Steam explosion of thin-walled glass capsules with water

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INTRODUCTION

The last decades all over the world technologies fire fighting dispersed (spray) water (DW) with the size of droplets less than about 100 microns [1,2] are developing. Also such technologies are developing in the hydrodynamic laboratory of SarFTI [3÷5]. The high efficiency of DW in fire-fighting is conditioned by its huge surface area that allows for rapid cooling of the hot zone of fire due to the rapid heat take-off by evaporation of droplets. However, there are fundamental limitations in the implementation of these methods in practice in actual fighting, especially large-scale fires as small droplets (with a size of less than~ 100 mm) rapidly lose speed in a gaseous medium and can not penetrate into the core of a large fire.

Method of extinguishing fires using thin-walled sealed capsules with water about 5÷7 mm of diameter [6] aims at solving this problem. Capsules of this size can penetrate deep into the great fire. At the same time, these capsules have explode in a few seconds after hitting the flames with the formation of clouds of a mixture of steam and DW. This is confirmed by experiments [7].

This paper presents the results of an experimental study of dynamics of the steam explosion capsule with water heated by the flame, in order to determine some characteristics of the explosion, including the time delay from the start of capsule heating, size and speed of the droplets, size of the DV cloud. Also, the results of experiments on the quenching of the flame by DW cloud.

EXPERIMENTAL TECHNIQUE

As a result of the search, it was found that the most suitable material for the manufacture of capsules is glass [8]. Technology of glass-capsules with water of varying geometry (spherical and cylindrical [9,10]) was worked out. As a part blank for the capsules making were used glass tubes marks C52 -1 and C37- 2. Typical dimensions of the spherical capsule (Fig. 1,a) used in the experiments: diameter d=7mm, the wall thickness $\Delta = 0.23 \div 0.25$mm, the volume of water in the capsule of ~0.14ml. Typical dimensions of cylindrical capsules (Fig.1,b) used in the experiments: the capsule diameter d = 5mm, the thickness of the walls of the cylindrical part of the capsule $\Delta = 0.4 \div 0.5$ mm, length 45 mm, the volume of water in the capsule of 0.3ml.

The water temperature in the capsule during heating in some experiments was measured with a thermocouple type chromel /alumel wire with a diameter of 0.2 mm (Fig.1a).

The capsules were heated flames of different types: gas burner, alcohol lamp and a wick dipped in kerosene and placed in a metal cell. Burners of various types were used for heating capsules , both standard and improvised. Non-standard gas burners made of aluminum tube with an inner diameter d = 8 mm. These burners have a straight or spiral shape.

 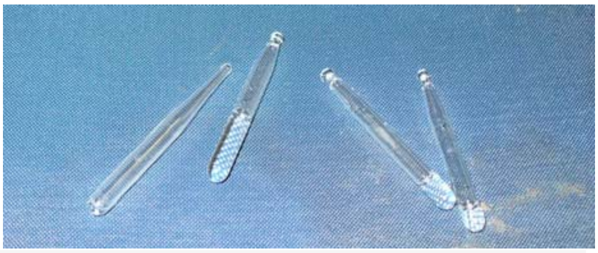

Fig.1. Photos: a) a spherical capsule with a thermocouple; b)cylindrical capsules

To register a flow pattern that occurs when the capsule burst, high-speed video camera GmbH-MotionBLITZ with speed recording of up to 1000 frames per second was used .

To study the mechanism of interaction of DW clouds with flame and more accurate visualization of the boundaries of the expanding cloud of DV used modification of the well-known method of laser sheet - a method of "laser needle." This method was used multiwave length argon laser LG106MS beam with a constant radiation 1W power at a wavelength $\lambda = 0.5145$mkm. Beam diameter was of ~ 1 mm.

Droplet sizes in the expanding cloud DW was measured by laser radiation scattering. Its essence consists in measuring the angular distribution (indicatrix) of the scattered light with subsequent determination of particle size on the tabulated values [11]. The light source used by the above laser. Registration of the angular dependence of the intensity of the scattered radiation was carried out by photomultipliers.

