

Combustion and Extinguishing of Structural Polymeric Materials in Microgravity

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ABSTRACT

Fire nowadays is one of the most dangerous factors during the flight of a manned spacecraft. In this connection there is a lot of research on combustion considering the influence of space flight factors. Specific attention is paid to research of combustion processes under microgravity. In recent years this research avenue expands more and more in countries developing manned space flights. The research on fire safety provision in inhabited pressurized compartments of manned spacecraft is particularly important both in creating fire-safety structures and in developing extinguishment systems. The second direction is research on the physical phenomena specific to combustion in microgravity. It is established, that the rates of diffusion of critical species basically define the rate of combustion of solid materials in microgravity conditions. There is no natural-convective movement of gases in microgravity conditions, which makes the flame spread hard to predict. Therefore, an important result of the research has been a calculation of such parameters, which are then used to establish the accuracy of numerical models of combustion, designed under controlled conditions with the interaction of forced gas motion in the oxidizing environment with the combustion zone. The present article contains the analysis of experimental studies on combustion in microgravity and the corresponding technical solutions applied in the spacecraft design. Research results on combustion in microgravity obtained by Russian scientists made it possible to develop new technologies to provide fire safety in inhabited pressurized compartments of manned spacecraft.

KEYWORDS: Polymeric material, combustion, microgravity, spacecraft.

INTRODUCTION

Systematic research on combustion and extinguishment of polymeric materials in microgravity was started in USSR in the early 70s to develop fire safety systems for the inhabited pressurized compartments of the manned spacecraft "Soyuz 7K-TM". This spacecraft was created for the joint Soviet-American flight "Soyuz-Apollo" in 1975, and for the modules of the long-term orbital stations "Salyut" and "Mir". Basic data on combustion and extinguishment of polymeric materials in microgravity, which did not have any analogs at the scientific and practical levels at that time (some of them still do not have any), were first published from 1980 [1].

These studies were initially (1973 to 1994) carried out in a flying bench, on the ground in the free-falling containers [1], and using the two-dimensional duct [2].

A specially outfitted IL-76 airplane flew over a parabolic trajectory, which made it possible to carry out the combustion tests with microgravity duration up to 30 s. An experimental unit placed on the work table consisted of the hermetic vessel of 0.18 m diameter and 0.8 m length. Experiments were carried out at oxygen concentration (C_{ox}) of 21 %, with the samples of organic glass, capron fabric,

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filter fabric, and cotton cloth. A sample of material was ignited by the electric coil 5 s before starting the parabolic flight. At the same time, camera, backlights, and fan were switched on.

As a result, the following observations were made:

- In the absence of forced gas flow, steady combustion in microgravity could not be sustained, if the time of microgravity was greater than 5 s;
- Steady combustion of the samples continued, if the sample was exposed to a ventilation flow with a speed of 0.2 m/s;
- Burning of small fire sources lasted longer;
- Smoldering fires had longer duration than fires involving flaming combustion;
- A rapid change of acceleration direction occurring during a change in engine thrust initiated by the pilot to fly the experimental bench over the parabolic path, lasting 0.05-0.08 s, did not lead to combustion interruption. The flame quickly followed the direction of the acceleration vector and did not extinguish. It indicates sufficiency of mass-exchange for combustion of polymeric materials under any direction of gravity, unlike combustion conditions during microgravity;
- Burning stopped when the gravity acceleration was below 3% of the normal value.

The data obtained about the behavior of fire sources in a flying bench formed the basis for the design of research methods of combustion processes under microgravity aimed at obtaining quantitative information about the processes.

Initially, combustion of polymeric materials in a free-falling container was studied at a qualitative level with recordings of the combustion scenario and identification of the physical phenomena characterizing the rapid transition from normal gravity combustion to microgravity one. These features were considered hard to identify by other methods known by that time, including the experiments onboard the long-term orbital stations.

The free-falling system, which included two containers, internal and external, was also used. The sample of tested material was placed in the internal container. During the drop, the external container reduced the aerodynamic drag of the assembly, and the residual acceleration of the internal container was below $2 \times 10^{-3} \text{ m/s}^2$. Such a low acceleration did not influence the combustion. One of the walls of both containers was transparent to enable video-recording of combustion development.

A sample of paper of 120×120 mm size was placed horizontally in the internal container. The container was filled with the mixture of the specified oxygen concentration. The sample was ignited in its center by the high-voltage discharge, and the camera was turned on. The holder was removed from the falling system after the paper reached a steady burning mode, thereby bringing the system to microgravity. Processes occurring following the rapid transfer from the normal gravity to microgravity were mostly observed during combustion of the paper [1], which had a small thickness (50 μm) and a low volume thermal capacity, resulting in a short thermal relaxation time. This provided a quick restructuring of the combustion zone in space after the rapid transfer from one mode to the other. Figure 1 presents records of combustion and extinction of a sheet of paper in initially quiescent nitrogen-oxygen environment under $C_{ox} = 30 \%$, after a rapid transfer from standard gravity to microgravity conditions after the beginning of a free fall of the containers.

