IMPACT OF SPACE DEBRIS ON INTERNATIONAL SPACE STATION: METHODS AND MEANS OF DETECTION OF A PLACE OF DEPRESSURIZATION

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ABSTRACT

The through breakdown of construction elements by particles with natural or artificial origin is probable during long-time operation of space vehicles and orbital space stations. The space vehicle depressurization can arise because of crack generation by different pressures and dynamical stresses. The equipment development for fast detecting of the depressurization locations is very important task for International Space Station (ISS) and other space vehicle types. This task solution requires creating of computing models for object considered (the gas flow source from space vehicle module) [1-3].

1. FLOWS CLASSIFICATION

Detection of the gas flow from space vehicle module is interesting in those cases: the gas flow via hole in a flat infinite thin plate, in long and short channels with circular and non-circular section and gas flow via flaws and space vehicle coating. Simulation results are dependencies of gas jet parameters on their characteristics accounting own external atmosphere dynamics of space vehicle.

1.1. The gas flow via diaphragm

Lets consider a breakdown of a flat infinite thin plate with hole area A_0. With usage of Mendeleev-Klayperon equation [1] the gas flow via the hole can be written as

$$I = m_0 k^{-1} T^{-1} v_{ap} A_0 (V^{-1} M^{-1} RTm - p_{out}), \quad (1)$$

where R is the universal gas constant, (R=62,36·10^3 Tor·cm^3·K^{-1}·mole^{-1}); T is the absolute temperature; m_0 is a mass of one molecule; k is the Boltzmann constant; V is the space vehicle volume; M is the molecular gas mass; $v_{ap} = \sqrt{\frac{8}{\pi} \cdot \frac{RT}{M}}$ is the mean arithmetic speed of gas molecules [2], for air with temperature T=293K v_{ap}=462,53 m/s;

m is the gas mass in space vehicle; p_{out} is the gas pressure outside the space vehicle.
Using Mendeleev-Klayperon equation and Eq.1 the pressure inside the space vehicle can be expressed in form

$$p = (p_0 - p_{out}) exp(-A_{eff} v_{ap} V^{-1} \tau) + p_{out} \quad (2)$$

Then the flow is

$$I = m_0 k^{-1} T^{-1} v_{ap} A_{eff} (p_0 - p_{out}) exp(-A_{eff} v_{ap} \tau V^{-1}). \quad (3)$$

1.2. Gas flow via channel

Lets consider the conductivity of long and short channels with circular and non-circular section in molecular model representation. Length of the long channel is much longer than linear section size. These channels occur with formation of small holes (up to hundreds microns) in space vehicle coating.
Molecule's speed in channel can be described by the following equation [1]

$$p = (p_0 - p_{out}) \exp\left(-\frac{RT}{MV} \frac{\pi}{v_{ap}} \frac{D^3}{L} \tau \right) + p_{out}, \quad (4)$$

where $(p + p_{out})/2$ is the mean pressure in channel; D is the channel section diameter; m_0 is the mass of one gas molecule; L is channel's length.
Accounting Eq.2 we get after some transformations

$$p = (p_0 - p_{out}) \exp\left(-\frac{RT}{MV} \frac{\pi}{v_{ap}} \frac{D^3}{L} \tau \right) + p_{out}, \quad (5)$$

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Then the flow is

$$I=\frac{\pi}{v_{ap}}\frac{D^3}{L}\left(p_0-p_{out}\right)\exp\left(-\frac{RT}{MV}\frac{\pi}{v_{ap}}\frac{D^3}{L}\tau\right). \quad (6)$$

