

PERFORMANCE OF 1N MODEL THRUSTER ON NITROUS OXIDE

⁽¹⁾Vladimir Sadov, Nikolay Yaroshenko, Taras Gaydey, Sergey Filatov, ⁽²⁾Alexander Kokorin, ⁽³⁾Nickolas Pillet
⁽¹⁾Russian Scientific Center "Applied Chemistry", St. Peterburg, Dobrolubov av.,14,
tel:7 812 4999779, Fax:7 812 7030557, E-mail: vsghp@yandex.ru: ⁽²⁾Russian Academy of Science, Institute of
Chemical Physics, Moscow, ⁽³⁾CNES, Toulouse, France

ABSTRACT

Nowadays interest is aroused for nitrous oxide as green monopropellant for space propulsion. At RSC-AC it was a prerequisite for conduction of studies directed to elaboration 1N catalytic thruster on nitrous oxide. In the course of the work the catalytic bed design was elaborated, different catalysts were tested, working capacity of the model thruster was demonstrated in continuous and pulsed modes. On the base of obtained results one might expect that with the use of catalytic thrusters on nitrous oxide different tasks of spacecraft control, such as attitude control, maintenance and changing of orbit, may be solved.

INTRODUCTION

Launching of mini- and micro-satellites as subsidiary payload considerably enlarges market of space services as it gives numerous firms and universities of modest means the chance to have their own satellites for solution their scientific and applied tasks. It is very attractive to use in the thrusters of such satellites a cheap and nontoxic propellant. Ordinary medical nitrous oxide is worthy substitute of highly toxic and dangerous but extensively used hydrazine. It is non-corrosive, explosive-proof, stable, non-toxic, compatible with variety materials, self-pressurized and comparatively inexpensive monopropellant. Nitrous oxide application in resistojet propulsion for the small satellites is not profitable because of rather high level of energy consumption. Cold-gas propulsion implies insufficient value of specific impulse. The best plan to be followed is make a catalytic thruster on nitrous oxide. Solution the problem requires preparation of an active catalyst, resistant to high temperature oxidizing medium and elaboration of catalytic beds with the performance competitive with that of existing hydrazine catalytic beds.

The extensive studies on catalysts for nitrous oxide decomposition were carried out at RSC AC [1]. Different types of the catalysts were under consideration: a) metallic catalysts, representing briquettes pressed twisted in spiral wire; b) catalysts on the base of transitional metal oxides; c) catalysts on the base of platinum group of metals coating the carrier. There were established activity ranks for each catalyst types. So, for the metallic catalysts the next rank was determined: Ni>Pt, Rt+Rh, Rt+Ir>nichrome. In doing so there was discovered tendency of Ni and nichrome to oxidizing in the high temperature medium of nitrous oxide decomposition products. The most active catalysts for nitrous oxide

decomposition are ones on the base of metals of platinum group. For them the next rank was established: Rh>Ru>Ir>Pt>Pd. For the inexpensive accessible catalysts on the base of transitional metal oxides the rank of activity is the next: Co₃O₄>NiO>MnO₂>CuO>Cr₂O₃>Fe₂O₃.

Efforts are underway to elaborate 1N model catalytic thruster with total firing time 10hours and capacity for function in continuous and pulsed modes. For this purpose there was a need to choose the most suitable catalyst, to elaborate catalytic bed design, to study catalyst behavior under real conditions, to evaluate life span and performance of the model thruster.

CATALYSTS

Keeping in mind discovered tendency of Ni and nichrome to oxidizing, cost of platinum, time- and labor-consumption of the fire trials of catalytic beds, less activity of metallic catalysts in comparison with another investigated catalysts, we did not test metallic catalysts in the model chambers. The nichrome briquettes were used to fix granulated catalysts inside of the catalytic bed shells.

Rhodium catalysts on different carries have the highest activity for nitrous oxide decomposition. But at the stage of setup of the test bench and elaboration of the catalytic bed design the using of expensive and scarce rhodium catalysts is not profitable. Thus, at the beginning of the work the inexpensive accessible catalysts on the base of transitional metal oxide were used. Clearly for fire tests in the catalytic beds the most active samples were chosen. The main characteristics of the catalysts tested in the model chambers are presented in the Table 1.

APPROACH TO CATALYTIC BED DESIGN

Development of self-accelerated exothermic catalytic reaction is possible if heat-evolution on the surface of catalyst pellets is more than heat-removal from this surface into flow of comparatively cold reagent by convection and into pellets by thermal conduction [2]. Taking into account a small temperature gradient across the width of the pellet, the last heat-removal component can be neglected. In this case the above-mentioned condition takes the form (1)

$$K \exp(-E/RT) C Q > a(T_s - T_f), \quad (1)$$

where K is preexponential factor, E , activation energy, R , gas constant, T_s , temperature of catalyst

pellet surface, Q , heat effect of reaction, a , heat transfer coefficient, T_f , gas flow temperature.