2.PARAMETERS OF STEAM EXPLOSION OF CAPSULES

Fig. 2 shows a typical picture of the scattering DW clouds after vapor explosion of spherical (Fig.2,a) and a cylindrical capsule (Fig.2,b). In the case of a spherical capsule DW cloud has a typical diameter of ~ 10 ÷12 cm; the edge of the cloud is strongly perturbed and the perturbations are irregular and irreproducible nature. With the explosion of a cylindrical capsule a DV cloud has diameter of ~ 30 cm and a height (along the axis of the capsule) ~10 cm, and has a relatively regular and reproducible nature.

In the initial stage of research experiments were performed with a spherical capsules. But later only cylindrical capsule was used.

Figures 3 ÷5 illustrate the typical features of an explosion of cylindrical capsule. Fig.3 shows the water temperature in the capsule of time, measured using a thermocouple. The typical temperature of the explosion of cylindrical capsules varied from ~250 to ~320^{o}C.

The rise time of the intensity of scattered laser light (at the level of 0.1 ÷ 0.9) on the front of the DW cloud was 5 ±1 mks. The average size of water droplets, defined of these measurements on the front of the cloud, was in the range 0.3 ÷ 0.4 mkm.

Fig.4 shows the view of the DW cloud along axis of the capsule. From these shots we see that the cloud takes the shape of a torus. In this case, not only the light diffused by "laser needle" is rendered, but also the secondary scattering of light in the DW cloud, characterizing qualitative the distribution DV in the cloud.

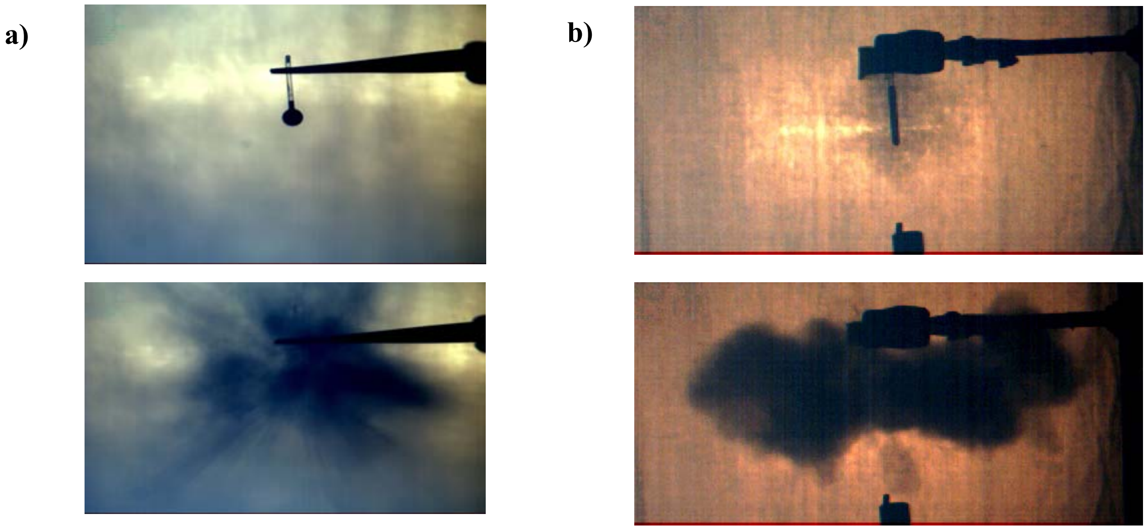

Fig.2. Frames videogram of DW cloud. a)a spherical capsule; b)a cylindrical capsule

Figure 5 shows a typical dependence of the size of the DW cloud: diameter (d) and height (h) of the time. At the initial stage of expansion, the cloud expansion velocity ~ 100 m / s, and in the final stage of ~ 10 m / s. It should be noted that the ratio d/h in the later stages of the expansion of the cloud can vary between 1.5 ÷ 3.

As seen from the video recordings frame, the DW cloud , produced by the explosion of a cylindrical capsule, has a regular reproducible shape compared to the cloud formed by the explosion of a spherical capsule. There is another advantage of the cylindrical capsule. Flames of fire shall heat the capsule before its explosion a few seconds. This condition imposes a restriction on the characteristic size of the capsule. In the case of a spherical capsule, this corresponds to the diameter of 3 ÷ 5 mm [6]. In the case of a cylindrical capsule the restriction is imposed only on the diameter of the capsule, but not for length, which is chosen for practical reasons. Accordingly, the volume of water in a cylindrical capsule may be an order of magnitude or more greater than the volume of water in a spherical capsule. And, therefore, it is necessary less capsules to extinguish the flame of the same size.