Viscosity conditions take place with pressure in space vehicle more than 10 Tors. In viscosity conditions gas speed is defined by its viscosity – the closer molecules to the channel's wall the more speed $v_в$ is. The speed distribution $v_в$ on radius is described as [1]

$$v_в(r)=\frac{p-p_{out}}{4\eta L}\left(\frac{D^2}{4}-r^2\right), \quad (7)$$

where η is the dynamical coefficient of gas viscosity.
Lets find gas flow changing in time for a long channel with circular section. Using Mendeleev-Klayperon equation we get

$$p=\left\{2\left[1-\frac{p_0-p_{out}}{p_0+p_{out}}\times\exp\left(-2p_{out}\frac{m_0}{kMV}\frac{\pi R}{256\eta}\frac{D^4}{L}\tau\right)\right]^{-1}-1\right\}p_{out}, \quad (8)$$

$$I=\left\{\left[\left[\frac{2}{1-\frac{p_0-p_{out}}{p_0+p_{out}}\exp\left(-2p_{out}\frac{m_0}{kMV}\frac{\pi R}{256\eta}\frac{D^4}{L}\tau\right)}-1\right]^{-2}-1\right]-1\right\}p_{out}^2\frac{m_0}{kT}\frac{\pi}{256\eta}\frac{D^4}{L}, \quad (9)$$

$$G_L=\frac{\pi}{256\eta}\frac{D^4}{L}2p_{out}\left[1-\frac{p_0-p_{out}}{p_0+p_{out}}\times\exp\left(-2p_{out}\frac{m_0}{kMV}\frac{\pi R}{256\eta}\frac{D^4}{L}\tau\right)\right]^{-1}. \quad (10)$$

Eq.10 describes the conductivity.

The intermediate conditions take place with pressure 1–10 Tor. In this case we use empiric expressions based on formula combinations obtained for molecular and viscosity conditions.

1.3. The gas flow through the flaw

Flaw is the most probable hole type formed as a result of space vehicle coating disruption because of constructions aging and impulse loadings.
With gas flow from hole three variants of molecular, viscosity and intermediate flowing are probable.
Incidentally the hole is the flaw. For simplification of calculations we consider that the flaw is represented by the hole with square form and linear size $b \geq L >> a$, where a is the narrow wall width ($a=2L$); b is the long wall width; L is the flaw length.
Lets see consider conditions of gas flow through the flaw. In case when $\lambda >> b \geq L$ gas molecules move individually – some of them move directly in tube and do not contact with walls, and the others contact with walls and perform zigzag moving. Since a period of time a molecule stays on the wall is finite, the molecule has speed loss towards direction of x-axis. That is equivalent to gas friction on walls.

$$p=\left(p_0-p_1\right)\times\exp\left(-\frac{1}{2}\frac{a^2b^2}{a+b}\frac{1}{v_{ap}m_0}kT\frac{1}{L}\frac{RT}{MV}\tau\right)+p_1. \quad (11)$$

$$I=\frac{1}{2}\frac{a^2b^2}{a+b}\frac{1}{v_{ap}}\left(p_0-p_1\right)\times\exp\left(-\frac{1}{2}\frac{a^2b^2}{a+b}\frac{1}{v_{ap}m_0}kT\frac{1}{L}\frac{RT}{MV}\tau\right)\frac{1}{L}. \quad (12)$$

In viscosity conditions gas flow resistance is defined by viscosity. Gas molecules located near tube walls have lower speeds than those near the tube axis. The component of molecule's speed v_x approximately equals to zero.
The speed distribution has symmetrical structure relatively the axis Oy for a channel with rectangular section $a\times b$, where $a<<b$. The gas column moves under force $F_+=ab(p_2-p_1)/2$ in parallelepiped with sides $a/2$ and b. This force equilibrates by friction force F_-, applied to surface $(a+b)L$ of gas column. In this case we can get equation for gas flow and pressure inside the system depending on time.

$$I=\frac{b^2\left(p^2-p_1^2\right)}{2\eta L}\left\{\frac{a^2}{8}++\frac{b}{2}\left[b\ln\left(\frac{a/2+b}{b}\right)-\frac{a}{2}\right]\right\}\frac{m_0}{kT}. \quad (13)$$

$$p=2p_1\left[1-\frac{p_0-p_1}{p_0+p_1}exp\left(-2p_1\cdot\frac{RT}{MV}\cdot\frac{b^2}{2\eta L}\times\left[\frac{a^2}{8}+\frac{b}{2}\left(b\ln\left(\frac{a/2+b}{b}\right)-\frac{a}{2}\right)\right]\frac{m_0}{kT}\tau\right)\right]^{-1}-p_1 . \quad (14)$$

1.4. Computing model of gas flow via space vehicle coating (SVC)

SVC represents layered structure. The first and the last layers are synthetic fabric. We assume that this fabric has cellular structure. Holes have square form with size of 100 μm, the distance between holes is 100 μm, the channel length (the thickness of the fabric) is 100 μm. Other layers are polymeric films with holes. Holes have 2 mm diameter and located with 1 cm step. The film thickness is 100 μm and we neglect it during calculations. The distance between SVC layers and between SVC and space vehicle surface is equal to 0.5 mm. The algorithm is developed to define gas flow via SVC and flow distribution.

2. EXPERIMENTS RESULTS

Experiments were conducted using test bench. Controlled induction-valve microphone, ionization and thermocouple sensors connected to power supply and control block with amplifiers and indicator were installed in vacuum camera on the way of gas flow. The gas flow was formed using few capillaries, and timer formed the flow time. Specified sensors performed the measurement of flowing gas characteristics. Sensors calibration was done using standard pressure meter VIT-2.

The internal capillary diameter checking was done by microscope. In Fig.1 the graphics of flow pressure p depending on angular gas flow distribution are shown. As Figs.1-2 indicate the flow maximum is smoothed by a barrier (the SVC) located before the flow source. The SVC diffuses the gas flow from its surface with diameter about 200-500 mm. Experiment shows that the gas pressure in this case has small dependency on angular distribution. Dependencies of gas concentration n on distance R from the flow source towards normal to SVC surface are shown in Fig.3.

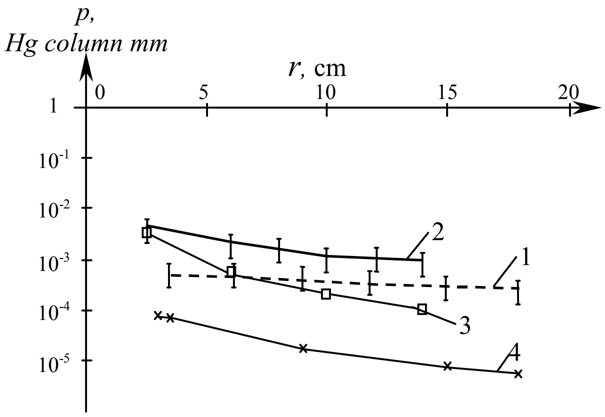

Fig.1. 1, 2 are experimental; 3, 4 are theoretical dependencies of flow pressure p on distance to the flow source towards normal with and without the SVC respectively.
Hole parameters: long channel, d=0,55 mm, L=42 mm, the temperature is 293K, gas type is air (M=29 gram/mole), the pressure in vacuum camera is $4\cdot10^{-3}$ Hg column mm.

The difference between experimental and theoretical data occurs because during experiments the vacuum camera with limited size (0,15 m^3) was used. Sensors detected both the direct flow via hole and the secondary flows reflected from camera walls. To decrease the effect of reflected molecules on sensor data measurements were performed at induction-valve opening.

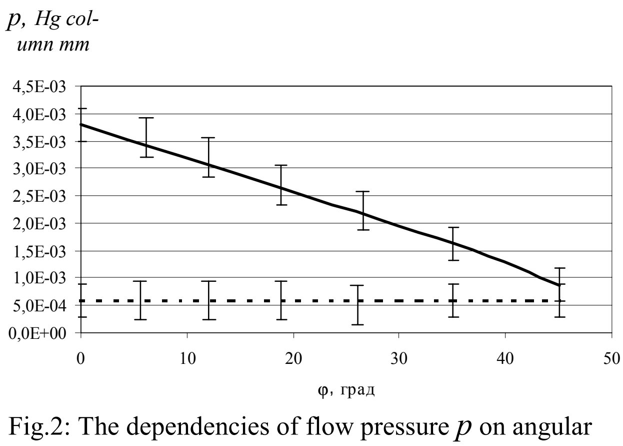

Fig.2: The dependencies of flow pressure p on angular distribution. Dashed line shows the dependency with the SVC and without it.