For illustration of the extent to which possibility of catalytic reactor start-up is affected by initial conditions (chamber pressure- P_{ch} , T_s , T_f , transverse consumption rate (loading factor) $q_f = 4m/\pi D^2$, where m is monopropellant flow rate, D , inner diameter of catalytic bed) calculation of heat-removal and heat-evolution was carried out for one of the experimental catalysts. Calculations were accomplished for kinetic regime only. The results are presented on Fig.1.

Intersection of heat-evolution curve with heat-removal line marks the minimal initial catalyst temperature, at which development of self-accelerated reaction is possible. Obtained results show that increasing of T_s , P_{ch} , T_f and decreasing of q_f are favoured for reaction development. But the extent to which reliable start-up of a catalytic bed is affected by fuel temperature is comparatively small. Therefore any steps for controlling of propellant temperature seem to be needless. The extent to which development of the catalytic reaction is affected by T_s , P_{ch} , q_f is essential. The distinctive feature of catalytic beds on nitrous oxide is the necessity of catalyst preheating to initiate decomposition. Allowable initial temperature of the catalyst depends on its activity, chamber pressure, velocity of gas flow in the catalytic layer. It goes without saying that the most active catalysts are preferable. It is important to keep in mind that the catalyst activity must remain on high level during required service life of the catalytic thruster. Decreasing of allowable initial temperature enables to decrease energy consumption. Increasing of P_{ch} by a factor of two results in decreasing of permissible initial catalyst temperature by 70°C . At given monopropellant flow rate, chamber pressure is dictated by nozzle throat area. At small thrust value, that is, at small flow rate, excessive decreasing nozzle throat diameter leads to some difficulties in its production process and, as it indicated further, it could increase the probability of the nozzle throat clogging. Increasing of q_f (that is velocity of gas flow in the catalytic layer) from 0.134 to 0.38g/s cm^2 leads to increasing of permissible catalyst temperature by 50°C . At given value of flow rate (that is at required level of thrust) velocity of gas flow is defined by inner diameter of the catalytic bed shell. Thus, increasing reactor diameter leads to the more reliable start-up of the catalytic bed, but at same time it deteriorates mass-dimensional characteristics of the engines. It is worthy of note that the less is catalyst activity, the more significant the above-mentioned dependencies are.

It is known [3] that minimal level of energy consumption for a catalytic thruster on nitrous oxide can be obtained if it have an inner electric heater and its starting-up goes on at varying value of monopropellant flow rate. But in this case start-up transient time on this reactor averages 50s . We had to elaborate the catalytic bed with value of pressure rise time no more than 0.2s . Moreover our catalytic bed must enable the thruster to function in pulsed mode with pulse duration from 0.3s and pause duration from 0.5s . Therefore the traditional outer electric

heater was used. During the work the aim to optimize heater design has not been set. An electrical coil from a serial hydrazine thruster was reeled upon outer surface of the shell. Preheating of the hydrazine catalytic beds is used for improvement of the start-up characteristics, but primarily for reduction of degree of catalyst destruction (that is for increasing of a catalyst life span). In this case the heaters turn on prior to the beginning of the spacecraft control in order that, the catalyst should have required temperature (for example, for space probe "Fobos" it is to be equal to 200°C). It is anticipated that the engines under consideration will function on nitrous oxide in the same manner.

Keeping in mind a large stock of equipment and accessories, we planned to use at the beginning of work the shells from the serial catalytic beds, developed for functioning on hydrogen peroxide. The initial scheme of the catalytic bed for nitrous oxide decomposition is shown in Fig.2a. This catalytic bed had the cylindrical shell (2) from stainless steel with inner diameter $D=18\text{mm}$ and length of catalytic layer $L=35\text{mm}$, the injector (1) of shower type with 8 orifices of diameter 0.7mm . $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ catalyst (3) was fixed in the shell with the use of the briquette (4) from pressed wire twisted in spiral and the grid (5) with cylindrical orifices. Briquette was made from nichrome ($20\%\text{Cr} + 80\%\text{Ni}$). The shell had surface thermocouple (9). The nozzle (6) had two connections for the inner thermocouple (8) and pressure sensor (7). To decrease thermal loss the simplest asbestos heat insulation was used. Mass-dimensional characteristics of tested catalytic beds are shown in table 2.

The results of the fire tests of the above-described catalytic bed permitted to make changes in reactor design. The elaborated scheme of the catalytic bed presented in Fig.2b and its appearance in Fig.3.

RESULTS

The firings of the catalytic beds were carried out at ambient pressure.

In the course of the tests values of pressure were measured in the balloon with nitrous oxide, just upstream the solenoid valve, in chamber downstream the grid. Values of temperature were measured in the propellant duct upstream the flow meter, on the outer surface of the decomposition chamber, inside the nozzle. There were measured monopropellant flow rate, current and voltage in the heater.

