or krypton, may reach 10000K. This temperature decreases rapidly in the radial direction. Electrons are much more mobile than the positive ions of xenon or krypton (Xe +, Kr +) so that their concentration near the inner surface of the cylinder is increased, which makes the inner surface of the electronegative. Positive ions drift to the surface by the field, where they recombine with electrons. The active electron-ion recombination on the inner surface of the cylinder tube gives rise to a high concentration of neutral Xe or Kr atoms, which have a much lower temperature than the ionized particles and, therefore, act as a thermal buffer between the plasma column and the inner surface of the cylinder. Inside the plasma at the same time there are three types of particles: electrons, positive ions and neutral atoms. The concentration of ionized atoms is less than 1%, and these ions are responsible for all the emitted light energy. The positively charged ions move from the anode to the cathode while the electrons move from the cathode to the anode. Mechanisms of damage to the cathode and anode are different. Consider the effects on the cathode. Near the surface of the cathode, there is a dark area of the ion current, the distance from the cathode surface to the luminous area δ is tens of micrometers. This area is called the space-charge region. The voltage drop across this area can be from 5 to 15 volts. This field accelerates the ions towards the cathode surface. Heavy charged particles bombard the surface; their power is enough for the physical destruction (sputtering) of the cathode material. This process is a major limitation of the lifetime of the cathode and the lamp as a whole.

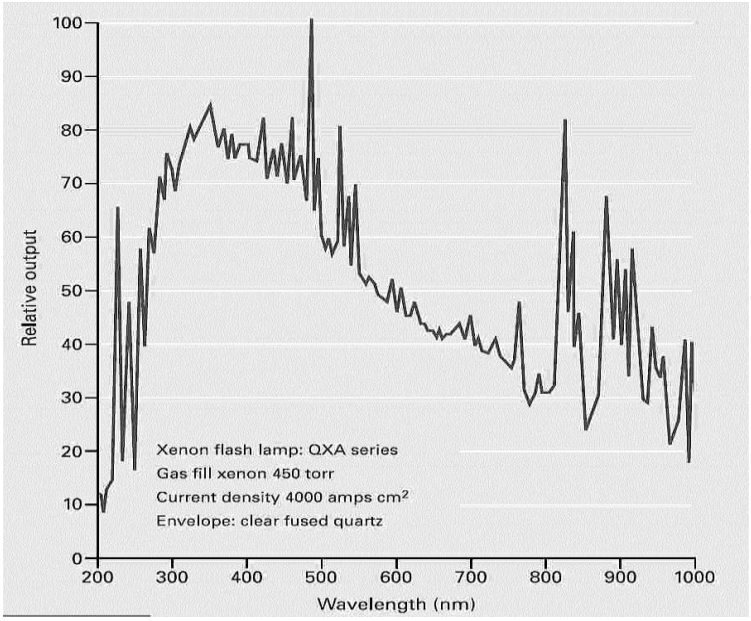

Fig. 4 The emission spectrum of a xenon flash lamp with a high current density

Pulsed and arc lamps emit light over a wide wavelength range. It extends from ultraviolet radiation, limited to the material passing the cylinder ([160-380]*10^{-9} m) to near infrared region (2.5*10^{-6} m), although the concentration energy locating at the edges is negligible. The radiation produced by pulsed arc lamps, and mainly depends on the density of the arc current and much smaller - gas pressure (the latter does not apply to mercury and sodium lamps). At low current densities present in the

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spectrum of the emission line, interband atomic transitions. At higher densities, there is mostly a uniform spectrum of the radiation corresponding to the free transitions, and line structure in the spectrum there is a slight variation on the environment of continuous radiation (Fig. 4). In high emission, current density can be approximated by a blackbody radiation at a temperature of 9500 ℃.

The conversion efficiency of electrical power applied to the arc in the optical radiation (200-1100)*10^{-9} m for flash lamps is about 50%. In general, the efficiency increases with increasing current density and gas pressure in the tube. Xenon lamps convert electrical power input of about 10% more efficient than krypton.

Generic methods, reliable assessment of the resource pulse lamps do not exist. However, it can use experimental data to estimate used by Perkin Elmer (Fig. 5).

