An experimental study of ignition of gaseous mixtures with mechanical sparks

A.Yu. Shebeko*, Yu.N. Shebeko, A.V. Zuban, N.V. Golov
All Russian Scientific Research Institute for Fire Protection
VNIIPO 12, Balashiha – 3, Moscow Region, 143903, Rassia
*Corresponding author email: ay_shebeko@mail.ru

ABSTRACT

This article describes a method for testing the safety of construction materials with respect to mechanical sparks (spark safety). This method was tested on examples of various materials and flammable gases. Hydrogen, acetylene, petrol, methane and LPG were used as the flammable gases. Various types of steel, aluminium, and copper and aluminium alloys were used as the construction materials. On the basis of the experiment a criterion for spark safety was proposed.

Key words: mechanical sparks; flammable gaseous mixtures; construction materials

1. Introduction

It is well known that particles formed as a result of a counteraction of moving surfaces can be heated to high temperatures depending on the sizes of these particles and the composition of the gaseous environment. These temperatures can be so high that they radiate in the visible part of spectrum. Such particles are called mechanical sparks and can be produced as a result of friction or the striking of moving bodies. Mechanical sparks are one of the most frequent ignition sources for flammable gaseous mixtures.

A series of normative documents contain requirements for the application of spark safety materials in cases where flammable gaseous mixtures can be produced, owing to accidents [1-4]. However, the normative documents determining a testing procedure for a determination of the spark safety of the construction materials are not complete. For example, documents [1,2] only contains common regulations for spark safety. The standards [3,4] contain method for testing of materials on spark safety in the case of friction or collision separately. But in practice at malfunctions of equipment both friction and collisions can take place quite simultaneously, and no method for testing was proposed for this case. There is a recommendation [5] which was used successfully for more than 10 years for the determination of the spark safety of construction materials. This study is aimed at an improvement of the method [5].

2. Background

An analysis of earlier works on investigations into ignition capability of sparks obtained from collisions and/or friction was published in [6,7]. Now we will consider more modern studies.

An experimental investigation of the ignition capabilities of mechanical sparks was performed [8]. It was found that the mechanical sparks in 30–50% of accidents were the cause of industrial fires and explosions, and this peculiarity does not change over time. This situation is also caused by the knowledge of such an ignition source. Therefore, in [8], mechanisms of dissipation of mechanical energy into heat at collisions and frictions, as well as probable mechanisms of ignition of gaseous mixtures with mechanical sparks, are considered.

In the experiments in [8] a set-up with a rotating wheel of a diameter 10 or 30 cm was used. The wheel was in contact with a horizontal plate of sizes 7×7 or 25×25 mm. Linear velocity of a part of the wheel contacting the plate was in the range of 0.2–20 m/s, with a load 5000 N. The temperature of the plate was measured by means of thermocouples and an infrared pyrometer. The wheel was made of tempered steel. The plate was made of tempered or non-tempered steel, aluminium and its alloys, quartz. According to estimations of the authors [8], the pressure in the zone of a contact was several MPa.

It was found that hot solid particles produced by friction had a typical size of several hundred microns. The temperature of the horizontal plate at the power of 4 kW was up to 1000 $^{\circ}$C for the wheel of diameter 30 cm, and 500 $^{\circ}$C for the wheel of diameter 10 cm. According to the estimations [8], nearly 80% of the energy released by friction was dissipated via thermal conductivity. The heated particles (mechanical sparks) had a mass in the range of 0.07 to 7.5 g, depending on conditions of friction and the type of materials. The frequency of particle formation was near several tens per second. Approximately 1% of the released energy was spent on particle formation.

For an investigation of the mechanical sparks produced as a result of collisions an experimental set-up with a target in the form of a steel plate of size 5×70×45 cm was used, and the investigated body collided with this target. The target was inclined at an angle of 60°, in order to produce optimal conditions for spark formation. The velocity of collisions was in the range of 5–50 m/s. The collision was registered by means of video camera. A colliding body was a cylinder of diameter 18 mm and length 5 and 20 cm, made of steel, copper and aluminium.

It was found that the temperature in the place of a collision can reach 600–700 $^{\circ}$C, and then drops substantially after 2–3 ms. Typical pressures in the place of the collision can reach several hundred MPa; that is, this pressure is twice the order of magnitude than pressures from friction. As a rule one particle of 2–4 min in size is formed, which moves with a velocity close to the velocity of the collision. The temperature at the place of the collision does not depend on the cylinder length and is determined mostly by the collision velocity.

An ignition resulting from friction and/or collision can be realized as a result of three mechanisms:

a) ignition by a hot surface in place of friction and/or collision;
b) ignition owing to the heating of a flammable gaseous mixture in a confined space, as a result of heat released by friction and/or collision;
c) ignition caused by mechanical sparks produced by friction and/or collision.

It was found that mechanism a) is the main one.