Test firings of the catalytic beds were carried out in continuous and pulsed modes. Under trials in continuous mode, function duration (τ_{on}) ranged from 25 to 3000s . Under tests in pulsed mode, pulse duration (τ_{on}) ranged from 0.3 to 10s , pause duration (τ_{off}) ranged from 0.5 to 10s , number of pulses in the test (n_{on}) ranged from 29 to 714 .

Required for start-up preheating temperature of the catalytic bed was achieved due to the electric heater functioning or due to heat of the preceding firing. The tests of the catalytic beds were accomplished at preheating temperature $T_{w.in} = 300 \dots 785^\circ\text{C}$. Inlet

temperature of nitrous oxide was $T_{N_2O} = 6...12^\circ\text{C}$. Preheating of nitrous oxide did not been considered.

The object of testing of the first catalytic bed (No765) was to determine admissible value of transverse consumption rate (loading factor) q_f at which development of self-accelerated reaction of nitrous oxide decomposition is possible. Indication on absence of such reaction as well as inadequate preheating temperature is monotonic decreasing of wall temperature and gas temperature in the nozzle. Tests were carried out in continuous mode with test duration 100s. Initial catalyst temperature was equal to 640°C . The zone of reliable ignition is illustrated in Fig.4. The "ignition" hereafter implies development of self-sustaining exothermal reaction of nitrous oxide decomposition. The main fact what had been noted is the reliable start-up of the catalytic bed took place at flow rate less than 0.2g/s . This value corresponds to admissible transverse consumption rate $q_f = 0.079\text{g/s cm}^2$. As required flow rate of nitrous oxide had to be equal to 0.64g/s the inner diameter of the catalytic bed must be equal to 32mm . Keeping in mind a large stock of the fixing briquettes 30mm in diameter, we choose inner diameter of 30mm for the catalytic bed shell as acceptable for continuing of experimental studies. All following catalytic beds corresponded to the scheme pictured on Fig. 2b. These catalytic beds had the bell-shaped shell (2) from stainless steel and the same injector (1) of the shower type. It was anticipated that such form of the shell could ensure some not uniform field of temperature across catalytic layer that could be favourable for protection of the reactor wall against overheating during prolonged firings.

The purpose of trials of the next catalytic bed (No689) with $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ catalyst was definition of the extent to which reliable start-up is affected by nozzle throat diameter (that is chamber pressure). Obtained results are presented in Fig.5. These data testify that chamber pressure has a profound effect on development of the decomposition reaction. So, at $d_{th} = 1.45\text{mm}$ permissible N_2O flow rate was equal to 0.12g/s , whereas at $d_{th} = 0.75\text{mm}$ it is 0.65g/s . In all on the catalytic bed No689 there were performed 18 tests of overall duration 4785s , the total number of startings-up was 165. Evidence of catalyst deactivation was noted after 16^{th} test. Thus, service life of this catalytic bed with $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ catalyst comprises 3560s in total firing time and 21 in number of startings-up. The distinguishing feature of the start-up of this catalytic bed was presence of abrupt jumps of decomposition products temperature. At the beginning of the test, decomposition products temperature in the nozzle increased relatively smoothly after then it abruptly increased up to $\sim 1200^\circ\text{C}$. It is the sign of the homogenous decomposition reaction of the remains of nitrous oxide passed through the catalytic layer. This is undesirable phenomenon for the catalytic beds, because it is the sign of instability of decomposition process in catalytic layer: any fluctuation of working parameters could cause extinction of the decomposition process. For the catalytic bed No 689

conditions for homogenous reaction development were realized since front of catalytic reaction was located in the vicinity of the end of the catalytic layer (here "front" implies zone of catalytic layer with maximal longitudinal gradient of temperature). In this case on the one hand not all nitrous oxide has a chance to decompose inside the catalytic layer, and on the other hand gas temperature is rather high.

It immediately follows that length of the catalytic layer (34mm) in the bed No689 was too short to be sufficient for reliable functioning. Therefore length of catalytic layer in the next catalytic bed (No21953) was enhanced up to 37.5mm . At the same time content of the active substance in the catalyst was raised. In all on the catalytic bed No21953 there were carried out 7 tests with total turn-on time 3336s at number of starting-up 291. There was no indication on the homogeneous reaction in the nozzle. Evidence of catalyst deactivation was noted after 6^{th} test. So, service life of the catalytic bed No21953 with $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ catalyst comprises 3286s in total firing time and 290 in number of startings-up. Maximal temperature of decomposition products (1130°C) was noted on the test No5 in pulsed mode with $\tau_{on} = 10\text{s}$, $\tau_{off} = 0.5\text{s}$, $n_{on} = 285$. Minimal initial temperature of the catalyst was equal to 630°C . Evaluating of starting-up performance was carried out during 2^{nd} and 3^{d} tests. It showed that value of chamber pressure rise time is at a high level ($\tau_{0.9} = 0.08\text{s}$). Value of pressure decay time ($\tau_d = 0.35-0.37\text{s}$) is close to the desired level (no more than 0.3s). Here $\tau_{0.9}$ is determined from the moment of solenoid valve opening up to the moment of gaining 90% from stabilized pressure level. τ_d is time interval from the moment of solenoid valve shutting-down up to the moment of gaining 10% from stabilized pressure level.