Fig.6 shows the known dependence of the saturated water vapor pressure depending on temperature [12]. This dependence, combined with measurements of water temperature at which there is explosion of the capsule, gives information on the scale the pressure achieved in the capsule. the temperature of the water, measured in a number of experiments with cylindrical capsules, indicating that the temperature varies in the range 250 ÷ 320^{o}C. Accordingly, the vapor pressure in the cylindrical capsule is varies in the interval 5 ÷ 10 MPa.

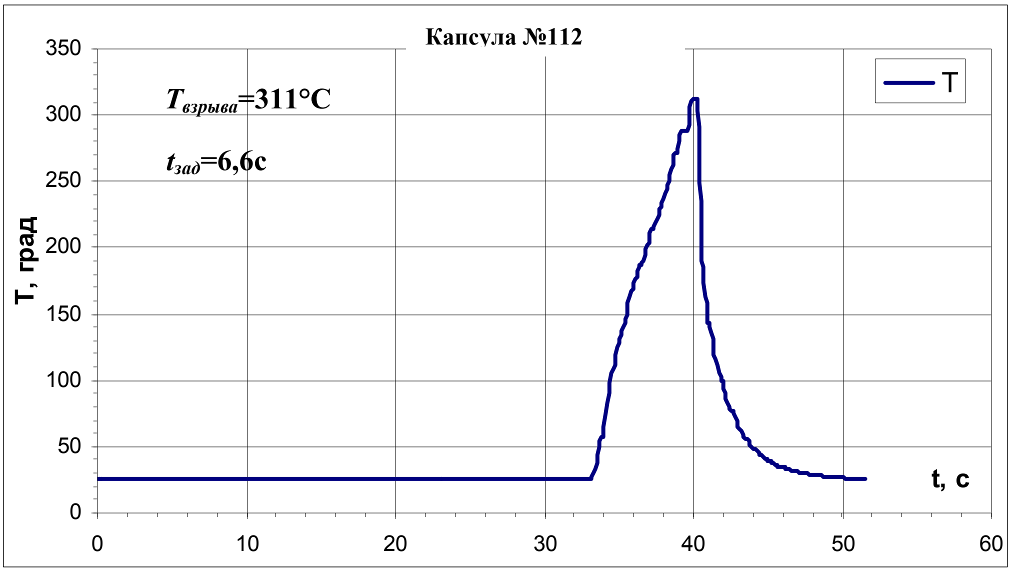

Fig.3. Time dependence of the temperature of the water in a cylindrical capsule (№ 112) in the heating process. Parameters of the capsule: glass C37 – 2, diameter d=4mm, wall thickness 0.2 mm, length 45 mm, the water volume of 0.25 ml (the start of heating matches the beginning of temperature increase).