Difference between experiment and theory can be explained by SVC mathematical model errors. They can be decreased by model improvement using results of the experiments, conducting experiments with lower inaccuracy and using vacuum camera with bigger volume.

As we can see from Fig.2 the experimental distribution characteristic of gas flow dependency on angle, the gas flow falls by two times with angle 30 degrees. Considering secondary flows we assume for theoretical calculations that gas jet has cone form with expansion angle 60 degrees.

Multi-parametric device is developed on the base of studies on detection of location of gas drain from space vehicle module using the microphone, ionization and thermocouple sensors. The ionization sensor is made using the scheme shown in [4]. The device sizes are 100mm × 90mm × 65 mm, the mass is 0.4 kg, power consumption about 3 Watts. Accumulator block mass is about 0.2 kg.

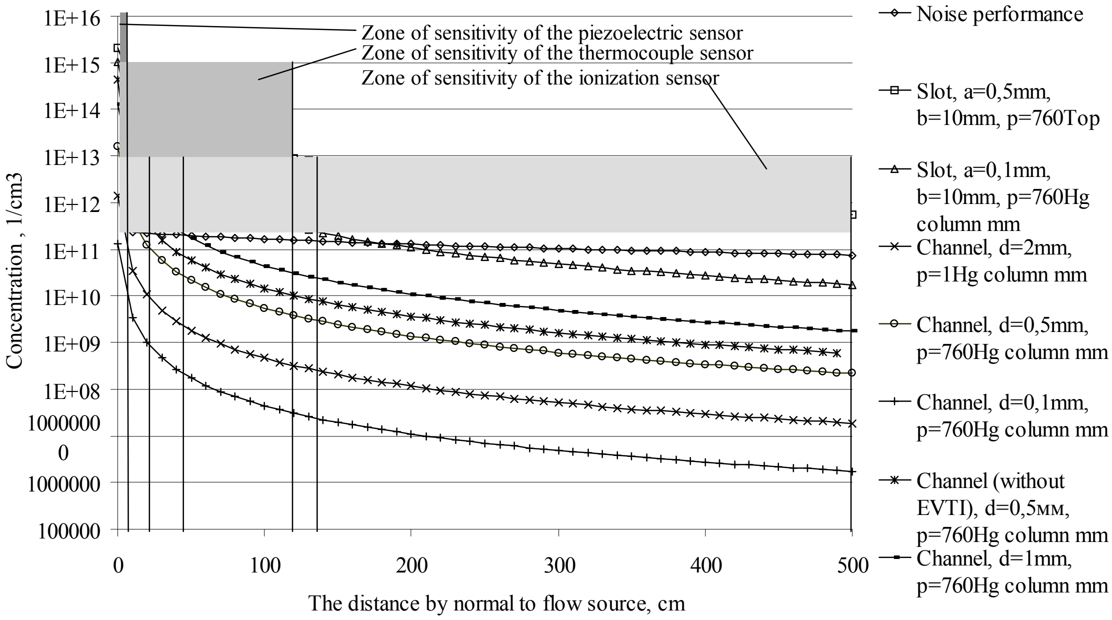

Figure 3: Gas concentrations n dependency on R by normal to flow source. Sensitive zones of different sensors. Space vehicle coated by SVC.
Space vehicle parameters: the volume is 180 m3, the temperature is 293 K, gas type is air (29 gram/mole), th epressure is p, coating thickness is 2 mm. Noises are 10^{-5} Hg column mm with r = 20cm.

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