During the test No 4 on 80^{th} s of catalytic bed firing, sampling of gas from the nozzle was carried out. Data of gas adsorption chromatography showed that in sample the nitrous oxide content is 1.23% , oxygen, 28.13% , nitrogen, 68.86% . The deviation of the content's sum from 100% characterizes in general the measurement error. But at the same time it indicates on the need to verify the presence of another nitrogen oxides in decomposition products.

The deviation of fixed decomposition products temperature (1130°C) from thermodynamic value ($\sim 1600^\circ\text{C}$) reflects share of real heat losses.

Survey of defects of the tested catalytic beds showed that the structural elements of the reactors had no evidence of melting; coking of the catalyst pellets was not observed; big part of the catalyst pellets changed its colour from black to blue; on the inner surface of the nozzle the coating of black colour is seen; loss of the catalyst from catalytic bed No21953 was account for 2.4g .

Investigation of $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ catalyst behaviour in catalytic beds revealed considerable reduction of its activity. Thus, after firing time of a bit more than 3000s rate constant of decomposition reaction was lowered by a factor ≥ 4 . Electron spectroscopic chemical analysis revealed interaction of the active component with the carrier to form CoAl_2O_4 (the last

explains change of catalyst color) and changing of carrier phase composition (content of α -Al₂O₃ increases). Reduction of catalyst specific surface by a factor of 10 and decreasing of pore volume by 20% were noted.

Hence data of fire tests and results of laboratory studies shows that the catalysts on the base of transitional metal oxides cannot ensure required service life of the catalytic thrusters for the space vehicles with prolonged mission duration. Nevertheless, taking into account low cost and accessibility of the catalysts on the base of transitional metal oxides, they may be recommended for use in the thrusters of the space vehicle with short lifetime. At the present such thrusters would have the next performance:

- minimal catalyst preheating temperature for reliable start-up is 630°C;
- maximal temperature of decomposition products is 1130°C;
- content of N₂O in decomposition products is about 1.2%;
- chamber pressure rise time up to 90% of stabilized level is 0.08s;
- chamber pressure decay time down to 10% of stabilized level is 0.35-0.37s;
- service life is a trifle over 3000s;
- maximal wall temperature is 1025°C.

Laboratory studies [1] revealed that rhodium catalysts are the most active and the most resistant to high temperature oxidizing medium. Therefore the next catalytic bed (No2234 with dimensions D=30mm, d_{th}=0.92, L=41mm) was loaded with Rh/ZrO₂ catalyst. In all on this catalytic bed with Rh/ZrO₂ catalyst there were carried out 57 tests with overall fire time 37605s with total starting-up number 2292. Evidence of catalyst deactivation was not observed. Trials were stopped after attainment of the required catalyst life span.

Minimal preheating temperature (T_{w.in}=310°C) for this catalytic bed was registered on the first test. But even after third test to ensure the reliable start-up of the catalytic bed we were forced to increase preheating temperature up to 450°C. Maximal temperature of the decomposition products comprised 1140°C. Maximal wall temperature comprised 1025°C.

Trials of this catalytic bed were accomplished in continuous and pulsed modes. Under trials in continuous mode, function duration ranged up to 3000s. Under tests in pulsed mode, pulse duration ranged from 0.3 to 5s, pause duration ranged from 0.5 to 5s.

At the beginning (on 2nd test) and at the end (on 54th test) of trials the samplings of the decomposition products were carried out. For 2nd test, the results of gas adsorption chromatography showed, that content of O₂ is 31.86%, N₂-65.44%, N₂O-0.01%. Evaluating of presence of another nitrogen oxides in decomposition products carried out by infrared spectroscopy showed that NO is absent, content of NO₂ is less than 0.1%. For 54th test, the results of gas adsorption chromatography showed, that content of

O₂ is 28.03%, N₂-70.50%, N₂O-0.11%. The results of infrared spectroscopy showed that NO is absent, content of NO₂ is 1.28%. These data indicate that the catalytic bed No2234 with Rh/ZrO₂ catalyst provides virtually full nitrous oxide decomposition during throughout required thruster service life; content of toxic nitrogen oxide in decomposition products is negligibly small.

The results of the survey of defects of this catalytic bed showed:

- melting of the structural elements including the nozzle is not detected. The bed shell is in the small degree barrel-shaped, but that in no way affected on working capacity of the catalytic bed;
- coking of the catalyst pellets is not observed. Big part of the catalyst pellets changed its colour from black to grey;
- black substance in the form of dust and scale-shaped particles were detected in the nozzle. Results of atomic-adsorption spectroscopy revealed that this substance contains Fe, Ni, Cr. It may be suggested that it is the products of stainless steel corrosion. The scale-shaped particles were accounted for periodical clogging of the nozzle throat that caused instability of monopropellant flow rate from test to test. During trials mass flow rate varied from 0.3 to 0.9g/s (Fig.6).