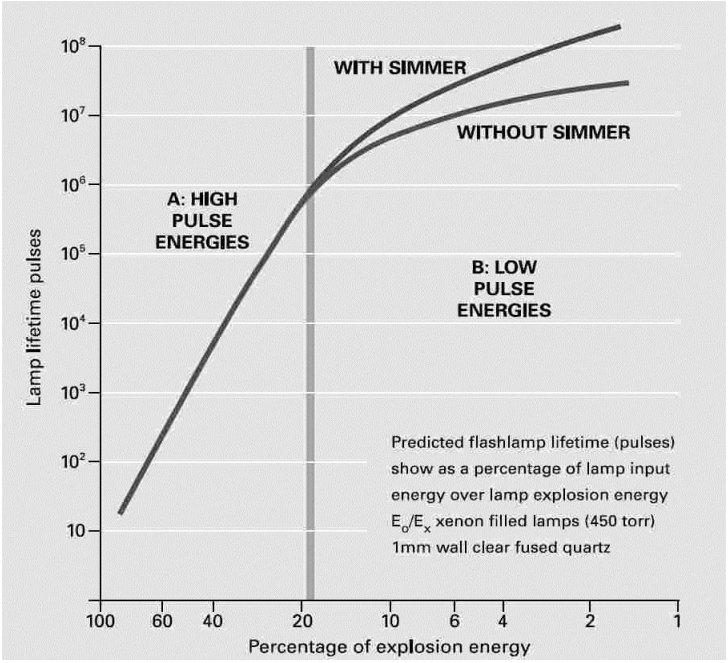

Fig. 5 resource evaluation of pulsed xenon lamp

In the high-energy flares (more than 20% of energy, which leads to the destruction of the lamp), the endurance is mainly determined by the mechanical stresses in the cylinder tube and partial degradation associated with the spray material container. At low power flare resource is mainly determined by the electrode effect expressed in the sputtering of the cathode. On the inner surface of the tube, sputtered material is deposited, weakening the light emission. Using the function to determine the time of the lamp IFK-120 (yield 10 000 flashes correspond to 35% of power failure), can expect an increase in the resource up to 1 million flashes at lower energy flashes two times, until the conditional boundaries of low-energy flash 18%.

An important factor in determining the operating lamp depreciation is the dynamics of the arc ignition and the formation of a pulsed discharge. Conventional methods of ignition are not optimal for use with large resources required. Ignited by an external electrode attached to the cylinder tube, it is simple and inexpensive to implement. However, in this way the arc goes around the inner surface of the cylinder, resulting in a spray bottle and the erosion of material at the stage of formation of the arc. Not only weakens the mechanical strength of the lamp, but it also leads to the deposition of sputtered material on the inner surface of the cylinder, substantially weakening the emitted light. In addition, a large amount of oxygen, the released spray material container, complicates the ignition and reduces the stability of the arc. Preferred methods for management of flash lamps submit more complex circuit solutions that realize the formation of pre-low-current gas discharge in the central part of the cylinder, followed by high-power pulse.

The developed method for detecting trace amounts of explosives and other compounds using a pulsed radiation heating surface, the study suggests the surface of human hands. The optical absorption spectrum of human tissue is presented in Fig. 6.

According to the law of Lambert, the radiation intensity (P) decreases with depth of penetration into the surface of the law

$$P = P0 \cdot (1 - Rs) \cdot \exp(\mu a \cdot L),$$

where P0 is the intensity of light incident on the surface, Rs are the coefficient of reflection from the surface; μa • (m^{-3}) is the coefficient of absorption (Fig. 6), L is the depth of penetration (cm).

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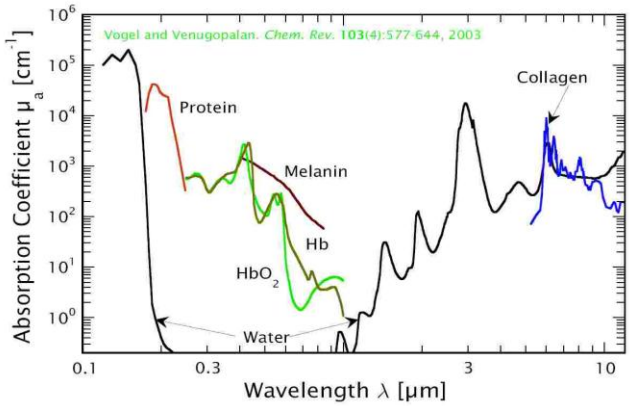

Fig. 6 Optical absorption spectrum of human tissue

The absorption of light determines the optical properties of absorption in the visible light for the human by hemoglobin (Hb and HbO2), and melanin. In the superficial layers of skin absorption is predominantly in the melanin - the pigment of brown and black, which determines the color of skin, hair and iris of the eye. As a rule, the content of melanin in the skin of human hands is low so it should expect that the heating of human skin by light flash lamp will exist at a sufficiently thick layer, the share or unit millimeters.