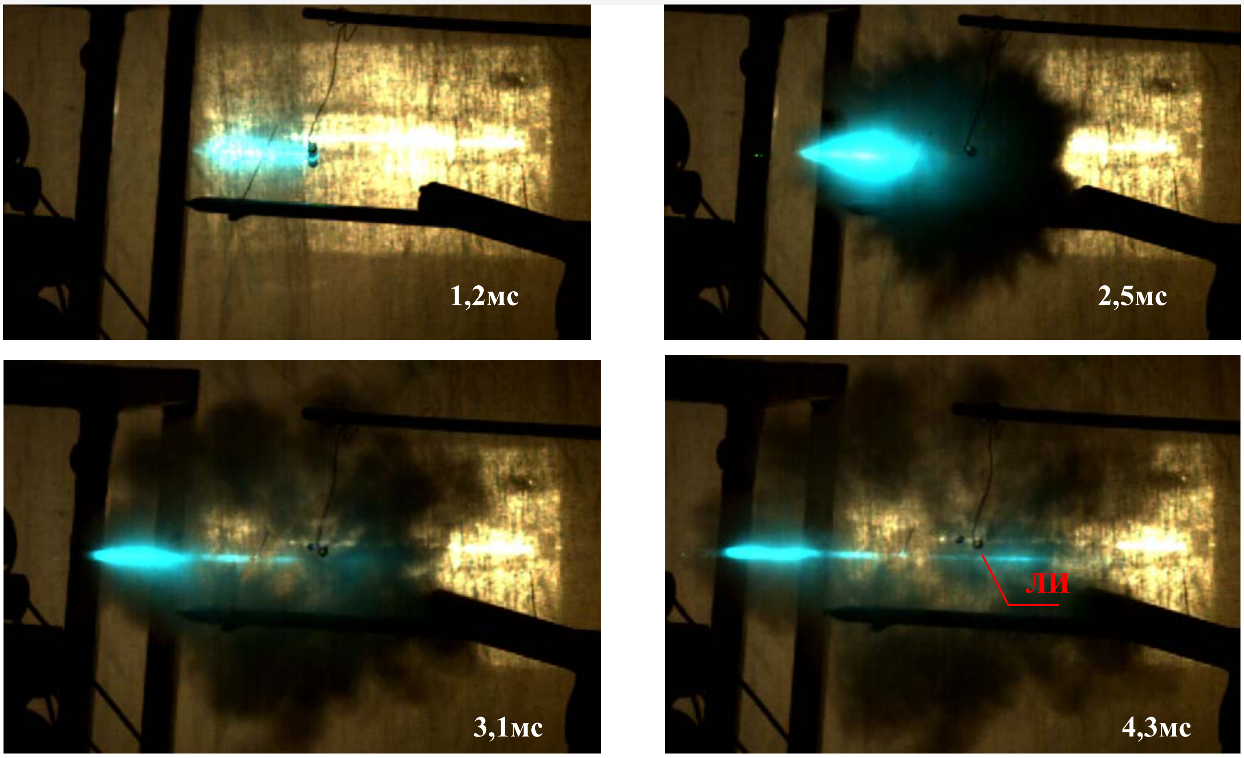

Fig. 4. Filming expansion of the DV cloud formed during the steam explosion of a cylindrical capsule, using laser needles. Survey was conducted in the direction of the capsule. Parameters of the capsule: glass C37 – 2, diameter d=5 mm, wall thickness 0.5 mm, length 45 mm, the water volume of 0.3 ml.

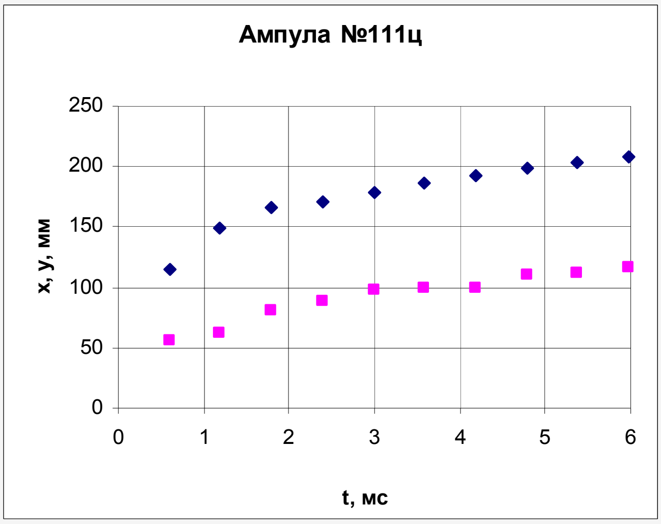

Fig.5. The kinematics of the expansion of DW cloud, formed by the steam explosion of a cylindrical capsule number 111.(• -diameter, ■ – height).

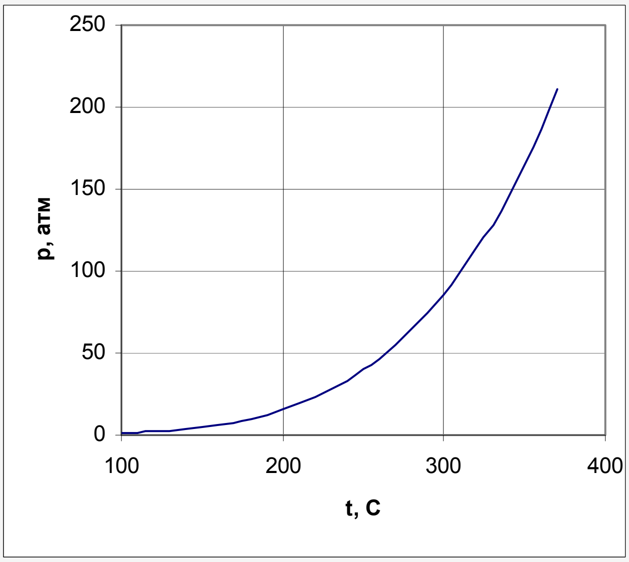

Fig.6. The dependence of the saturated vapor pressure of water depending on temperature [12].