The next catalytic bed (No2247 with dimensions D=30mm, d_{th}=0.92, L=41mm) was loaded with more active catalyst (Rh/Al₂O₃) than above-mentioned one (Rh/ZrO₂). In all on the catalytic bed No2247 with Rh/Al₂O₃ catalyst there were carried out 37 tests of overall fire time 36120s with total starting-up number 2217. Evidence of catalyst deactivation was not observed. Trials were stopped after the attainment of the required thruster service life.

Minimal preheating temperature (T_{w.in}=300°) for this catalytic bed was registered on the first test. But even after 4th test to ensure the reliable start-up of the catalytic bed we were forced to increase preheating temperature up to 420°C.

Maximal temperature of the decomposition products comprised 1070°C. Maximal wall temperature was a bit more than 1100°C.

Trials of this catalytic bed were accomplished in continuous and pulsed mode. Under trials in continuous mode, function duration ranged up to 3000s. Under tests in pulsed mode, pulse duration ranged from 0.3 to 10s, pause duration ranged from 0.5 to 2s. Results of start-up performance definition on the tests No 7, 8, 9, 10, 11 are presented in table 3. Data of table 3 shows that pressure rise time of this catalytic bed lies between 0.06 and 0.15s; pressure decay time lies in the ranges from 0.29 to 0.39s. Pressure recordings of tests No 9, 11 are presented in Fig. 7 and 8.

Sampling of decomposition products was carried out on 14th test. The results of gas adsorption chromatography showed that content of O₂ is 30.36%, N₂-68.12%, content of N₂O is no more than 0.01%.

As for another catalytic beds the periodical clogging of the nozzle throat took place. It caused instability of monopropellant flow rate and oscillation of chamber pressure. The last is seen from Fig. 9. During trials mass flow rate at the end of tests range from 0.2 to 1.2g/s (see Fig.6). Fig. 10 shows that at the beginning of the test, oscillations of chamber pressure are entirely absent. Then on 140s of the catalytic bed operation the discrete pressure oscillations were observed in the chamber. At the end of the firing oscillation amplitude of chamber pressure ranges up to 5% from stabilized pressure level at frequency of oscillation equaled about 10Hz.

The results of the survey of defects of this catalytic bed showed:

- melting of the structural elements including the nozzle is not detected;
- black substance in the form of dust, scale-shaped and cylindrical-shaped particles were detected in the nozzle (see Fig. 10). The cylindrical-shaped particles are formed in orifices of the grid. The scale-shaped particles are formed on the inner conical surface of the nozzle. The big particles caused nozzle throat clogging. The small particle caused oscillations of chamber pressure. Results of investigation of this substance on X-ray photoelectronic spectrometer ESCA-5400 Perkin Elmer revealed, that this substance is largely composed of iron and chromium oxides (atomic concentration of Ni is 1.2%, Fe, 12.2%, Cr, 10.4%). They are the products of stainless steel corrosion;
- the coking of the catalyst pellets is not observe;
- big part of the catalyst pellets changed its colour from black to grey. Loss of the catalyst mass was accounts for 1.1g.

Investigation of changes in properties of rhodium catalysts in the course of the fire tests revealed noticeable reduction of their activity in comparison with initial value. So, rate constant of decomposition reaction was lowered by a factor 15 for Rh/ZrO₂ catalyst and by a factor 200 for Rh/Al₂O₃ catalyst. Pore volume decreased by a factor 2.2 for both catalysts. Specific surface reduced by a factor 80 for Rh/ZrO₂ catalyst and by a factor 100 for Rh/Al₂O₃ catalyst. Electron spectroscopic chemical analysis revealed that: changing of Al₂O₃ carrier phase composition takes place (content of α -Al₂O₃ increases); changing of ZrO₂ carrier phase composition occurs (content of monoclinic modification increases); oxidizing of Rh happens to form Rh₂O₃ of hexagonal (low temperature) modification and then orthorhombical (high temperature) modification.

Nevertheless because of high level of initial activity both catalysts endured lifetime required for the model catalytic thruster on nitrous oxide. Based on a study of catalysts behavior under operating conditions it may be concluded that, application of Rh/ZrO₂ catalyst in the actual thrusters offers the greatest promise in view of its highest resistance to attack by high temperature oxidizing media.

CONCLUSION

Obtained results shows, that at the present the catalytic model 1N thruster on nitrous oxide with rhodium catalyst has the next performance:

- catalyst preheating temperature is 450°C;
- maximal temperature of decomposition products is 1140°C;
- content of N₂O in decomposition products is about 0.12%;
- chamber pressure rise time is in the range 0.06-0.15s;
- chamber pressure decay time is in the range 0.29-0.39s;
- catalyst service life is more than 36000s;
- total number of starting-up is 2200;
- wall temperature is a bit above 1100°C.