Therefore, the advantages of pulsed heating associated with an active energy release in a thin surface layer to the surface of human hands have significant limitations.

In the study of the surface of the documents in the presence of trace amounts of explosives and other compounds, pulsed radiation heating may be subjected to paper or cover paper. As a general rule, identification documents made of thick colored paper. For such a material reflection of light, it is not exceeding 50%, and the absorption of the passage of a single sheet of up to 80%. This result corresponds to a complete separation of the sheet (typically thickness $0.125*10^{-3}$m) to 40% of the energy of the incident light. When the absorbed energy 10J section of the paper and the density of 0,15 kg/m^2 square 0,001m^2 warmed by more than 60 ℃. If the efficiency of generation of a light bulb is 25%, for the example above, will need electrical power flash 100J. This option is in the operating modes of the lamp IFK-120.

The absorption of light in the plastic cover is a similar absorption in paper or better (except for the transparent cover).

Contact method can solve the problem by the heating of the surface of human skin. This process creates a pulse heating with a small net mesh size, such as $0.5*10^{-3}$m and optical transparency of 50%. The surface of a finger pressed against the grid. One possible way, that is either electrical or radiation, the grid pulsed heat and contact heat transfer of the analyzed surface. The optical transparency of the mesh provides an effective evacuation of evaporation from the surface.

III. SAMPLING DEVICE WITH A PULSE OF RADIATION HEATING OF THE SURFACE

The structure of the sampling device present in Fig. 7. The test object takes place at the information areas of the study, made in the form of a grid of high transparency and low thermal capacity. From the volume under the mesh is continuously sampling the air, the gas enters the channel ion mobility spectrometer. After placing the object under study, it is initiated to the grid flash lamp pulse, resulting in rapid heating of the surface of the object and the evaporation of particles of matter. The air flow delivers vapor to the ion mobility spectrometer.

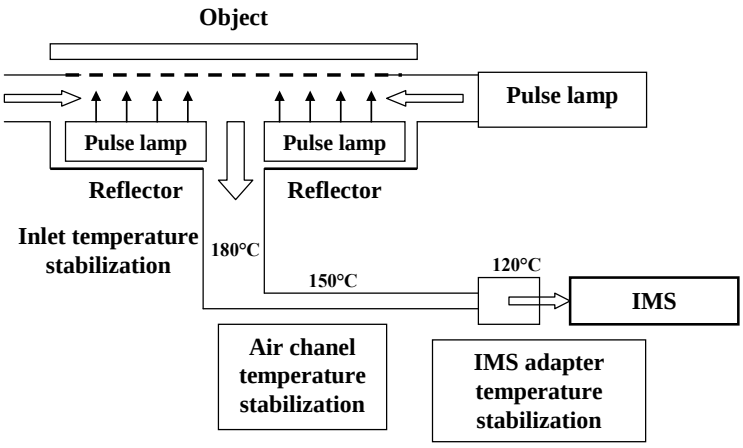

Fig. 7 Block diagram of the sampling device with a pulse of radiation heating of the surface

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Structurally the sampling unit of IMS device has three separate areas - windows for sample inlet (Figs. 8 and 9). Person should locate three fingers or paper documents over all information areas (three windows) or at intermediate carrier of the replica (napkin). The two gas-discharge lamps settle down input grid areas. The grids are transparent and have a subtle thermal capacity. After location an examined object above grids, the flash of gas-discharge lamps is started. That leads to a very quick heating of the tested object surface and evaporation particle from the surface. The impulse power equals 25 J, and the time of the energy release is $5*10^{-2}$ s. The evaporated molecules move from tested surface as narrow group to ion mobility spectrometer. The sampling unit has a system with three levels of the temperature stabilization: 1800 ℃ in sample inlet area, 1500 ℃ in gas transfer channel, 1200 ℃ in interface module where the sampling unit has links with the ion mobility spectrometer. Operating software synchronizes the initiation of the gas-discharge lamp operation, molecule group moving and the process ionization in the ion mobility spectrometer. Thus, the sampling unit and spectrometer are integrated into total construction and control program device. Finding space object on the grid can be accomplished by conventional methods, using optical or capacitive sensors. To ensure proper operation of the system requires stabilization of the temperature of all elements of the gas channel. The sampling device has a separate system of temperature stabilization in three successive areas of transportation of the sample.

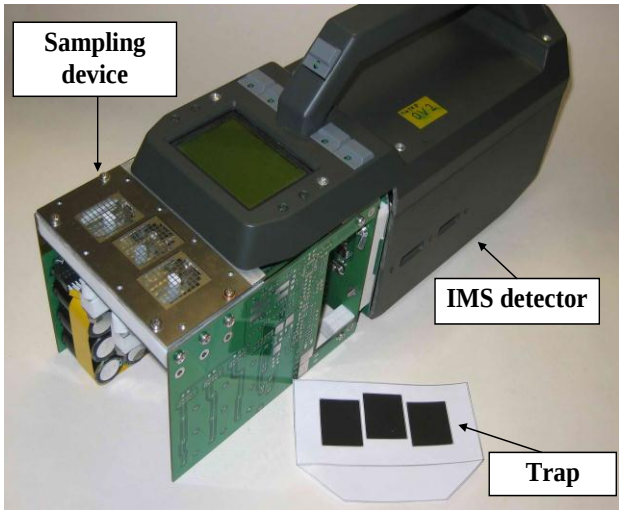

Fig. 8 Sampling devices connected to the ion mobility spectrometer

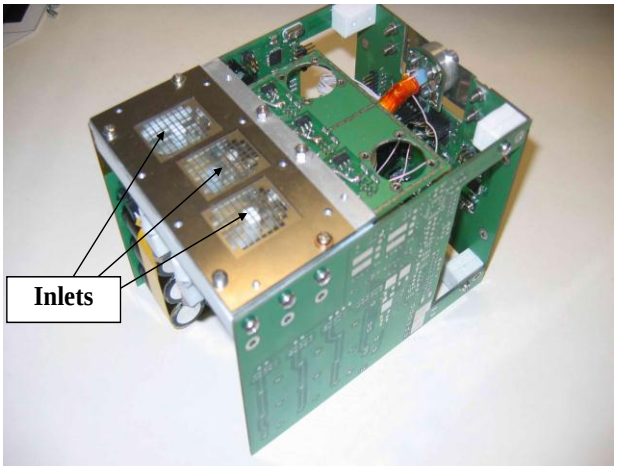

Fig. 9 Sampling device, the front view

Evaporation products are formed on the analyzed surface and transported in a compact cloud, so the system is complete, with the exact synchronization of the flash lamps and spectrometric measurements.

A typical technique for producing ultra-low concentrations of substances associated with the dissolution of the material in a liquid medium. Based on density and volume of a material, it is selected set ratio of solute and solvent. This method allows to obtaining a solution of desired concentration. In the process of dissolving, ultrafine explosive concentration can be achieved in solution - about 10^{-3} kg/m^3.

Further, part of the solution is sampled using a micro syringe, and applying it to the surface. When choosing the most volatile solvent after a set time surfaces of the test material remains in trace amounts. After this procedure, there are all conditions for carrying out experiments to detect trace amounts of substances on the surface of materials.

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The device was designed and created during the experiments which showed its functionality and suitability for the detection of trace amounts of explosives in trace concentrations. Test system held using samples of TNT, PETN, RDX by ion mobility spectrometer with corona discharge ion source [11].

Fig. 10 shows the background signal of the system. Fig. 11 presents the spectrum that occurs when registering substances TNT (trinitrotoluene). TNT is one of the most common classes of homogeneous chemical explosive nitro compounds. It is a yellowish crystalline solid, prepared with the nitration of toluene with nitric acid in admixture with sulfuric acid [5]. Blasting TNT does not apply, but is widely used as an integral part of most of the explosives, which it is mixed with ammonium nitrate, which has excess oxygen. TNT explosives refer to average power ratio (efficiency).

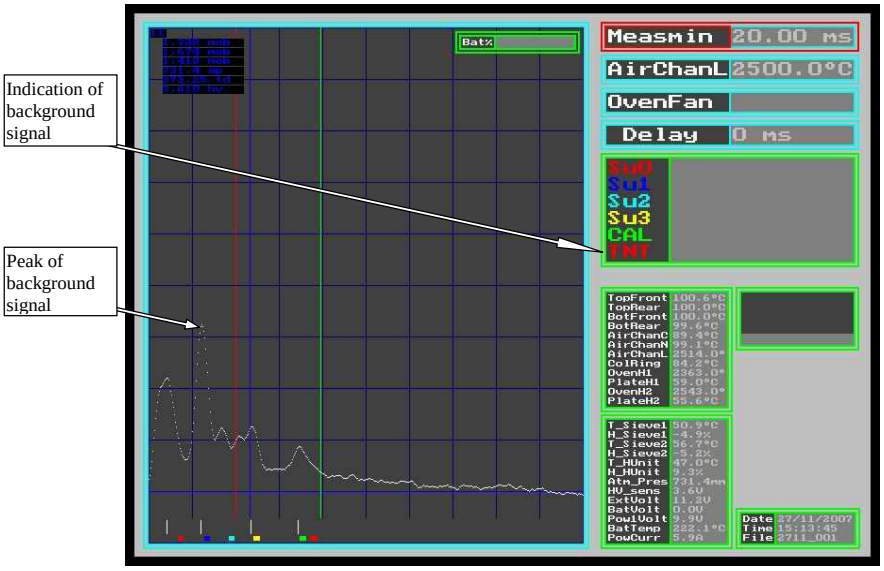

Fig. 10 Spectrogram of the background signal

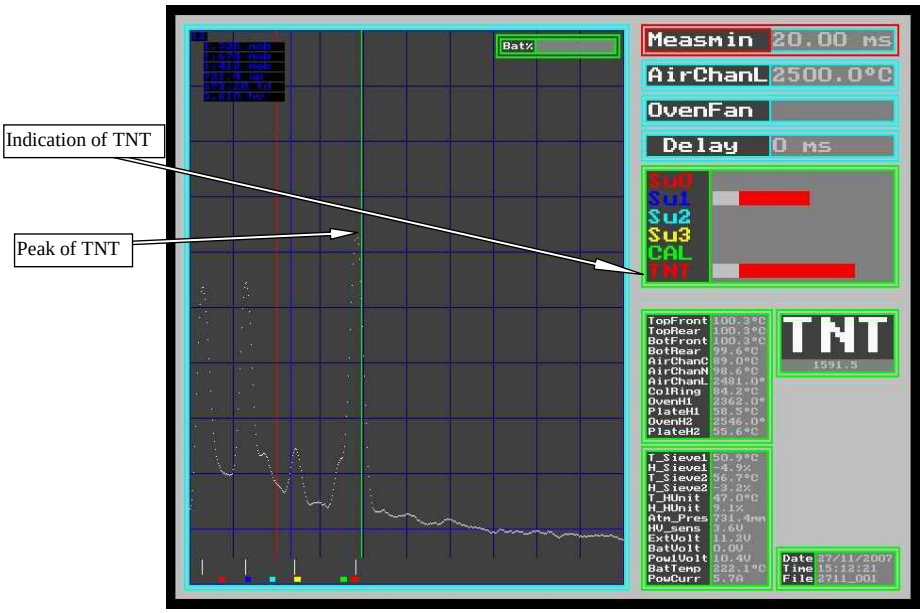

Fig. 11 Spectrogram of the TNT

Fig. 12 presents the spectrum arising during registration technical RDX. Technical RDX looks like a fluffy white powder. It is characterized by an extremely high susceptibility to knocking. In addition, the RDX has toxic properties and is one of the most powerful and the most common explosives. RDX used in alloys with TNT for making checkers TG- 500. Used as boosters for equipment detonator cap, manufacturing ammonite rock, shaped charges and torpedoes for the oil industry.

Fig. 13 introduces the spectrum that occurs when registering explosive PETN. PETN (tetranitropentaeritrit) - a white crystalline substance chemically resistant, so there is no need to constantly monitor its storage stability. A significant number (over 1 kg) moves into his burning explosion. Confinement detonation occurs even small amounts during the combustion. Military detachments widely use TEN for filling blasting caps as a secondary charge. High explosive features and small critical diameter allow the use for the manufacture of PETN detonating cord.

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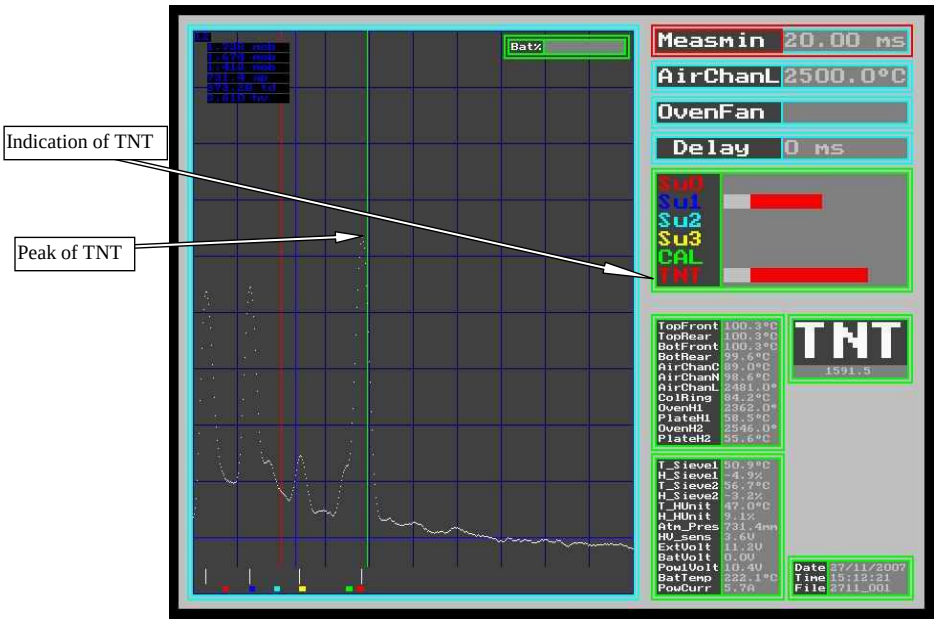

Fig. 12 Spectrogram of the RDX

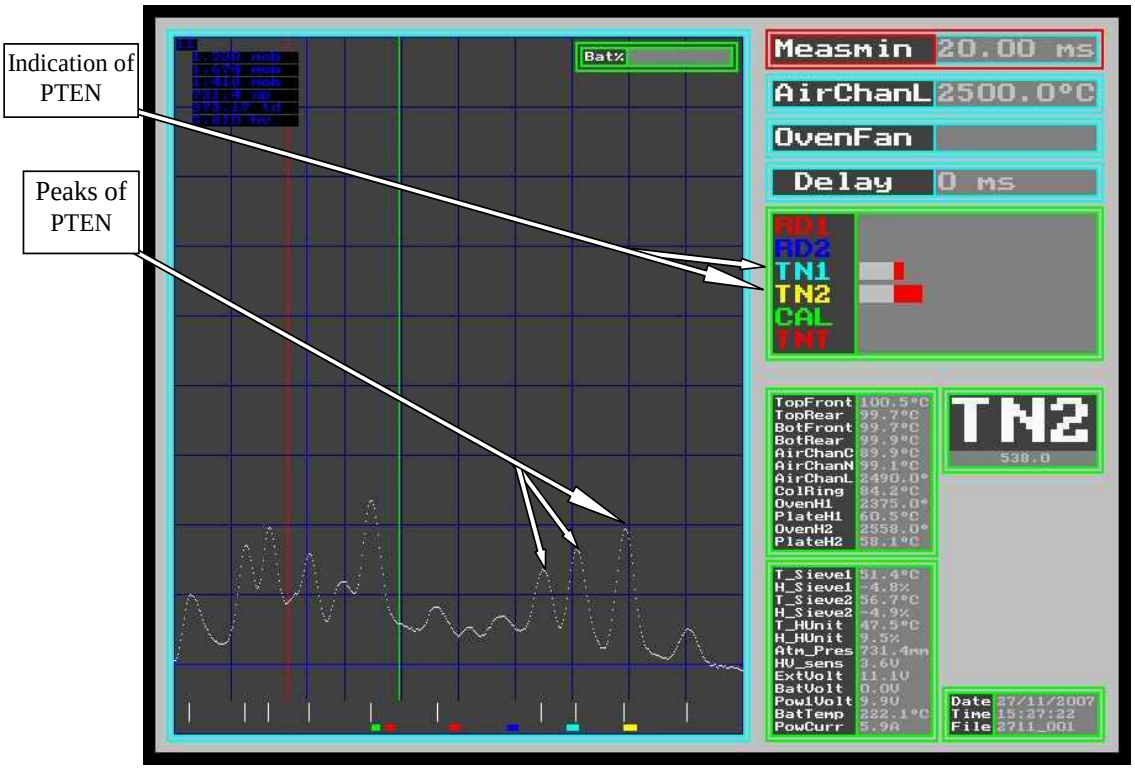

Fig. 13 Spectrogram of PETN

As shown by tests, established system can facilitate the detection of trace amounts of chemicals in small concentrations from the surface of the material.