Frames 1-8 in Fig. 1 correspond to combustion under gravity. The combustion front moves on the sample with a speed of 4.6 cm/s. The beginning of zero-gravity corresponds to frame 9. The fire source diameter at that point is 6 cm. It can be seen that the extinction process has two stages. In the first stage (frames 9-16) there is a decrease of natural-convection velocity flow during 0.25 s by means of viscosity dissipation of mechanical energy. Such fast interruption of flow is provided by the high environment viscosity, which results from the high temperature (1750 K) in the combustion

area, and also the horizontal placement of the sample, the surface of which provides interruption of natural convection of the surrounding gas, occurring in the combustion area due to gravity acceleration. After interruption of the natural-convection flow, the leading edge of the flame extends away from the surface of the material. As a result, heat transfer between the material and the flame is disrupted and combustion stops. The flame size then decreases.

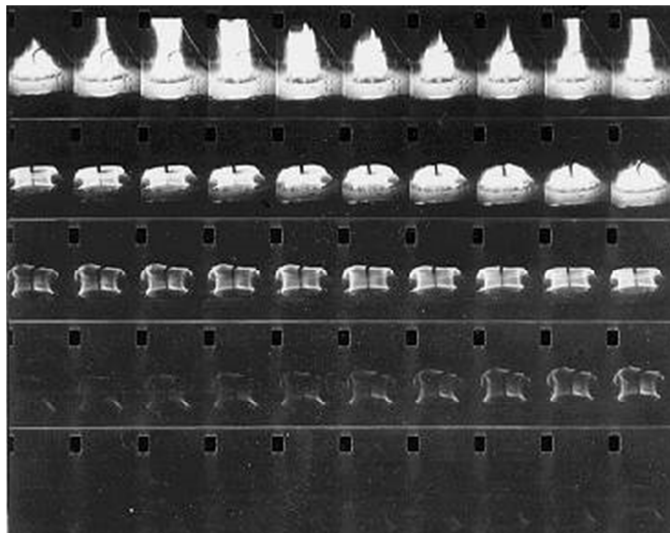


Fig. 1. Records of the paper extinction process after transition from a combustion mode under standard gravity to microgravity with $C_{ox} = 30\%$. Order of frames: from right to left, from top to bottom, frame frequency 64 1/s.

Reference [3] shows that, in the second stage, the glow of the flame gradually decreases due to the heat loss to the environment by radiation from the smoldering soot particles initially heated in the flame to a temperature of 1750 K. Due to this effect, the flame cools at first to a temperature equal to 800 K, at which the soot particles do not glow in the visible range of the radiation spectrum, and then to a temperature equal to 710 K. At this lower temperature, the products of thermal decomposition of the paper cannot self-ignite in the surrounding gas atmosphere. An example can be seen at the end of the fall of the container, as it happened in experiments when a sample of paper burned in a nitrogen-oxygen medium under $C_{ox} = 35\%$, and higher. So, in the experiment at $C_{ox} = 30\%$, there was a reliable extinction of the paper. According to the data of [3], reliable extinction of the paper occurred 0.7 s after transition from normal gravity combustion to combustion under microgravity conditions. The shape and size of the glowing zone until the emission ceased completely, from frame 11 till extinction, practically did not change.

With availability of the gas flow in the experiments, directed along the flat surface of the paper sample with a velocity of 0.2 m/s, paper combustion under normal gravity as well as in microgravity conditions was almost the same; in other words, paper burns steadily under the influence of a ventilation flow.

In order to show the combustion process of other materials, in Fig. 2, there are frames from a combustion and extinction record of capron fabric combustion with the density 100 g/m^2 under $C_{ox} = 30\%$ without forced gas flow before and after the transfer of the free-falling container to microgravity conditions. A fabric sample of $150 \times 100\text{ mm}$ was placed in the internal container vertically.

In microgravity conditions, the combustion process of capron fabric is completely different from

that of paper. There is combustion of the sample after 4 s of ignition in frame (a). The combustion zone moves along the sample with different velocities: upwards – around 1.8 cm/s; downwards and horizontally – around 0.5 cm/s. The flame has a much smaller size than the one during paper burning, which explains why it does not pulsate under standard gravity. Activity by the convection flows stopped right after transition to zero-gravity conditions (frame 2). The flame split into separate fragments. The areas of the combustion zone became rounded (frames b-d). The sizes of the fabric at that moment were: height – 60 mm, width – 35 mm. Then, the larger fire sources extinguished (frames b-e). Combustion in the fire sources of smaller sizes stopped after all the others (frames e-f). This behavior is explained by increased diffusion flows of the oxidant due to significant folding of the fire source of the capron fabric. Combustion stopped at 0.7 s. Forced gas flow with a velocity of 0.2 m/s, directed along the flat surface of the sample, provided a steady combustion of the capron fabric in microgravity conditions with the same intensity as under normal gravity.

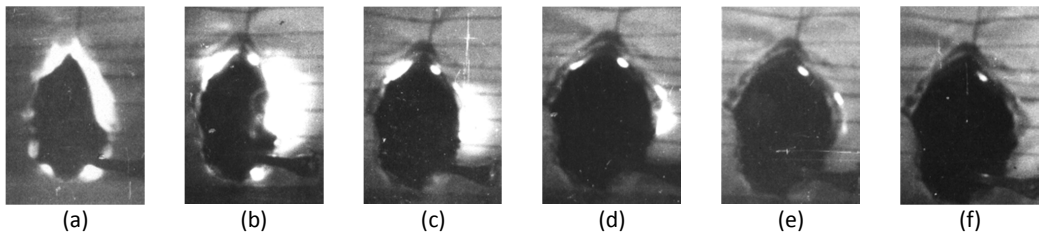


Fig. 2. Frame selection from the record of the extinction process of capron fabric during the transfer to microgravity conditions in a free-falling system ($C_{ox} = 30\%$): Time from the moment of transition to a burning system in microgravity for each frame is as follows: (b)–0.1 s; (c)–0.2 s; (d)–0.4 s; (e)–0.5 s; (f)–0.6 s.

So, even in the first stage of research of combustion and extinction processes of polymeric materials in microgravity conditions it was confirmed that no steady combustion of structural polymeric materials occurs even under short-term microgravity in a calm gas environment.

GETTING THE KEY DATA

The results discussed here have pointed out one of the fundamental features of the burning behavior of materials in microgravity conditions. Considering that there is steady combustion under the availability of ventilation flow in the combustion zone of a polymeric material and there is no combustion in a calm gas environment, it became obvious that materials had a lower combustion limit depending on the gas flow velocity under a given concentration of oxidizer (V_{lim} value).

There is a dependence of V_{lim} on C_{ox} values in Fig. 3 for an organic glass sample with the following sizes of 1x8x50 mm obtained in a free-falling container in microgravity conditions.

The V_{lim} value is the main parameter characterizing a physical model and limiting conditions for the combustion of polymeric materials in microgravity. A polymeric material burns steadily in microgravity under velocities of forced flow of the gas oxidizing environment exceeding the V_{lim} value for the particular material. There is no combustion for velocities of forced flow of the gas oxidizing environment lower than the V_{lim} value of the material. As velocities of natural-convective flows, determined during combustion in normal gravity, exceed the V_{lim} values of all known polymeric materials, it is impossible to calculate V_{lim} values under normal gravity in unconfined spaces.

The V_{lim} value makes it possible to specify the conditions for the development of ignition of structures from polymeric materials in an inhabited pressurized compartment of a spacecraft in

microgravity conditions in an orbital flight. If the V_{lim} values of the materials under the maximum possible oxygen concentration in the atmosphere are less than the maximum possible velocities of ventilation flows in an inhabited pressurized compartment, then development of sustained ignition of structures from such polymeric materials in microgravity is possible. Conversely, if the V_{lim} values of the materials exceed the maximum possible velocities of ventilation flows of an inhabited pressurized compartment, development of sustained ignition in microgravity is impossible.

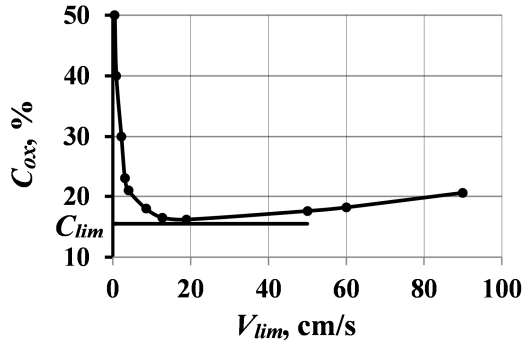


Fig. 3. Dependence of lower combustion limit on the flow velocity from oxygen concentration in the atmosphere for organic glass CO-120 obtained from experimental values of V_{lim} . C_{lim} – value of combustion limit depending on the oxygen concentration for organic glass equal to 15.5 %.

The dependence given in Fig. 3 was determined for a wide range of oxygen concentrations considering that the oxygen concentration in the atmosphere of inhabited pressurized compartments of modern Russian spacecraft is in the range from 21 % to 40 %. The dependence diagram of V_{lim} vs. C_{ox} has a minimum, which separates conditions under which the combustion progresses towards the lower and upper combustion limits depending on the flow velocity during combustion of material in zero gravity. The minimum C_{ox} value in the diagram, which is equal to 16.2 ± 0.5 %, corresponding to extinction in zero gravity, is almost similar to C_{lim} equal 15.5 ± 0.5 % calculated for organic glass under standard gravity. This proves the correctness of the evaluation methods used with combustion both under standard gravity and under microgravity in a free-falling container.

Russian scientists introduced fire hazard indexes to the practice of fire safety of inhabited pressurized compartments of manned spacecraft. These indexes characterize limiting combustion conditions of materials in a wide range of accelerations of gravity and in microgravity. Among them there are the following combustion limits of materials depending on: oxygen concentration, C_{lim} ; gas flow velocity, V_{lim} ; gravity, g_{lim} . A clear physical meaning of these parameters and a practical focus made it possible to use them as basic indexes of the fire hazard of materials in developing fire safety guidelines for manned spacecraft. Unfortunately, there are no results for limiting combustion conditions in papers by scientists from the USA [4] devoted to research of combustion process of materials in microgravity. They did not analyze this process and did not use such concept.

The part of the diagram in Fig.3 to the right of the minimum of the dependence of V_{lim} on C_{ox} corresponds to the upper limit dependence on flow velocity. The length of the flame increased towards gas movement together with the increase of flow velocity, combustion expanded along the surface of the sample and, under some flow velocity value, fire break occurred – the upper limit of combustion was reached. Interruption of the flame in the upper combustion limit of the material occurs because of high convective thermal losses from the combustion zone under increased gas flow velocity.

In conjunction with results of experimental [5] and theoretical [6] research, it can be concluded that combustion of polymeric materials in microgravity under velocities of forced flow of the oxidizing

environment lower than the V_{lim} values of the materials, and at the working pressures of the atmosphere of the inhabited pressurized compartments of manned spacecraft, does not occur because of lack of sufficient flow of oxidizer delivered to the combustion zone via molecular diffusion.

In the article in [7], the authors of the present work used obtained data to characterize a physical model and limiting combustion conditions for polymeric materials under microgravity. That work showed that there should not be any fire covering the entire surface of large-sized elements in the pressurized compartment of a manned spacecraft. Experiments carried out on the “Cygnus” spacecraft can confirm this [8].

REPLICATING MICROGRAVITY ON EARTH: THE EXPERIMENTAL SETUP

Research of combustion process of materials in microgravity conditions is met with considerable technical difficulties and material expenses. That is the reason why from the beginning of research efforts in this area the issue of design of experimental units and methods of determination of combustion of materials has been relevant. It has been a challenge to recreate the conditions of real microgravity, while running experiments under gravity conditions. Research in this direction has shown that the most representative condition is when a combustion process is carried out in a flat, horizontally-oriented moving gas layer enclosed between two parallel surfaces. Classic work [9] has shown that, by decreasing up to some height value a flat horizontally-orientated gas layer, it is possible to emulate a heat transfer process which is equivalent to a conductive one, thereby excluding natural convection with vertical movement of gas in the layer. This approach solved the issue of specification of combustion parameters of materials for microgravity conditions, when tested in normal gravity in a gas layer moving in a flat horizontally-orientated duct of a certain height.

It has been observed that, under limiting combustion modes of polymeric materials in nitrogen-oxygen environments under oxygen concentrations from 15 % to 100 % and pressures from 0.001 to 0.1 MPa, the maximum temperature in the flame zone practically does not depend on environment parameters and type of material [10]. Furthermore, by considering the parameters in the Grashof number, it can be seen that the intensity of natural convection in a flat horizontally-orientated two-dimensional duct under calculation of V_{lim} values of materials depends only on the height of the duct.

On the basis of the results of comparisons of V_{lim} values for different materials obtained in a free-falling container [5] and in horizontally orientated two-dimensional ducts of different heights [2], a fundamental correlation was found. A correlation was established for the height of the two-dimensional duct with which it is possible to obtain V_{lim} values for polymeric materials in standard gravity conditions, which correspond to V_{lim} values for microgravity conditions.

RESEARCH IN AN ORBITAL FLIGHT: THE “MIR” STATION

The reliability of the present research results for the combustion of polymeric materials in a flying bench, in a free-falling container and a two-dimensional duct, was checked by performing three series of experiments on the combustion of polymeric materials in microgravity conditions on EU “Skorost” on the “Mir” space station. The experiments were carried out, according to plans developed by Russian scientists, by Russian cosmonauts: A. Viktorenko, E. Kondakova, G. Padalka, S. Avdeev. Experiments were conducted with materials, which had different properties: non-melting organic glass of Russian manufacturing, melting plasticized organic glass manufactured in the USA, cotton braid, glass-fiber laminates and also with polyacetal and polyethylene, which melted during combustion.

During the first series of experiments, tests were conducted with six gas-phase combustible samples from organic glass and with six samples of a smoldering cotton braid. Figure 4 shows a sequence of frames from a record of one of the experiments with a sample from organic glass with a size of $70 \times 8 \times 3$ mm under an atmosphere pressure of 0.087 MPa and $C_{ox} = 23\%$.

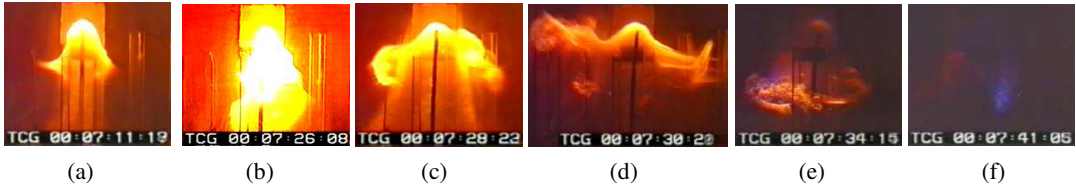


Fig. 4. Process of combustion development and extinction of a flat element from organic glass on the “Mir” station in zero gravity conditions in the orbital flight.

A sample of organic glass, which was ignited via electric coil 35 s prior to the moment recorded on frame (a), is shown. Here the sample burns under a gas flow velocity of 6.4 cm/s. The flame length is 30 mm. Frame (b) shows the burning of the sample after an increase of the flow velocity to 15 cm/s. Combustion intensity increased rapidly and approached that under normal ground conditions, according to the length and brightness of the flame. The flame length increased to 65 mm. Then, the ventilation was switched off in the chamber. The flame moved more and more forward from the surface of the burning samples, frames (c) and (d), to the space with an environment with an oxygen concentration sufficient to provide continuity to the flame. In this connection, the flame became separated from the surface of the sample. It can be seen in frame (e) that the flame had a shape close to spherical, which is most effective for diffusion of oxygen to the flame zone. As a consequence of decrease of oxygen environment delivery to the flame because of the absence of natural and forced convection, the flame temperature decreased. As a result, the surface temperature of the sample decreased and flow of pyrolysis gases from the surface of the sample was stopped. Because of the interruption in the decomposition of organic glass, formation of carbon particles in the flame also stopped. Their glowing made the flame yellow-orange. Because of the decrease of oxygen, carbon monoxide started to form in the flame. As a result of its increase, the flame became blue, frame (f), and then extinguished because of thermal losses via emission. The blue color of the flame points to the fact that the given combustion system before extinction went through limiting combustion conditions, which are the main phenomenon in a combustion process in microgravity. The cut-off time of combustion of the sample after switching off the ventilation in this experiment was 15 s.

In the same way it is possible to explain flame color changes, which were observed during experiments carried out by scientists from the USA in 1996 while studying the combustion of materials and substances in microgravity conditions on the “Mir” orbital station [4].

The following results were obtained in the same experiments with cotton-braid samples under the same atmosphere parameters. Under gas flow velocities less than 2 cm/s, cotton-braid smoldering without flame combustion was observed. Under gas flow velocities greater than 2 cm/s, the flame front initially expanded along the cotton braid right after its ignition. A smoldering front started to expand along solid combustion products of the cotton braid after the flame extinguished. The smoldering front developed along decomposition products of the cotton braid a little slower than the flame front. The cotton braid was fully smoldered without residue of solid products. The spreading velocity of the flame front (V_{fl}) along the cotton braid depended on the velocity, V_{vf} , of the gas flowing over the cotton-braid sample. For V_{vf} approximately equal to 20 cm/s, the V_{fl} value was 0.39 cm/s. For lower V_{vf} values, V_{fl} also decreased. For V_{vf} equal to 2 cm/s and V_{fl} equal to 0.25 cm, the smoldering front behind the flame expanded a little bit slower than the flame front. The length of the flame during combustion of the cotton braid decreased for a decrease of the V_{vf} value, from

1.6 cm under a V_{vf} value of 20 cm/s to 1.2 cm under a V_{vf} value of 2 cm/s. The flame diameter was not changed at all.

On the basis of the revealed regularities of the smoldering process, a smoldering model was developed, the predictions of which made it possible to formulate the conditions for the termination of smoldering and to optimize extinguishment parameters of the smoldering source [11].

In the second series of experiments on “Mir” station in 1996, the main goal of the experiments was the calculation of the V_{lim} value of materials. Experiments were carried out under $C_{ox} = 21.5\%$ and atmosphere pressure around 0.1 MPa.

Comparison of V_{lim} values of materials with essentially different chemical and mechanical properties obtained on the experimental unit on the basis of a two-dimensional duct, in a free-falling container and in the experimental unit “Skorost” on the “Mir” station [2, 5, 7], made it possible to determine that V_{lim} values obtained in a free-falling container and experimental unit “Skorost” on the “Mir” station, in other words under true microgravity, differed by 30 % at most.

The glass-fiber laminate chosen for experiments on the “Mir” station is a composite material. It has $C_{ox} = 19\%$ and is a material, which is combustible at $C_{ox} = 21.5\%$ (under which it was examined). Experiments on board the “Mir” station showed that samples of glass-fiber laminate, after ignition via electric coil under a gas flow velocity of 15 cm/s, which is much higher than the V_{lim} value of any non-modified thermoplastic, were ignited, but extinguished in several seconds. In order to explain the rapid extinction of glass-fiber combustion, special experiments of the combustion of composite materials on the “Mir” station were conducted using a two-dimensional duct. As a result of this research, a phenomenon of self-extinction of elements from composite materials during availability of the ventilation flow (which does not occur with non-composite materials) was discovered.

The mechanism of the combustion process and self-extinction of composite materials in zero-gravity is illustrated in Fig. 5 by the example of fiberglass.

The reason of self-extinction of composite materials in zero-gravity is the following. Polymeric composite materials consist of a reinforcing agent, for example from glass, carbon, ceramic fibers and binder, which is represented by compositions from polymeric resins which, as a rule, are combustible in an oxygen-rich atmosphere. After the ignition of an element from a composite material with gas flow velocity exceeding the V_{lim} value for the binder, firstly the burn-off of the binder from the face part of the element occurs, frame (a). Under a small thickness of a boundary layer in a flowing face part of the element, heat and mass exchange of the element with the gas environment takes place, which is needed for combustion of the binder. After the burn-off of the binder on the face part of the element, there is a non-combustible solid residue from glass and combustion products of the binder left behind the flame. That is why the flame moves to a side surface of the element and expands in the direction of the gas flow along the surface of the element, frames (b) and (c).



Fig. 5. Combustion and self-extinction of an element from fiberglass plastic in zero-gravity under gas flow rate velocity of 20 cm/s, and oxygen concentration of 23.0 %.

The thickness of the formed dynamic boundary layer near the streamlined element is increased moving away from the face of the element. That is why, as it moves forward, the flame deviates

from the surface of the element, heat convection between the flame and the surface of the element is interrupted, outflow of combustible products of thermal decomposition of the binder from the surface of the element is stopped and the flame becomes extinct /frame (d)/ at some distance from the face part of the element. Combustion in zero-gravity with availability of gas flow of all composite materials with non-combustible reinforced filler is stopped according to the same mechanism. There was no such effect during the development of the combustion zone against any gas flow.

Experiments to study the combustion of materials manufactured in the USA via EU “Skorost” were carried out after the publication of the first research results [7] in two series of experiments on the Mir station with the help of EU “Skorost”, carried out by Russian research workers in agreement with NASA.

For experiments on the “Mir” station, the following materials were selected: Delrin (polyacetal; organic glass (polymethylmethacrylate); polyethylene (High Density Poli) with known combustion properties defined for ground conditions using a two-dimensional duct. There is a selection of frames from the record of one of the experiments with polyethylene samples of 6 mm diameter in Fig. 6.

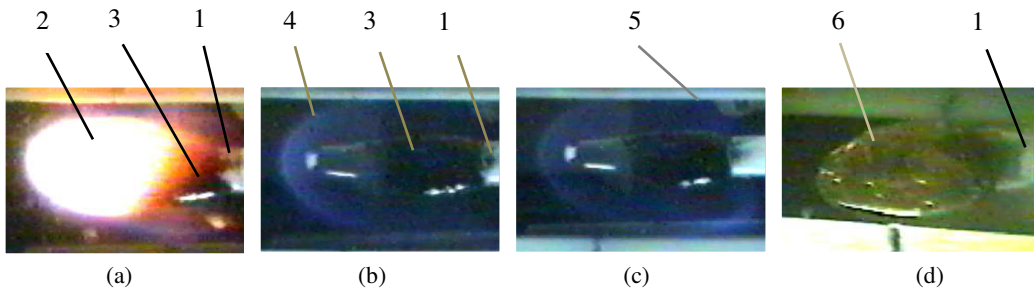


Fig. 6. Polyethylene element combustion before switching off ventilation flow and extinction of the element after switching off ventilation flow in the combustion chamber of EU “Skorost”.

Frame (a) shows combustion of sample (1) from polyethylene after its ignition under a gas flow velocity of 8.5 cm/s and $C_{ox} = 22.5\%$. The gas flow is directed to the left flat end of the sample. After sample ignition (flame (2)) a yellow color is formed, which points out the formation of soot particles under thermal decomposition of polyethylene in the process of its combustion and with a gas flow velocity of 8.5 cm/s, which is much greater than the V_{lim} value of 1 cm/s under the given C_{ox} . The sample burns with formation of a drop (3) of polyethylene melt. Drop sizes increase in time and do not reach stationary levels during the time interval of 150 s. There was the formation of small gas bubbles in the volume of a transparent drop, but no jet emissions from the surface of the drop. After switching off the ventilation between frames (a) and (b), flame (4) became blue and an oscillatory flame motion was observed, which is a significant extinction mode of materials with a 1.3 Hz frequency. In frame (b) flame (4) was short; in frame (c) flame (5) was long. During combustion, a drop of polyethylene melt was transparent. The drop (6) became non-transparent after extinction and cooling, frame (d). Polyethylene drop melt in zero-gravity steadily was held into a solid mass of polyethylene, in contrast to the behavior under gravity where the polyethylene melt would flow down from the burning element in the form of burning drops. The self-extinction time of the polyethylene sample in this experiment was 11 s.

COMPARISON WITH OTHER STUDIES

The availability of the value of combustion limits depending on gravity, g_{lim} , plays an important role in prescribing fire safety guidelines for inhabited pressurized compartments of spacecraft and long-

term orbital stations [7]. Values for this quantity were determined by Russian scientists as a result of studies on combustion and extinguishment processes under different gravity conditions. For materials with different chemical and mechanical properties, g_{lim} values were found as a function of oxygen concentration in the atmosphere. Based on these new data, engineering solutions for monitoring of conditions and extinguishment of fires in inhabited pressurized compartments of manned spacecraft with artificial gravity were designed. Artificial gravity is necessary for normal life activity of crews during long-term space flights. There are no data about works concerning this type of fire safety guidelines for inhabited pressurized compartments of manned spacecraft done by other researchers.

Along with the research of Russian scientists, other works should be recognized. One of the most informative works is by American scientists [4]. The experimental study of combustion of polymeric materials and substances in microgravity was carried out in 1996 onboard the Russian space station "Mir". Flat sheets of paper, a wire with polyethylene insulation, cylinder-shaped cellulose (paper), and candles were studied. Most informative combustion experiments were those with the paper sheets. In these experiments, ambient temperature and that in a flame zone were varied. A physical model of sheet paper samples combustion is clear and simple, as contrasted to a physical model of combustion of cylinder-shaped samples of paper. During combustion of paper in closely packed assemblies, combustion effects of composite materials can appear. These effects are expressed in the formation of carbon residue, which is incombustible. In this case the expansion of the combustion zone along a cylinder-shaped sample of paper in the direction similar to the direction of a gas flow may not occur as it happens with a fiberglass element in Fig. 5. Possibly, that is why in the work of [4] combustion along the cylinder-shaped paper sample is observed in the direction opposite to the gas flow direction.

Combustion of samples of sheet paper was studied in the test container, with the air flow (the atmosphere was taken from an inhabited pressurized compartment of the "Mir" station) created by the fan. There were lattices, which were installed at the entrance and exit of the container. These lattices prevented outflow of solid particles formed during combustion of material samples. Thermocouples placed near the paper samples were used to measure the temperature of the environment in the flame zone of the paper. There is no information in [4] about oxygen concentration of the atmosphere under which each experiment was carried out. The experiments were performed for oxygen concentrations in the range from 22 to 25 %.

We analyzed an experiment of paper combustion with surface density of 160 g/m^2 , where a picture of paper combustion was captured at the best quality. It is noted that the flame during paper combustion in such conditions had a blue color without yellow-orange highlights. Considering data about flame color given by Russian scientists and provided above, a firm conclusion can be made that combustion of the paper sample in this experiment occurs near a combustion limit of paper depending on gas flow velocity. According to the data from Russian scientists, the V_{lim} value of cellulose materials during their gas-phase combustion under oxygen concentrations in the range of 22-25 % is within the limits of 1.4 to 2.5 cm/s. Based on the authors' data, the flow velocity in this experiment taking into account errors in measurements was about 2 cm/s.