Presented data show that the catalytic thrusters with rhodium catalysts on nitrous oxide can have the acceptable level of the performance what creates a prerequisite for their serial production. This calls for further investigation on search for corrosion-proof materials for decomposition chamber (it is anticipated that refractory alloys with ceramic coating are the most suitable) and elaboration of effective design of the electric heater and the heat insulation.

REFERENCES

1. T. Gaydey, A. Kokorin, N. Pillet, M. Strukova, E. Haustova, G. Shmurak, V. Sadov, N. Yaroshenko. *Development of Catalysts for Decomposition of Nitrous Oxide*. Present conference.
2. D.A. Frank-Kamenetsky. *Diffusia i teploperedatcha v khimicheskoy kinetike*, Moscow, 1963.
3. V. Zakirov, L. Li, G. Ke. *N₂O Propulsion Research at Tsinghua: 2003*. 2nd International Conference on Green Propellants for Space Propulsion. Sardinia, Italy, 2004.

Table 1. The main characteristics of the tested catalysts

№	Composition	Content of active metal, %	Packed density, g/cm ³	Pore volume, cm ³ /g	Specific surface, m ² /g	Activation energy, kJ/mole	Preexponential factor, cm ³ /g s
1	Co ₃ O ₄ +Al ₂ O ₃	26	1.43	0.17	84	120	3.4*10 ⁷
2	Co ₃ O ₄ +Al ₂ O ₃	30	1.67	0.14	84	-	-
3	Rh+ZrO ₂	12	2.19	0.11	-	160	2.8*10 ¹²
4	Rh+Al ₂ O ₃	19	1.28	0.26	108	180	2.7*10 ¹⁵

Table 2. Mass-dimensional characteristics of tested catalytic beds

№ of bed	Catalyst	D, mm	L, mm	dth, mm	Catalyst mass, g	Catalytic bed mass*, g
765	Co3O4/Al2O3	18	35	0.72	14.0	70
689	Co3O4/Al2O3	30	34	1.45(0.75)**	24.7	152
21953	Co3O4/Al2O3	30	37.5	0.98	26.9	-
2234	Rh/ZrO2	30	41	0.92	37.5	131
2247	Rh/Al2O3	30	41	0.92	20.7***	129

Comment. * – Catalytic bed mass is indicated without mass of nozzle, heater, heat insulation.

** - During studies of pressure effect on nitrous oxide decomposition, the nozzles with different throat diameters were used.

***- Pay attention to different densities of Rh/ZrO2 and Rh/Al2O3 catalysts (see. table1).

Table 3. Start-up performance of catalytic bed №2247

Number of test	τ_{on}, s	τ_{off}, s	Number of pulse	$\tau_{0.9}, s$	τ_d, s
7	0.3	0.5	1	0.134	0.388
			125	0.071	-
			250	0.063	0.341
			375	0.063	0.341
			500	0.054	0.340
			625	0.060	0.348
8	0.3	0.5	1	0.118	0.368
			125	0.078	0.363
			250	0.059	0.294
			375	0.059	0.343
			500	0.059	0.343
9	0.3	0.5	1	0.149	0.378
			125	0.086	0.288
			250	0.078	0.339
			375	0.070	0.339
			500	0.088	0.333
			625	0.078	0.294
10	5.0	2.0	1	0.086	0.298
			71	0.078	0.327
			143	-	0.327
11	10.0	2.0	1	0.077	0.308
			25	0.058	0.346

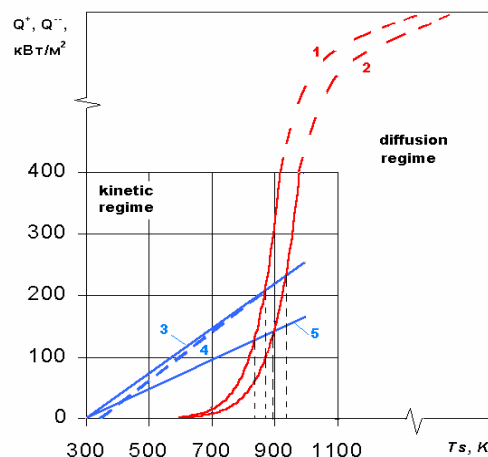


Fig.1. Heat-evolution (Q^+) and heat-removal (Q^-) from catalyst pellet surface vs. catalyst surface temperatures

(1, $Q^+ = f(T_s)$, $P_{ch} = 1.0\text{MPa}$; 2, $Q^+ = f(T_s)$, $P_{ch} = 0.5\text{MPa}$; 3, $Q^- = f(T_s)$, $T_f = 300\text{K}$, $q_f = 0.38\text{g/s cm}^2$; 4, $Q^- = f(T_s)$, $T_f = 350\text{K}$, $q_f = 0.38\text{g/s cm}^2$; 5, $Q^- = f(T_s)$, $T_f = 300\text{K}$, $q_f = 0.134\text{g/s cm}^2$).