Steam explosion of the glass capsule is accompanied by dispersal of the fragments. From our experiments it follows that the explosion of a cylindrical capsule, together with the DW cloud forms a cloud of flying glass fragments with a characteristic size of ~ 1 ÷ 2 mm and a characteristic mass of ~ 20 ÷ 30 mg. The fragments fly away in the form of a ring whose axis coincides with the axis of the capsule, and have initial velocity of ~ 80 ÷ 90 m/s.

Along with the production of thin-walled capsules with water from a glass, attempts were made to manufacture capsules made of polymeric materials. However, these attempts were unsuccessful. Studies have shown that the polymer film burn through when the water temperature inside the capsule, close to the boiling point. Perhaps this is due to the low thermal conductivity of the film. In the process of water heating on the surface of the film formed by a gas bubble, and the conditions of heat removal from the water film to deteriorate sharply. Therefore, there is a local burning-out of the film.

The use of films with a thin aluminum coating did not significantly change the result. Thus, it was experimentally shown that the polymeric materials used as material for the manufacture of capsules with water, do not provide the opportunity for effective steam explosion.

Tests of samples from aluminum foil showed opportunity to receive overheated liquid and vapor explosion with the destruction of the foil. However, the nature of the destruction of the foil is essentially different from the nature of breakage in glass capsules. The foil breaks into separate large scale pieces. A similar result was obtained when testing cylindrical capsule manufactured from aluminum. These capsules are are not destroyed into small pieces; just the crack is formed along a generatrix of cylindrical body capsule. In this case, reproduced and regular DW cloud can not be formed. Thus, only the unique combination of properties of glass allow to create a thin wall sealed capsule with water to extinguish the flames. On the one hand, it is sufficiently high thermal conductivity, which prevents local burning-through of the capsule wall under the action of the flame. On the other hand, the high brittleness of the glass allows the destruction of the capsule into small fragments, thereby allowing formation of DW clouds of acceptable regular and reproducible forms.

However, it is possible to perform a composite capsule, and the component parts of capsule should be connected by the substance loses its strength at a given temperature steam explosion [13]. One can imagine a capsule made of metal, assembled from two halves, and soldered with solder having a melting point of about 200^{o}C. Upon reaching the melting temperature of the solder body capsule will disintegrate symmetrically into two halves, and thus, the formation of a symmetric regular and reproducible DW clouds will ensure.

In the case of composite capsules from metal to the destruction will be determined by one parameter - the melting point of solder, which they are attached. This value is constant, and that, in principle, allows a high degree of synchronization of the explosion of the ensemble of capsules.

Steam explosion of the capsule is accompanied by sufficiently powerful sound pulse amplitude corresponding to the sound of pistol shots. This makes it possible to develop a simple and very economical way to alert the fire started [14]. Simple devices, such as those described above, capsules can be placed in a potentially flammable locations. At occurrence in these places open flame, such devices will operate for a few seconds after hitting the flames with enough loud sound. In view of simplicity, these devices are not lose efficiency over time. In addition, such devices because of their simplicity, are highly reliable and virtually unlimited service life.

3. INTERACTION DW CLOUD AND FLAME

It has been suggested that a shock wave, that occurs at a steam explosion of the capsule, plays a significant role. The results of experiments carried out using "laser needle" can give an answer to this question. Videogram frames of DW cloud interaction with the flame of the burner are presented in Fig.7.

The burner is an aluminum tube with a diameter of 9 mm with 1 mm diameter holes on the side surface. After steam explosion of capsule a DW cloud is generated. The spread of this cloud is well visualized by laser needle.

It can be seen that quenching of the flame is on the moving front of the DW cloud, and the impact of the shock wave is not observed.

Quenching of the flame column of spiral gas burner by explosion of cylindrical capsule ` is presented on fig.8. The capsule is located on the axis of the the column of flame above the burner. After the explosion of the capsule a DW cloud extinguishes the flame. Experiments show that the quenching of the flame is directly in contact with the flame of the DW cloud . By increasing the diameter of the cylindrical capsule (as compared to that used in our experiments) has also been an increase in the size of the DW cloud. Accordingly, such a device can extinguish flame of large gas fountains, as suggested in [15].

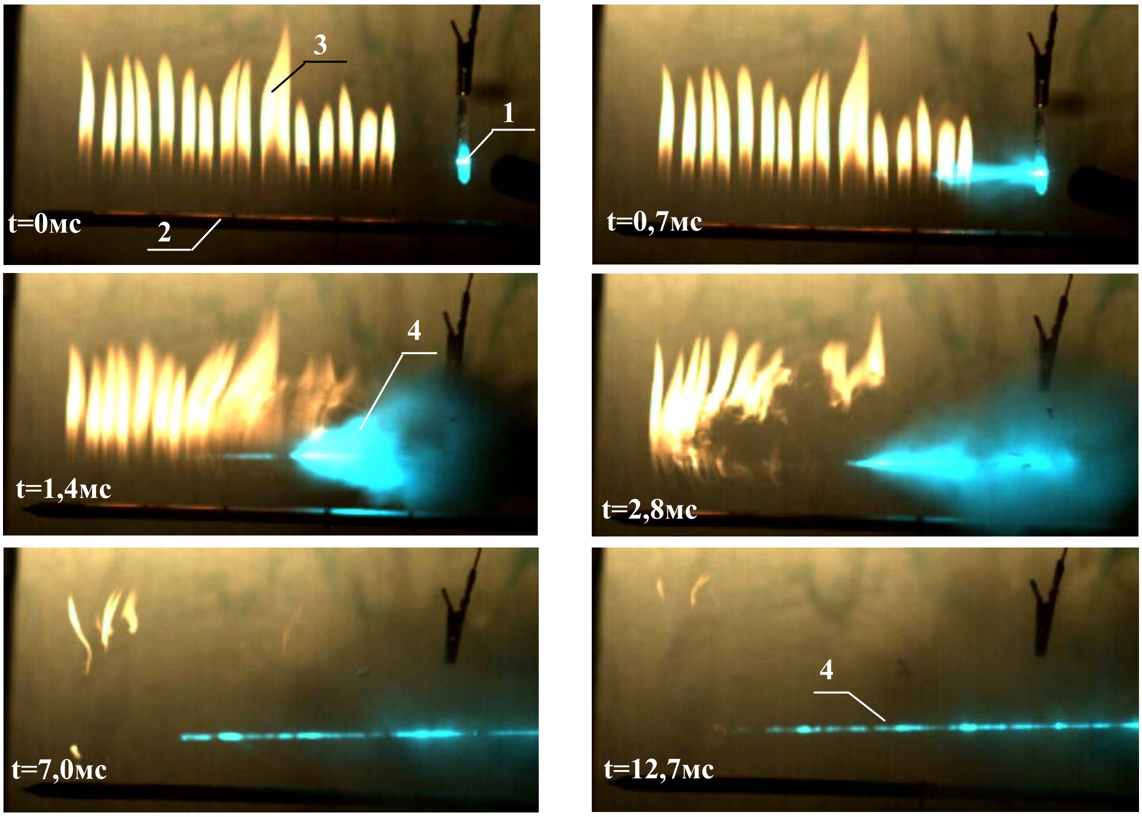

Fig. 7. Extinguishing of the horizontal line gas burner flame with DW cloud of cylindrical glass capsule vapor explosion . Parameters of the capsule: L = 45mm, d = 5 mm, Δ = 0.5 mm. The volume of water in the capsule V = 0.25ml. 1 - capsule with water (heated by a separate burner), 2 - linear gas burner, 3 - burner flame, 4 - "laser needle" light scattered by DW cloud .

Fig8. Quenching the flame of the spiral (diameter ~ 10 cm) gas burner by DW cloud of steam explosion of cylindrical glass capsule (L = 45mm, d = 5 mm, Δ = 0.5 mm, V= 0.25ml), placed in a burner flame. 1 – spiral burner, 2 - burner flame, 3 - DW cloud, formed by the explosion of the capsule.

Figure 9 shows an example of the interaction of DW cloud with another type of flame - burning wick placed in a metal cell with kerosene. As can be seen from this figure, the DW cloud effectively extinguishes this kind of flame.

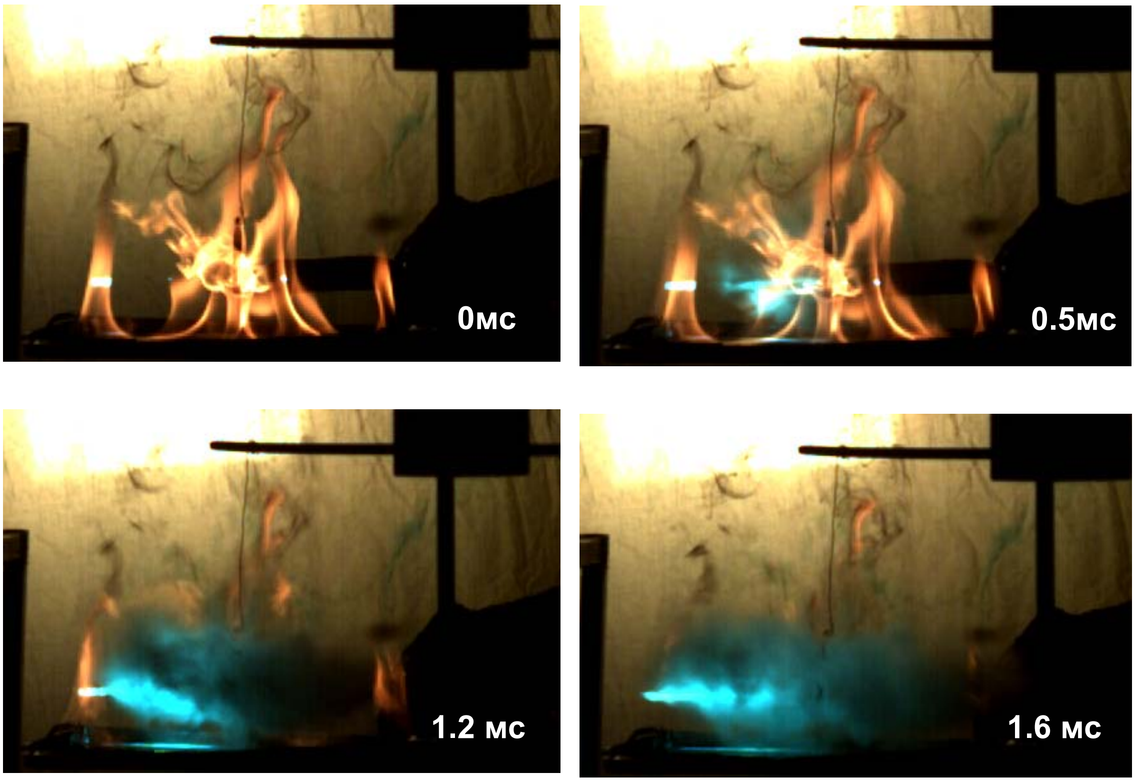

Fig. 9. Quenching the flame of a flat wick soaked with kerosene by DW cloud formed in the steam explosion of a cylindrical glass capsule 45 mm long, placed over the flame.

The experimental results are in agreement with the results of one-dimensional calculations which are were performed with a previously formulated model [4], based on the theory of multiphase heterogeneous environments, just as was done in [4]. Steam explosion of the capsule with water was simulated by specifying the initial conditions in the discontinuity that separates the region of the compressed vapor and droplets in the capsule and the surrounding air. Drops of DW during the calculation considered monodisperse. The area of the flame was imitated by hot gas (combustion products) with an initial temperature of approximately equal to the maximum flame temperature.

The results of the calculations show that for DW droplets of diameter 1mkm (approximately corresponding to that measured in experiments) flame quenching occurs in a narrow zone of contact between the droplets cloud and the flame (the expanding DW cloud just licks flame), in qualitative agreement with experimental results. This confirms the conclusion about the mechanism of thermal quenching of the flame from the explosion of the capsule with water.

Note also that the observed quenching of the surface mode is typical for the interaction a relatively small droplets (~1 mkm in size) with the flame. According to the calculations [4] for DW clouds with larger drops (~ 100mkm)] suppression has a volume character

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