Russian scientists proved [10] that the maximum flame temperature at the combustion limit under normal gravity is $1500 \pm 50 \text{ K}$, regardless of oxygen concentration and type of material. A maximum flame temperature value during paper combustion equal to 1463 K was specified in the experiment set up by the American scientists with paper combustion on the "Mir" station under microgravity and flow velocity equal 2 cm/s, which is close to V_{lim} value of paper. This means that, considering measurement errors in the experiments, the maximum flame temperature at the combustion limit of materials with standard gravity and under microgravity is the same. This is one of the most important conclusions after comparison of the data obtained by the two groups of scientists.

Thus, results of works performed by research teams of Russia and the United States in the field of combustion under microgravity conditions are consistent.

CONCLUSIONS

Russian scientists have studied the following issues on combustion of materials and substances in microgravity:

- Establishing the basic physical model of combustion of polymeric materials, interpreting the interconnection of phenomena and parameters in the combustion zone, the limiting conditions for the burning of materials and substances with different chemical and mechanical properties;
- Discovery of previously unknown parameters of combustion of materials in microgravity conditions and their introduction as indicators of fire hazard into the practice of developing new tools and methods that currently form the basis of fire safety in the inhabited compartments of Russian spacecrafts;
- Determination of combustion parameters for microgravity for all classes of polymeric materials at oxygen concentrations from 21 % to 40 %;
- Establishing the principles of the design and implementation of automatic fire extinguishment systems, which are currently used in the inhabited pressurized compartments of the Russian segment of the International Space Station.

REFERENCES

- [1] A.S. Melikhov, V.I. Potyakin, About combustion limits of solid substances in zero gravity conditions, Chemical physics of combustion process and explosion, 6th All-Union Symposium on Combustion and Explosion, Alma-Ata (1980) 48-51 (In Russian).
- [2] A.S. Melikhov, I.A. Bolodyan, V.I. Potyakin, A.V. Ivanov et al, The Study of Polymer Material Combustion in Simulated Microgravity by Physical Modeling Method, Proceedings of the Fifth International Microgravity Combustion Workshop, Cleveland, Ohio (1999) p. 7.
- [3] A.S. Melikhov, A.V. Ivanov, S.G. Rebrov, Role of heat emission from diffusion flame by particles of soot in flame extinction process in zero-gravity conditions, Essential problems of fire safety: Theses of reports of XXI International science-practical conference, Balashikha (2009) 22-27 (In Russian).
- [4] P. Ferkul, K. R. Sacksteder, P. S. Greenberg, D. L. Dietrich, H. D. Ross, J. S. Tien, R. A. Altenkirch, L. Tang, M. Bundy, M. Delichatsios, Combustion experiments on the “Mir” space station, In: Report No. AIAA-99-0439, American Institute of Aeronautics and Astronautics, p. 14.
- [5] A.S. Melikhov, V.I. Potyakin, A.M. Ryzhov, B.A. Ivanov, About combustion limits of polymers in conditions of absence of a natural convection, Fizika Gorenia I Vzryva. 4 (1983) 27-30 (In Russian).
- [6] I.A. Bolodyan, A.F. Zhevlakov, A.S. Melikhov, About calculation of limit conditions of polymeric materials combustion, Fire preventive measures, Publication 13 (1977) 81-88 (In Russian).
- [7] I.A. Bolodian, A.S. Meliklov, L.T. Tanklevskiy, Automatic fire-extinguishing system for inhabited pressurized compartments of manned spacecraft, Acta Astronautica 135 (2017) 100-108.
- [8] G. Jomaas, J. L. Torero, C. Eigenbroc, J. Niehaus, S. L. Olson, P. V. Ferkul, G. Legros, A. C. Fernandez-Pello, A. J. Cowland, S. Rouvreau, N. Smirnov, O. Fujita, J. S. Tien, G. A. Ruff, D. L. Urban, Fire safety in space – beyond flammability testing of small samples, Acta Astronautica 109 (2015) 208-216.
- [9] M.A. Mikheev, I.M. Mikheeva, Basics of heat-transfer, “Energia” publishing house, Moscow, 1977, 344 P. (In Russian)
- [10] A.S. Melikhov, V.I. Potyakin, E.V. Flankin, Limiting combustion conditions of materials under low pressures, Fizika Gorenia I Vzryva, 3 (1982) 44-47 (In Russian).
- [11] A.S. Melikhov, Research of spreading of smoldering front and setting up conditions of smoldering interruption inside a gas-proof block of finely a dispersed material, Fire safety, 4 (2017) 74-89 (In Russian).