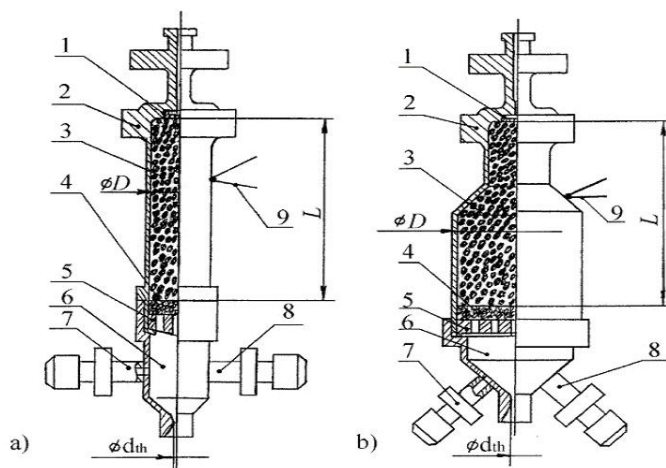


Fig.2. Initial (a) and elaborated (b) schemes of catalytic beds.

1- injector, 2- catalytic bed shell, 3- catalyst, 4- briquette of pressed wire, 5- grid, 6- nozzle, 7- connection for pressure sensor, 8- connection for gas thermocouple, 9- thermocouple



Fig.3. View of elaborated catalytic bed

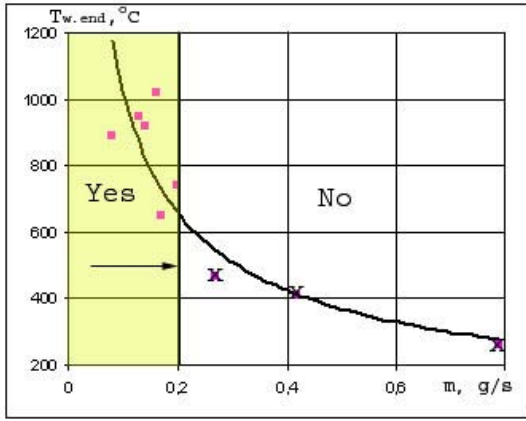


Fig.4. Zone of reliable ignition determined with the use of catalytic bed with dimensions $D=18\text{mm}$, $L=35\text{mm}$, $d_{th}=0.72\text{mm}$.

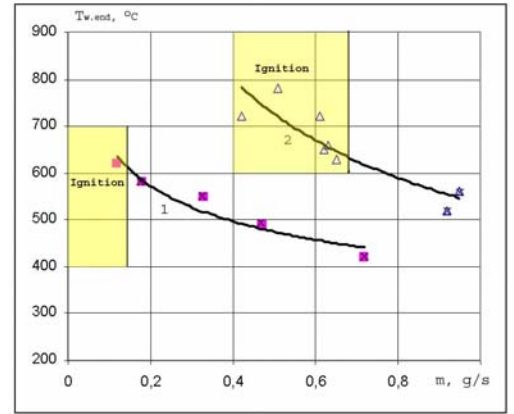


Fig.5. Action of nozzle throat diameter on boundary of ignition zone. 1- $d_{th}=1.45\text{mm}$, 2- $d_{th}=0.75\text{mm}$.