IV. CONCLUSIONS

The device was designed and created during the experiments which showed its functionality and suitability for the detection of trace amounts of explosives in trace concentrations. Studies include experiments with samples of TNT, PETN, RDX by ion mobility spectrometer with corona discharge ion source [11].

Complex of works on creation of devices for pulsed heating surface for the analysis of trace amounts of substances ion mobility spectrometer:

- Developed proximity device pulsed heating surface.

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- A device contact thermal pulsed heating surface.
- Made Experimental studies of small-sized devices for ion mobility spectrometry with ionization corona.

Applying the above construction allowed to provide reliable high-speed sampling of trace concentrations of explosives from the surface of the fingers and documents. The module structure of the device makes it easy to upgrade the system to the real conditions of detecting trace amounts of chemicals. In particular, there exists the need to optimize power consumption and software to reduce the size and modify the mechanical component of the system.

REFERENCES

[1] H. Borsdorf and G.A. Eiceman, "Ion mobility spectrometry: Principles and application," *Appl. Spectrosc. Rev.*, vol. 41, pp. 323-375, 2006.

[2] C. Wu, W.E. Steiner, P.S. Tornatore, L.M. Matz, W.F. Siems, D.A. Atkinson, and H.H. Hill, "Construction and characterization of a high-flow, high-resolution ion mobility spectrometer for detection of explosives after personnel portal sampling," *Talanta*, vol. 57, pp. 123-134, 2002.

[3] J.W. Gardner and J. Yinon, "Fast Detection of Explosives Vapours and Particles by Chemiluminescence Technique," *Electronic Noses & Sensors for the Detection of Explosives*, vol. 159, Chapter 5, pp. 71-80, 2004.

[4] V. Matsaev, M. Gumerov, L. Krasnobaev, V. Pershenkov, V. Belyakov, A. Chistyakov, and V. Boudovitch, "IMS Spectrometers with Radioactive, X-ray, UV and Laser Ionization," *International Journal for Ion Mobility Spectrometry*, vol. 5, no. 3, pp. 112-114, 2002.

[5] P.V. Johnson, L.W. Beegle, H.I. Kima, G.A. Eiceman, and I. Kanik, "Ion mobility spectrometry in space exploration," *International Journal of Mass Spectrometry*, vol. 262, pp. 1-15, 2007.

[6] W. Vautz, B. Bödeker, J.I. Baumbach et al., "An implementable approach to obtain reproducible reduced ion mobility," *Int. J. Ion. Mobil. Spectr.*, vol. 12, pp. 47-57, 2009.

[7] Y. Salinas, R. Martínez-Máñez, M. D. Marcos, F. Sancenón, A. M. Costero, M. Parra, and S. Gil, "Optical chemosensors and reagents to detect explosives," *Chem. Soc. Rev.*, vol. 41, no. 3, 1261-1296, 2012.

[8] S.M. Melissa and V. L. McGuffin, "Luminescence-based methods for sensing and detection of explosives," *Anal. Bioanal. Chem.*, pp. 2557-2576, 2008.

[9] E. Maiolini, S. Girotti, E. N. Ferri, P. Caputo, G. Guarnieri, S.A. Eremin, A. Montoya, M. J. Moreno, and M. Dellia, "Development of chemiluminescent methods for explosives detection," *Ovidius University Annals of Chemistry*, vol. 20, no. 1, pp. 57-60, 2009.

[10] R. H. Dishington, W. R. Hook, and R. P. Hilberg, "Flash lamp Discharge and Laser Efficiency," *Applied Optics*, vol. 13, no. 10, p. 2300, Oct. 1974.

[11] N. Samotaev, A. Golovin, V. Vasilyev, E. Malkin, E. Gromov, Y. Shaltaeva, A. Mironov, and D. Lipatov, "IMS development at NRNU MEPhI," *Lecture Notes in Electrical Engineering (LNEE)*, vol. 268, pp. 447-451, 2014.

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