On the basis of the experiments, the authors [8] made the following conclusions. In the case of friction, ignition always occurs quite near the surface heated by the friction. The ignition temperature does not correlate to the standard auto-ignition temperature. The power released by the friction is usually several per cent of the total power. In order to obtain a high enough temperature for ignition a time interval of not less than several seconds is usually required. Maximum temperature in the friction zone depends strongly on the power released, owing to the friction.

In the case of a collision, ignition takes place by means of a hot surface. The possibility of ignition is determined not by the kinetic energy of the collision, but by relative velocity.

The particles produced as a result of friction and/or collision have a low capability of igniting the flammable gaseous mixtures in comparison with the hot surface. The temperature of this surface is the most important parameter.

The ignition of methane–air mixtures by mechanical sparks produced by light metals and alloys was investigated in [9]. It was found that the ignition from friction is caused by a hot surface and mechanical sparks (hot fine particles). Ignition is more probable from the friction of bodies made of light alloys and the surface of rusty steel. Experiments have been carried out in which the mechanical sparks were produced from the free-falling of the tested specimen on to the surface of rusty steel. Four specimens were tested (Table 1).

The specimen had a length of 50 and a diameter of 60 mm. The energy of collisions was regulated by the mass of the specimen and its height over a target. The target was a plate made of rusty steel, with horizontal sizes 400×160 mm and a thickness of 12 mm. The specimen and the plate were located in a chamber of volume 1 m^3. Maximum height from the specimen and the plate was 4 m. The specimen fell on to the plate at an angle of 45°. The chamber was filled with a methane–air mixture of the required composition.

The probability of the ignition's dependence on the a height of the fall of the specimen, of mass 14 kg, for various mixture compositions, was measured. The most easily ignitable mixtures contained 6.5–7% methane in air. A probable reason for this peculiarity is the reaction of oxygen for the oxidation of the particles. For a 4 m height and the optimum methane concentration, the probability of ignition is close to 90 %. For 3 and 2 m heights this probability is equal to 60 and 25%, respectively. The ignition probability depends on the roughness of the surface and the mass of the specimen. If this mass is lower than 5 kg and the height is lower than 4 m no ignition takes place. The authors concluded that the ignition probability is not determined by the mass of the specimen and its height separately, but by the potential energy of the specimen.

On the basis of the investigations in [9], the following conclusions can be made:

1) collisions of specimens made of light alloys and steel have a high ignition capability, owing to the formation of a hot surface heated additionally by the exothermic reaction of the light alloys with rusty steel.
2) the height of the fall of the specimens is one of the most important parameters determining the ignition capability.
3) collision energy, which results in an ignition probability of 50%, can be used for the evaluation of the ignition capability.
4) the availability of Mg in light alloys substantially increases the ignition capability.

The investigation [10], aimed at the exploration of the influence of a footwear material and the material of a floor on the ignition capability of gases and vapours by mechanical sparks. A hot surface and mechanical sparks are produced. These mechanical sparks in a process of their movement can be additionally heated, owing to a reaction with air. Lean gaseous mixtures have a higher ignition capability. Mechanical sparks with a high ignition capability usually occur in the case of light metals (alloys of cerium, aluminium, magnesium, titanium) and sometimes in the case of heavy metals (hafnium, zirconium).

At present there is no systematic classification of flammable gases and vapours on their ignition capability by mechanical sparks. The classification connected with explosion-proof electrical equipment can be only used very approximately.

Experiments were carried out to model the ignition of gaseous mixtures of methane–air (7% CH_4) with mechanical sparks from the collision of footwear with a flooring material. The typical velocity of the sliding collision was 7.6 m/s. The experiments were performed with specimens made of steel and tungsten carbide. Nearly 500 collisions were made with the velocity 9.4 m/s, and 500 collisions with the velocity 6.4 m/s. Nearly 33% of the collision energy was dissipated into heat. It was found that quartz as a flooring material has a much greater ignition probability than metals.

A high ignition probability in the case of light alloys is due to the reaction of the light metals with rusted steel. Metals with low boiling points are quite safe from the viewpoint of the ignition of gaseous mixtures. The most hazardous are materials which produce hot particles at collisions (titanium, cerium, hafnium, zirconium). Less hazardous is magnesium, owing to its reactions with rusty steel and aluminium. Methane–air mixtures are not ignited by the collisions of steel specimens (even rusted), so the probability of ignition is lower than 0.02. The ignition probability of ethylene–air mixtures is much higher. If steel surfaces collide with construction materials the probability of the ignition of the methane–air mixtures is low, but ignition is possible for C_3H_8–air and C_2H_4–air mixtures.

The ignition of gaseous mixtures by mechanical sparks produced by collisions with an energy of up to 240 J was studied in [11]. The possibility of the ignition of propane–air mixtures was detected. A mixture of petrol vapour and air was ignited at the collision of two specimens made of high-carbonized steel with an energy of 177 J. For a hydrogen–air mixture an energy of only 3.4 J is sufficient for the ignition. Collisions of specimens made of alloys of aluminium with Cu and Be, Ni with Cu and Si with rusty steel cause the ignition of hydrogen–air mixtures.

A method for testing the capability of high alloys to ignite gaseous mixtures by friction was described in [12]. The essence of the method is as follows. The tested specimen fell from an appropriate height on to a rusty steel plate inclined at 50° in a horizontal direction. The flammable gas was a methane–air mixture with a CH_4 content of 7.5%. The surface of the plate was covered with a thin water film. The size of a track on the water film after the specimen fall was measured. If the mixture in the chamber did not ignite, an area of the track was measured. If no ignition took place and the area was lower than 25 mm^2 the material of the specimen was considered spark-safe. If the area exceeded 25 mm^2 a rusted steel specimen fell on the plate. If no ignition took place the tested alloy was considered spark-safe.

The method analogous to the set-up with a rotating disc is described [5, 13].

The ignition of gaseous mixtures by friction and collisions of various materials was studied in [14,15]. It was found [14] that frictional processes caused by malfunctions may lead to hot surfaces and mechanical sparks which can be ignition sources for gaseous mixtures. To assess the formation of hot surfaces, tests for temperature development at contacts of different materials were performed in a friction apparatus. The experimental setup was realised via a friction pin which is pressed onto a rotating friction disk. The variation of the power density was carried out by changing the velocity and load per area. Tests have been carried out with hydrogen, ethylene, diethyl ether, propane and pentane. The experiments have shown that a larger thermal conductivity of the steel used can lead to slow down heating of the pin material. The result was a graduation of the explosion limits analogous to the order of maximum experimental safe gap values. No significant relationship between the ignition limits and the temperature class of the respective substances was revealed.

The ignition probability of gaseous mixtures of acetylene, hydrogen and ethylene with air due to mechanical impacts between stainless steel components was studied for various impact energies [15]. The influence of the chromium content on the ignition probability was investigated. It was found that impact energies below 126 J resulted in ignition of the gaseous mixture at the hot surface of the pin or the plate in most cases. At higher energies< initiation of ignition due to abraded particles was more probable when using stainless steel components with lower chromium content. But the source of ignition was almost exclusively limited to the hot surfaces of pin and plate for the steel with the highest chromium content.

On the basis of the presented analysis a conclusion can be made that the universal method for testing materials on spark safety is not described in the literature. The mechanisms of the ignition due to friction and/or collisions are also not fully investigated. Therefore, this study aims to create a method for testing materials for spark safety in the case of simultaneous friction and collisions and to obtain new experimental data in this area.

3. Experimental

From the presented analysis it is clear that for the evaluation of a mechanical spark hazard we should take into account not only the energy of collisions but also the velocity and mass of a specimen. Mechanical sparks from collisions are produced at velocities of 10–16 m/s and higher, and in the case of a rotating disc at velocities of 10–20 m/s. Both friction and collisions should take place. This principle was chosen as the base for the creation of an experimental set-up in this study. A diagram of the set-up is shown in Fig.1.

The set-up has a reaction chamber of a cylindrical form (1), of internal diameter 380 and height 800 mm (volume near 90 dm^3). The chamber is closed and has in the top a round window of diameter 160 mm, closed by a glass plate (2). A tight contact of the testing specimen (3) with the rotating disc (6) is reached by means of mechanisms (4) and (5). The rotating disc is moved by means of an electrical motor (7), with the aid of mechanism (8). Gaseous mixture is produced immediately in the reaction chamber by partial pressures, using a vacuometer (11). Before each experiment the chamber was evacuated with a vacuum pump (10). Ignition was detected with a manometer (9) and a pressure transducer connected to a computer. If no ignition was obtained during the experiment the mixture was ignited by a fused nichrome wire of a diameter 0.3 mm and a length 4 mm at a supply of an electric voltage 42 V on it from a transformer (13).

At first the experiments were carried out with a circular rotating disc, but no ignitions were detected in this case, even for hydrogen. Therefore, in the second stage of the experiments, the four segments were removed, and collisions became possible together with friction. In this case, the ignition of the flammable gaseous mixtures became possible.

The specimen of the tested material was in the form of a plate of size 140×25×7 mm. The mass of the specimen was near 300 g. The rotating disc had a diameter of 100 mm and a thickness 10 mm. The segments with a base of 40 mm were removed from four sides of the disc (Fig.2). This measure gives a possibility to combine friction and collision, and this is the main difference between the proposed method and other methods. The mass of the disc was 630 g. An angular velocity of rotation was up to 11000 sec^{-1}. This angular velocity gives a collision velocity of up to 55 m/s.

The experiments were carried out on the following way. The testing specimen and the rotating disc (the testing couple) were located in the reaction chamber applying a 20 N force for the pressing of the disc and the plate. The top cover of the chamber was closed, and the chamber was evacuated till the residual pressure was no higher than 0.5 kPa. The flammable mixture was created by partial pressures in the reaction chamber. The electric motor was turned on and the time for the mixture ignition t_{ign} was registered visually by a high-speed camera and by the manometer. If the mixture did not ignite during a time of 1 min, the mixture was initiated with the fused nichrome wire. The result of such experiment was considered to be an absence of ignition by mechanical sparks. For each composition of flammable mixture the experiment was repeated 2–5 times, and an average time of an ignition delay t_d was determined. A number of collisions per second N was calculated by a formula:

$$N = 2nk, \quad (1)$$

where n is an angular velocity of the rotation, s^{-1}, and k is the number of segments in the rotating disc (k=4). The probability of ignition for the given couple of specimens P is calculated by the formula:

$$P = 1/(t_{ign}N). \quad (2)$$

Fig.3 shows the typical dependence of the angular velocity of the disc rotation on a mass of a body providing the pressing of the specimens. At a mass of 2000 g the angular velocity was near 7000 s^{-1}. This mass was used in our experiments.

4. Results and discussion

The results of the experiments are presented in Table 2. The most interesting data are shown in Figs. 4 and 5.

As observed from Table 2, only the mixtures of hydrogen and acetylene with air were ignited, and the mixtures of methane, petrol, liquefied petroleum gas (LPG) with air were not ignited with materials investigated in this work. A qualitative explanation of these results can be done on the basis of the peculiarities of the ignition of the gaseous mixtures mentioned in this study from the previous experimental work. As was mentioned [8, 9], for our configuration of the tested specimens the main parameter for determining the possibility of ignition is the temperature of the specimen's surface. This temperature depends on the kind of material, the size and form of the specimen, velocity of a collision and the force of the pressing of the specimens.

In [16] it was shown that for the ignition of gaseous mixtures it is necessary to create a volume of hot gases, whose size is close to the thickness of a laminar flame front δ. The temperature of these hot gases should be not lower than the adiabatic flame temperature. The value of δ is inversely proportional to the laminar burning velocity S_u ($\delta \sim 1/S_u$); that is, the higher the laminar burning velocity S_u, the lower the δ value critical for ignition (the ignition occurs more easily). The laminar burning velocities of hydrogen and acetylene are sufficiently higher than those of methane, petrol and LPG [17]. This fact explains the possibility of the ignition of hydrogen and acetylene, and the absence of ignition for the other gases investigated. The ignition capability does not correlate with the standard auto-ignition temperature, which is lowest for petrol among the studied gases (the absence of ignition in the case of petrol) and highest for hydrogen (the highest ignition probability) [17]. This result coincides qualitatively with the conclusions of [8,14]. Some data characterizing the relationship between the ignition probability and the fire hazard indexes are presented in Table 3.

In Table 2 and Figs. 4 and 5 the ignition probabilities are presented for the mixtures investigated, which were calculated by means of formula (2). For the cases where ignition was not detected, the presented probabilities are upper estimations, taking the value t_{ev} to be equal to the total time of the testing in all tests (that is in 2–5 experiments). If in some experimental series both ignitions and non-ignitions occurred, then for the calculations of t_{ev} the value 60 s (that is a time of one test) was taken into account for each case of non-ignition. As follows from the data for hydrogen, the maximum ignition probability is observed for lean mixtures containing 11–12% H_2 (Fig. 4). This result coincides with the data in [8, 10]. As it mentioned in [9], this fact is due to a consumption of oxygen by oxidizing hot solid surfaces.

Interesting data were obtained for acetylene (Fig. 5). There is a local minimum in the dependence of the ignition probability on the fuel concentration at $[C_2H_2]$ = 7.5%, and a local maximum at $[C_2H_2]$ = 10–12% (this value corresponds to not lean but reach mixtures). This is a difference with other gases. This peculiarity is probably a result of the tendency of acetylene–air mixture to form soot and to the kinetics of this process, which differ substantially from the kinetics of combustion of the hydrocarbons studied in this work.

An influence of the type of material on the ignition probability by mechanical sparks is shown on the basis of hydrogen (Table 2). It can be seen that the ignition of hydrogen–air mixtures does not occur if one of the two colliding materials has a higher thermal conductivity in comparison with steel (aluminium, bronze). In this case, the thermal energy released due to friction and/or collision is dissipated very quickly across the volume of the specimen, and it is difficult to reach the surface temperature required for ignition. However, for stainless steel the situation is unclear.

As mentioned above, the ignition capability of the mechanical spark produced by the friction and/or collisions does not correlate with the standard auto-ignition temperature of gases and vapours. The ignition in most cases is a result of the heating of the solid surface as a result of friction and/or collisions. Therefore, the ignition probability is determined by the possibility of the heating of the flammable gaseous mixture with a volume close to the thickness of the laminar flame front, up to the adiabatic flame temperature. Qualitatively the same effect takes place at the ignition of flammable gaseous mixture with an electrical spark [16]. Therefore, we can speak about the correlation between the ignition capability of mechanical sparks and the minimum ignition energy.

It follows from our investigations that the spark safety of any material is connected with the other material participating in the friction and/or collision, and also with what flammable mixture is being considered. The minimum ignition energy can be considered as a reference parameter; that is, if the pair of materials is safe in relation to certain gaseous mixtures with a given minimum ignition energy, then this pair of materials will be safe for other gaseous mixtures with a higher minimum ignition energy.

Another important question is the determination of the value of the ignition probability, which distinguishes the spark safety and unsafe spark materials. According to [5] this value is accepted to be equal to 10^{-5}. The results of this study confirm this choice. But there is a question: if the value of the ignition probability does not exceed 10^{-5}, are these materials absolutely spark-safe in these cases for the given gaseous mixture? It is clear that energetic parameters of the set-up are restricted, and in practice, friction and/or collisions with higher energies are possible. This fact should be taken into account for the practical application of the proposed method.

5. Conclusions

In this study a method for testing materials for spark safety in the case of friction and/or collisions is proposed. This method was used for various pairs of materials and various gaseous mixtures. It was found that it was possible to ignite hydrogen–air and acetylene–air mixtures, but no ignitions were detected in the case of mixtures of methane, petrol and LPG with air. Lean mixtures were found to be the most ignitable (for hydrogen the optimum H_2 concentration was 11–12%). A conclusion was made that spark safety should be determined only for a given pair of materials and a given gaseous mixture; that is, spark safety cannot be considered as a universal fire hazard index.

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Figure captions

Fig.1. Diagram of the experimental set-up. 1. experimental chamber; 2. upper cover; 3. testing specimen; 4. specimen holder; 5. clamping mechanism; 6. rotating disc; 7. electrical motor; 8. transfer mechanism; 9. manometer; 10. vacuum pumping; 11. vacuumeter; 12. electrodes; 13. transformer; 14. cylinder with a flammable gas.

Fig.2 Diagram of the rotating disk.

Fig.3. Dependence of angular velocity on the mass of the body pressing the specimens.

Fig.4. Dependence of the ignition probability of hydrogen–air mixtures by mechanical sparks on a hydrogen concentration at collisions of the specimens made of steel, with a low content of carbon and steel, and with a high carbon concentration treated thermally.

Fig.5. Dependence of the ignition probability of acetylene–air mixtures on the acetylene concentration at collisions of the specimens made of steel with a low carbon content.

Tables

Table 1. Compositions of specimens made of light alloys

№	Chemical compositions of the specimens, %										Type
	Si	Fe	Cu	Mn	Zn	Ni	Ti	Cr	Mg	Al	
1	11.5	0.9	0.3	0.4	0.3	0.1	0.2	0.2	0.2	the rest	Al-Si
2	0.4	0.5	1.6	0.3	5.5	-	0.2	0.2	2.5	the rest	Al-Mg-Zn
3	0.2	0.3	0.1	0.6	0.2	0.2	0.2	0.2	4.5	the rest	Al-Mg
4	0.3	-	0.3	0.2	1.0	-	-	-	the rest	3.0	Mg

Table 2. Experimental data for testing various materials for spark safety

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	2	3	4	5	6	7	8
1	Steel with a low carbon content	Steel with a high carbon content treated thermally	Hydrogen	9.0	+	9.0	$1.8 \cdot 10^{-4}$
					+	8.0	
					-	2 times	
				10.0	+	4.5	$7.7 \cdot 10^{-4}$
					+	2.5	
					+	3.0	
					+	3.0	
					+	2.0	

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	2	3	4	5	6	7	8
					+	2.0	
					+	1.0	
				11.0	+	4.5	$11.5 \cdot 10^{-4}$
					+	3.5	
					+	1.5	
					+	1.2	
					+	1.8	
				12.0	+	2.0	$11.6 \cdot 10^{-4}$
					+	2.0	
					+	3.0	
					+	3.0	
					+	3.5	
				13.0	+	3.5	$7.4 \cdot 10^{-4}$
					+	3.0	
					+	2.0	
					+	6.0	
					+	4.0	
				13.5	+	3.0	$5.6 \cdot 10^{-4}$
					+	7.0	
					+	2.5	

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
				14.0	- + + + +	1 time 10.0 7.0 6.0 7.0	$2.5\cdot10^{-4}$
				15.0	+ + + + +	6.0 10.0 9.0 6.0 4.0	$3.4\cdot10^{-5}$
2	Steel with a low carbon content	Steel with a high carbon content treated thermally	Methane	6.0	-	5 times	$<0.7\cdot10^{-5}$
				7.0	-	5 times	$<0.7\cdot10^{-5}$
				8.0	-	5 times	$<0.7\cdot10^{-5}$
3	Steel with a low carbon content	Steel with a high carbon content treated thermally	Petrol	1.0	-	5 times	$<0.7\cdot10^{-5}$
				2.0	-	5 times	$<0.7\cdot10^{-5}$
				3.0	-	5 times	$<0.7\cdot10^{-5}$

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
4	Steel with a low carbon content with corrosion	Aluminium	Hydrogen	10.0	-	5 times	$<0.7\cdot10^{-5}$
				12.0	-	5 times	$<0.7\cdot10^{-5}$
				14.0	-	5 times	$<0.7\cdot10^{-5}$
5	Steel with a low carbon content with corrosion	Aluminium	Methane	6.0	-	5 times	$<0.7\cdot10^{-5}$
				7.0	-	5 times	$<0.7\cdot10^{-5}$
				8.0	-	5 times	$<0.7\cdot10^{-5}$
6	Steel with a low carbon content with corrosion	Aluminium	Petrol	1.0	-	5 times	$<0.7\cdot10^{-5}$
				2.0	-	5 times	$<0.7\cdot10^{-5}$
				3.0	-	5 times	$<0.7\cdot10^{-5}$
7	Steel with additives of chromium	Steel with a high carbon content treated thermally	Methane	6.0	-	5 times	$<0.7\cdot10^{-5}$
				7.0	-	5 times	$<0.7\cdot10^{-5}$
				8.0	-	5 times	$<0.7\cdot10^{-5}$
8	Steel with additives of	Steel with a high carbon content	Petrol	1.0	-	5 times	$<0.7\cdot10^{-5}$
				2.0			$<0.7\cdot10^{-5}$

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	2	3	4	5	6	7	8
	chromium	treated thermally		3.0	-	5 times	$<0.7\cdot10^{-5}$
9	Steel with a low carbon content	Stainless steel	Hydrogen	10.0	-	5 times	$<0.7\cdot10^{-5}$
				12.0	-	5 times	$<0.7\cdot10^{-5}$
				14.0	-	5 times	$<0.7\cdot10^{-5}$
10	Steel with a low carbon content	Stainless steel	Methane	6.0	-	5 times	$<0.7\cdot10^{-5}$
				7.0	-	5 times	$<0.7\cdot10^{-5}$
				8.0	-	5 times	$<0.7\cdot10^{-5}$
11	Steel with a low carbon content	Stainless steel	Petrol	1.0	-	5 times	$<0.7\cdot10^{-5}$
				2.0	-	5 times	$<0.7\cdot10^{-5}$
				3.0	-	5 times	$<0.7\cdot10^{-5}$
12	Aluminium	Aluminium	Hydrogen	12.0	-	3 times	$<1.2\cdot10^{-5}$
				15.0	-	3 times	$<1.2\cdot10^{-5}$
				18.0	-	3 times	$<1.2\cdot10^{-5}$
				21.0	-	2 times	$<1.8\cdot10^{-5}$
				24.0	-	2 times	$<1.8\cdot10^{-5}$
				27.0		2 times	$<1.8\cdot10^{-5}$
				30.0	-	2 times	$<1.8\cdot10^{-5}$
13	Aluminium	Aluminium	LPG	3.0	-	3 times	$<1.2\cdot10^{-5}$

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	2	3	4	5	6	7	8
				5.0	-	3 times	$<1.2\cdot10^{-5}$
				7.0	-	3 times	$<1.2\cdot10^{-5}$
14	Bronze	Bronze	Hydrogen	15.0	-	3 times	$<1.2\cdot10^{-5}$
				18.0	-	3 times	$<1.2\cdot10^{-5}$
					-		
15	Bronze	Bronze	LPG	3.0	-	2 times	$<1.8\cdot10^{-5}$
				5.0	-	2 times	$<1.8\cdot10^{-5}$
				7.0	-	2 times	$<1.8\cdot10^{-5}$
16	Steel with a low carbon content with corrosion	Steel with a low carbon content	Hydrogen	8.0	+	2.0	$10.7\cdot10^{-4}$
					+	2.0	
				10.0	+	2.0	$16.5\cdot10^{-4}$
					+	1.0	
				12.0	+	2.0	$5.5\cdot10^{-4}$
					+	11.0	
					+	10.0	
					+	3.0	

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	2	3	4	5	6	7	8
				15.0	+ + + +	2.0 57.0 48.0 4.0	$6.1 \cdot 10^{-4}$
				18.0	-	2 times	$<1.8 \cdot 10^{-4}$
				24.0	-	2 times	$<1.8 \cdot 10^{-4}$
				30.0	-	2 times	$<1.8 \cdot 10^{-4}$
17	Steel with a low carbon content	Steel with a low carbon content	Acetylene	5.0	+ +	2.0 3.0	$8.9 \cdot 10^{-4}$
				7.5	+ + + + + +	2.0 15.0 49.0 12.0 21.0 7.0	$3.7 \cdot 10^{-4}$
				10.0	+ +	1.0 6.0	$12.5 \cdot 10^{-4}$
				12.5	+ +	4.0 2.0	$8.1 \cdot 10^{-4}$
				15.0	+	2.5	$7.9 \cdot 10^{-4}$

N	Material 1	Material 2	Flammable gas	Concentration of flammable gas. %	Availability of the ignition	Time delay till the ignition. s	Ignition probability
1	2	3	4	5	6	7	8
					+	3.0	
				20.0	-	2 times	$<1.8 \cdot 10^{-5}$
18	Steel with a low carbon content	Steel with a low carbon content	Acetylene	5.0	+ + + +	9.0 3.0 2.0 2.0	$7.8 \cdot 10^{-4}$
				7.5	+ +	3.5 3.0	$6.6 \cdot 10^{-4}$
				10.0	+ +	2.0 3.0	$8.9 \cdot 10^{-4}$
				12.5	+ +	1.0 1.0	$21.4 \cdot 10^{-4}$
				15.0	+ +	2.5 2.0	$16.1 \cdot 10^{-4}$

Figures

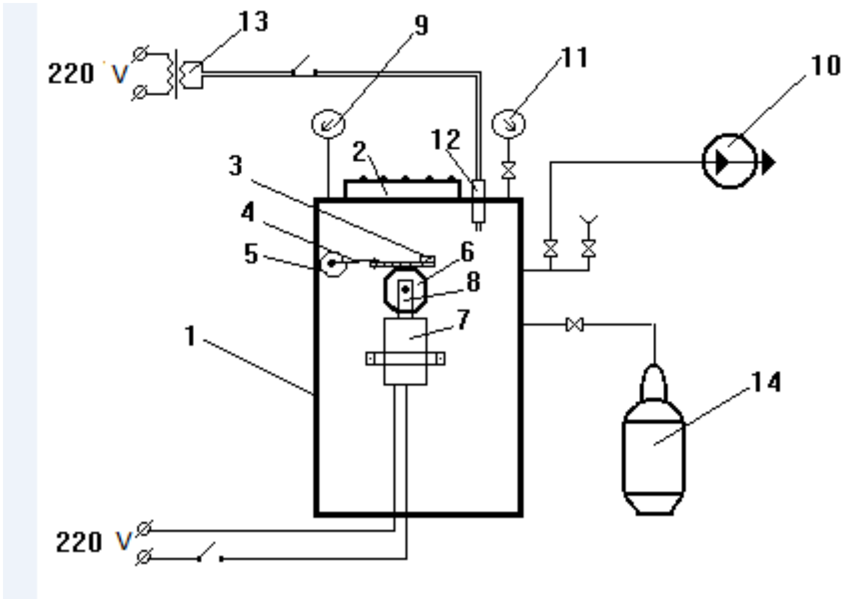

Fig 1.

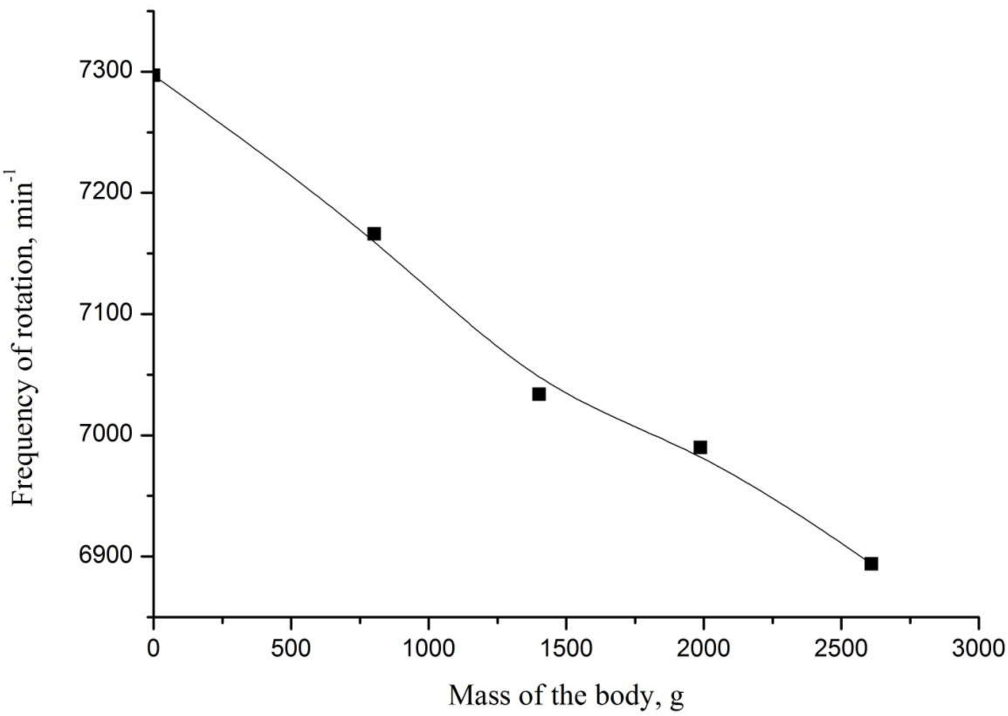

Fig. 3

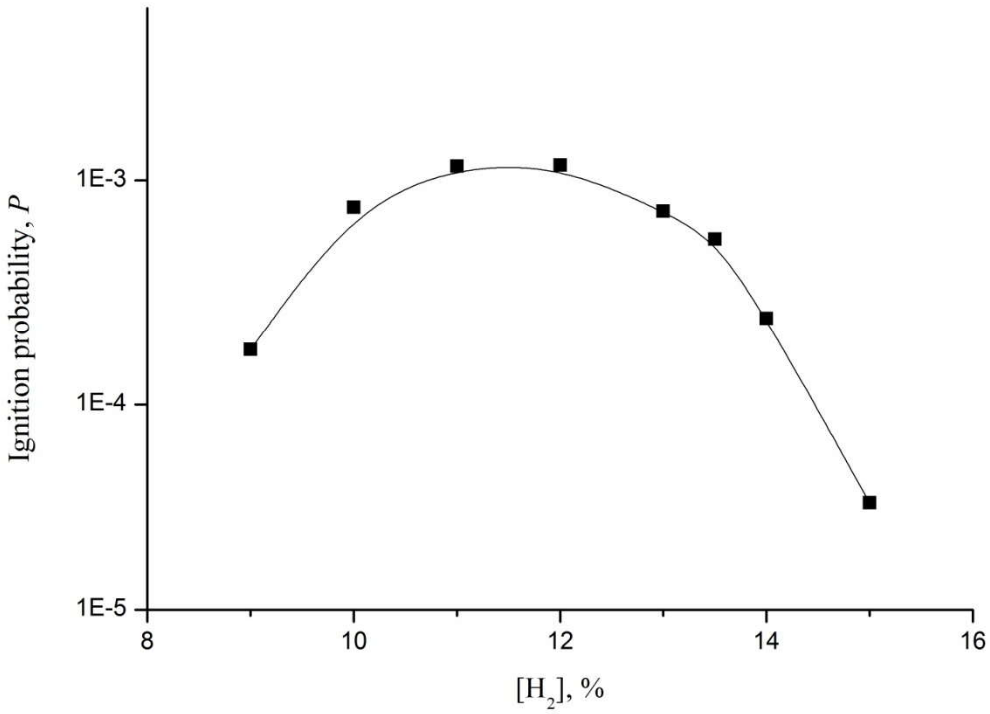
Ignition probability, P
1E-3
1E-4
1E-5
8
10
12
14
16
[H2], %

Fig. 4

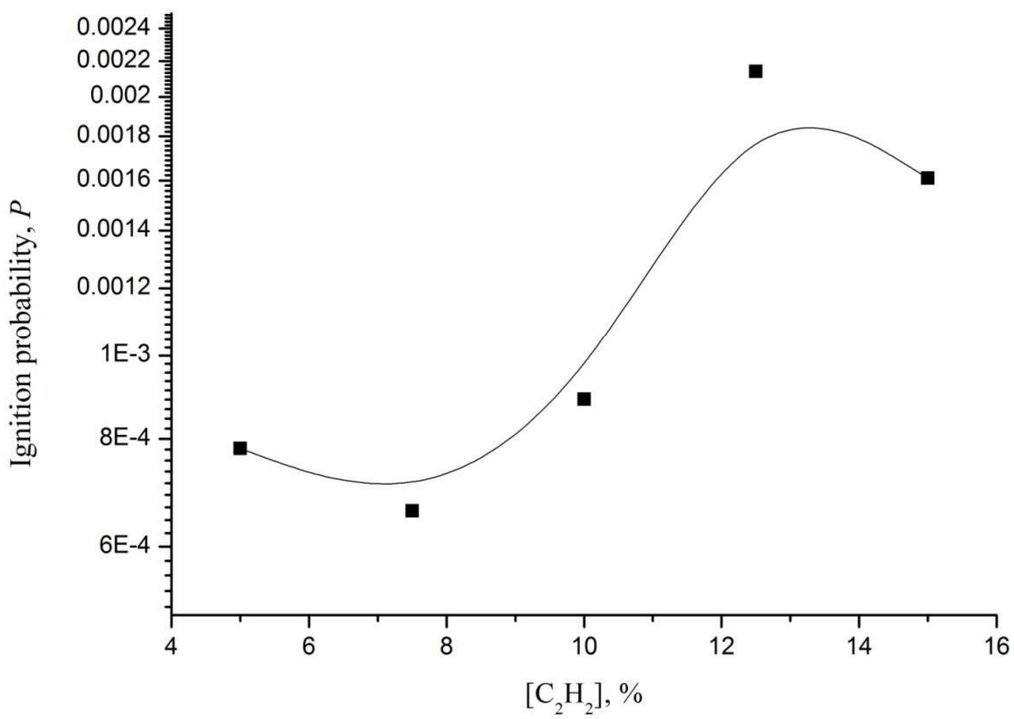
Ignition probability, P
0.0024
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
1E-3
8E-4
6E-4
4
6
8
10
12
14
16
[C2H2], %

Fig. 5