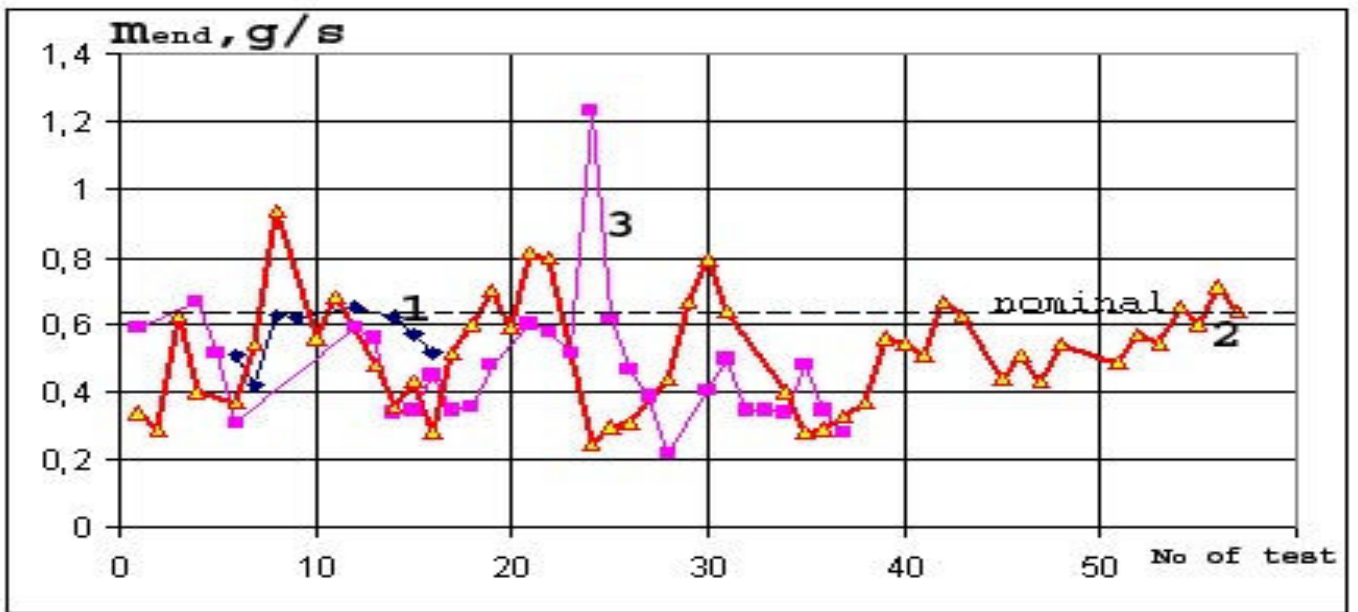


Fig.6. Relationship between monopropellant flow rate at the end of fire test in continuous mode and number of test. 1- catalytic bed No 689, 2- No 2234, 3- No 2247.

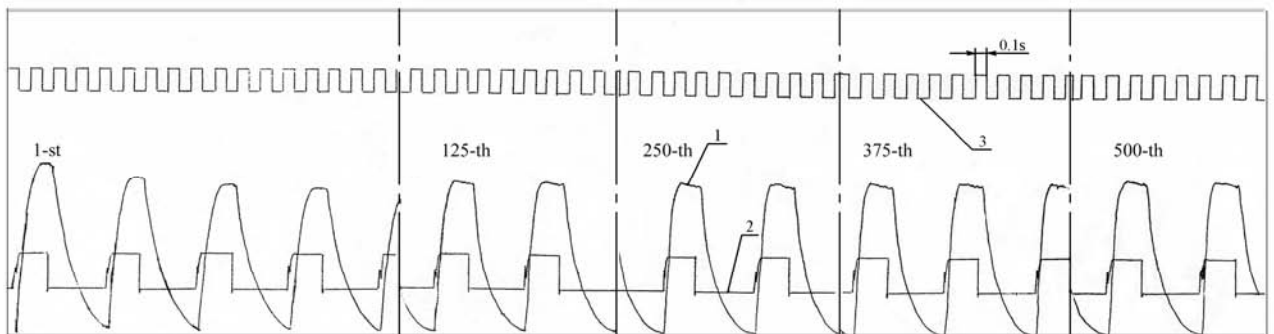


Fig.7. Test No9 of catalytic bed No2247 in pulsing mode with $\tau_{on}=0.3\text{s}$, $\tau_{off}=0.5\text{s}$ (1 is Pch, 2, current in solenoid valve, 3, time mark)

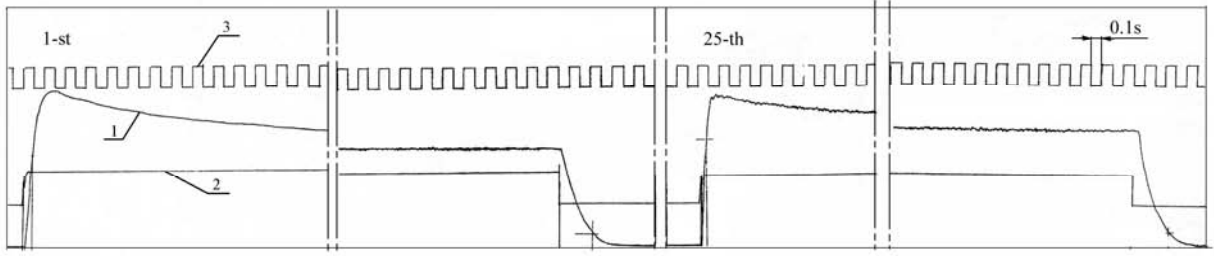
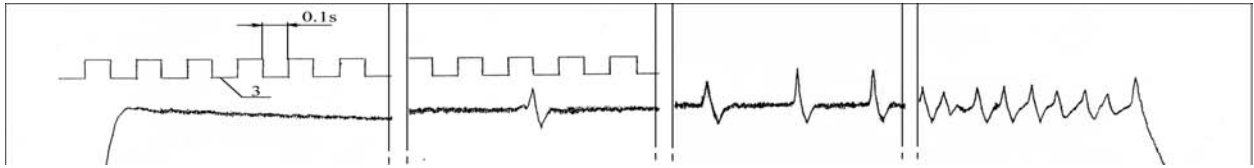


Fig.8. Test No11 of catalytic bed No2247 in pulsing mode with $\tau_{on}=10s$, $\tau_{off}=2s$ (1 is Pch, 2, current in solenoid valve, 3, time mark)



ERROR: ioerror
OFFENDING COMMAND: image

STACK: