DEVELOPMENT OF RD-8 ENGINE SHUTDOWN AT FULL DEPLETION OF PROPELLANTS FROM TANKS OF ZENIT-3SL LV SECOND STAGE

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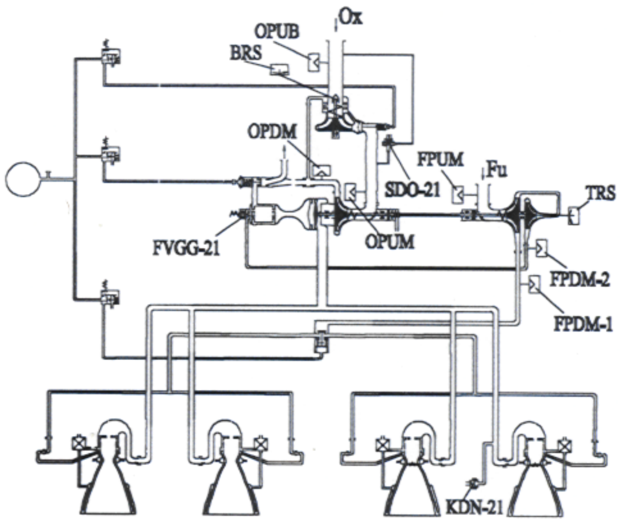
SUMMARY

The system has been elaborated on a safe shutdown of liquid rocket engine (LRE) at full depletion of propellants from tanks of space launcher's 2nd stage. The system has been experimentally verified through LRE firing tests that confirmed its high reliability. Implementation of the engine's shutdown system at full depletion of propellants from tanks of Zenit-3SL LV 2nd stage will allow increase of the payload by more than 100 kg.

INTRODUCTION

The liquid rocket engine RD-8 powered by liquid oxygen + kerosene is a steering engine of Zenit-3SL second stage. It is designed under the staged combustion cycle with preliminary gasification of a complete oxidizer in a gas generator followed by afterburning of the generator's gas with liquid kerosene in a combustion chamber.

The engine's schematics is given in Figure 1.



OPUB, OPUM, OPDM, FPUM, FPDM-1, FPDM-2 – pressure transducers; BRS, TRS – rotational speed transmitters; KDN-21, SDO-21 - pressure indicators, FVGG-21 – fuel valve on gas generator.

Figure 1 – RD-8 schematic

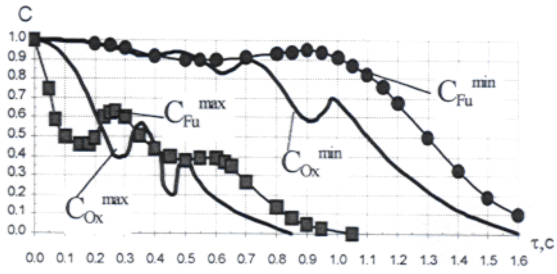
The engine consists of four one-plane-gimbaled combustion chambers, one oxidizer booster pump, one turbopump and automatic units providing under control system's commands the startup, steady-state operation and shutdown of the engine. The vacuum thrust is 8 tf; mixture ratio is 2,41; specific impulse is 342 s; operational time is 500–1200 s. The engine was employed in 38 missions of Zenit LV. There were no any Zenit LV malfunction associated with RD-8 engine.

During an active leg of the second stage flight the engine operates over ≈300 s jointly with the main engine RD-120. After the main engine's shutdown the steering engine continues its operation ensuring achievement of required flight parameters for the 2nd stage. In order to compensate any disturbing factors the 2nd stage is provided with a guaranteed propellant reserve. At a launch of three-stage launcher, like Zenit-3SL LV, its power characteristics may be considerably increased through utilization of that guaranteed propellant reserve from the 2nd stage in capacity of the operational propellant stock. Any influence of disturbing factors acting during 2nd stage operation may be compensated during operation of the 3rd stage. The guaranteed propellant reserve of the latter has to be increased, however this increase will be significantly lower than the 2nd stage reserve to be used as an operational one. For obtaining the power gain it is necessary to provide full propellant depletion from tanks of the 2nd stage.

INFLUENCE OF THE FULL PROPELLANT DEPLETION ON RD-8 ENGINE'S CHARACTERISTICS

The full propellant depletion from tanks is accompanied by increase of gas inclusion (free gas) in the propellant at the engine inlet, since jointly with the propellant a pressurant gas is delivered to the inlet. As the propellant is consumed, the gas fraction is growing. This process is influenced not only by value of remaining propellants, but by pressure in tanks, accelerations, free liquid surface sloshing and by design of the intake device.

Figure 2 presents theoretical diagrams of propellants continuity change at the RD-8 engine inlet (versus time) at their full depletion from tanks of Zenit LV 2nd stage.



C_{Ox}^{max} - max gradient of Ox continuity;

C_{Ox}^{min} - min gradient of Ox continuity;

C_{Fu}^{max} - max gradient of Fu continuity;

C_{Fu}^{min} - min gradient of Fu continuity.

Figure 2 – Analytical change of oxidizer continuity (C_{Ox}) and fuel continuity (C_{Fu}).

The continuity parameter is determined as:

$$C = \frac{Q_{LQ}}{Q_{LQ} + Q_{GS}}, \quad (1)$$

where C is a continuity of propellant flow,

Q_{LQ} is a liquid (propellant) volume flowrate, l/s;

Q_{GS} is a gas volume flowrate, l/s.

The full propellant depletion may be realized in three ways:

1. With fuel outpacing depletion;
2. With oxidizer outpacing depletion;
3. With simultaneous depletion of both propellants.

The analysis of the engine's schematic and results of experimental development of RD-8 engine allows a statement that at full depletion of fuel the engine's operational mode will smoothly decline right until a self-shutdown under favorable change of parameters for all units and with provision of their integrity.

The process of oxidizer full depletion will be accompanied by generator's gas temperature rising. This will lead to overheating and melting of the gas duct elements and finally to the burn-out of the gas duct. It is extremely undesirable for the stage flight, since the mission may be interrupted. Therefore the main task at the full oxidizer depletion is the prevention of these disrupting consequences and provision of engine's shutdown before an ignition begins in the gas duct.

At simultaneous depletion of both propellants the operational mode may have features from the both above cases. However, the generator's gas temperature will rise to a lesser degree than in the second case, if it all, and the operational mode will decline more drastically.

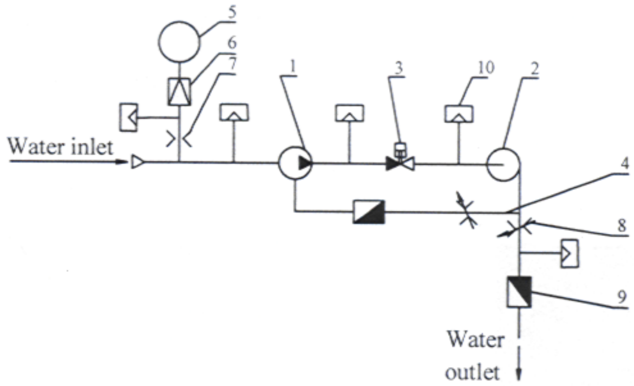
For achievement of the safe shutdown of RD-8 engine under full propellant depletion from the stage tanks the experts of Yuzhnoye SDO have performed substantial volume of experimental work.

CHARACTERISTICS OF RD-8 ENGINE'S PUMPS IN THE CASE OF LIQUID'S CONTINUITY CHANGE AT INLET

In order to determine pumps characteristics in the case of liquid's continuity change at the inlet, the both oxidizer pumps - booster (OBP) and main (OMP) – were tested at the cold flow test bench under simulation of the full oxidizer depletion.

The test setup is shown in Figure 3.

OBP, inlet valve and OMP were assembled like in the engine. The OBP represents an axial-helicoidal pump driven by hydraulic turbine. The OMP is an inducer-centrifugal pump driven by electric motor. The inlet valve is installed directly upstream of the OMP like in the engine. The high-pressure working liquid for the OBP's hydraulic turbine is tapped at OMP outlet like in the engine. In capacity of the working liquid a potable water was used.



1-OBP; 2–OMP; 3-inlet valve; 4-water tapping for OBP hydraulic turbine; 5-air vessel; 6-reducing valve; 7-air flowmeter orifice; 8-throttle; 9-flowmeter; 10-pressure transducer.

Figure 3 – Test setup for cold flow testing of oxidizer booster and main pumps.

The water continuity was changed by air delivery to the OBP inlet. It was performed in two ways:

- through a mixer, presenting a pipe of 20 mm diameter, which was inserted into the inlet line normally to the flow; in the pipe's half facing into the flow multiple holes of 0,5–1 mm are bored; the pipe's end is closed;
- directly through a hole of 20mm diameter in the inlet line wall.

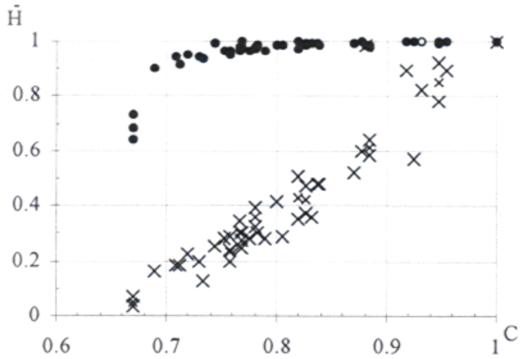
The air was injected through a reducing valve and flowmeter device. The latter was an orifice of 7 mm diameter. The operational modes of OBP and OMP were nominal. The electric motor provided nominal rotational speed under nominal flowrate.

The pumps were tested as follows. After achievement of the nominal mode by the main pump the OBP's parameters were being adjusted to nominal values by changing water flowrate through the hydraulic turbine under use of the throttle. Also the specified pressure at the OBP inlet was provided.

The operational parameters were recorded, and the air feed valve at the OBP inlet was being opened.

Without changing positions of throttles providing required for the nominal mode flowrates through the pump and hydraulic turbine, the amount of injected into the line air was smoothly, at specified intervals, increased. At this all necessary parameters were recorded. The tests were performed at various inlet pressures. For each mode a volume flowrate of injected air (Q_{GS}) was calculated and a volume flowrate of liquid (Q_{LQ}) was measured. The continuity was determined by formula (1).

As a result of flow tests, the influence of the flow continuity on the pump head characteristics was determined. The respective curves for both OMP and OBP are presented in Figure 4.



• - OMP relative head

× - OBP relative head

Figure 4 – Dependence of relative heads of OMP and OBP on flow continuity.

Here, on the vertical axis is given a scale of a parameter $\bar{H}$ that is a relation of the current head value at C_{var} to the head at C = 1. On the horizontal axis – the flow continuity.

As can be seen from these curves, the OBP's head is drastically falls at continuity decreasing and at C ≈ 0,68 is close to zero.

The OMP's head changes insignificantly until C ≈ 0,72 and then drastically falls at C<72.

It should be note also that decline of continuity rises the OBP's rotational speed. It is connected with the fact that the aerated liquid reduces the power consumed by pump at the constant power of the hydraulic turbine.

The tests have not revealed influence of the air injection method on the pump's parameters. At the change of inlet pressure in the range from 0,3 to 5,2kgf/cm^2 any considerable influence on the head decline degree at continuity decrease were not detected as well.

SELECTION OF REFERENCE PARAMETERS AND INSTRUMENTATION PROVISION

An analysis of former experimental data on development of RD-8 engine has resulted in following conclusions:

- the fuel depletion has revealed itself by decrease of engine's operational mode evolving right until a self-shutdown without a loss in serviceability;
- the oxidizer depletion onset causes a drop in OBP head and rise of its rotational speed owing to continuity decline at the engine inlet.

In order to detect the decline of propellant's continuity as a result of depletion, and release respective information to the control system (CS) for generating a shutdown command, the engine is provided with two pressure indicators:

- pressure indicator KDN-21 following the course of fuel depletion. It releases a signal to the CS when the engine's operational mode decreases to 60% from the nominal level. Consequently, the CS after time τ releases a command to shutdown the engine. The indicator KDN-

21 monitors pressure of the oxidizer-rich gas upstream of one from the engine's chambers (Figure 1);

- differential indicator SDO-21 following the course of oxidizer depletion. It releases a signal to the CS for generating a command to shutdown the engine when the OBP head drops to 60% from the nominal level. The indicator SDO-21 monitors pressure difference between the OMP inlet (parameter OPUM) and OBP inlet (parameter OPUB), in other words, the OBP head (Figure 1). The maximum time between a moment of the indicator's action (onset of propellant depletion) and engine's shutdown is composed of the following constituents:

$$\tau_\Sigma = \tau_1 + \tau_2 + \tau_3$$

where τ_Σ is a delay of the engine's shutdown;

τ_1 is a sluggishness of the indicator;

τ_2 is a time between the indicator's action and release of a command for closing fuel valve on the gas generator (FVGG-21) (Figure 1). This time is determined by:

- CS discreteness of indicator's contacts polling;
- necessity to confirm the close state of indicator's contacts for two polling;
- time of CS executive relays action;

τ_3 is a time from a moment of the command delivery to the gas generator's valve till the closing of the latter.

At fuel depletion the time of shutdown delay does not affect the engine's state, but at oxidizer depletion the delay time is one of decisive factors during development of engine's shutdown.

SIMULATION OF PROPELLANT FULL DEPLETION FROM THE STAGE TANKS AT BENCH FIRING TESTS OF RD-8 ENGINE

At bench firing tests of RD-8 engine, it was necessary to verify reliability of developed shutdown system under propellant continuity change at the engine's inlet in accordance with curves in Figure 2. These curves present an analytical evaluation of continuity at the RD-8 engine's inlet at full depletion of oxidizer and fuel from Zenit LV 2nd stage tanks.

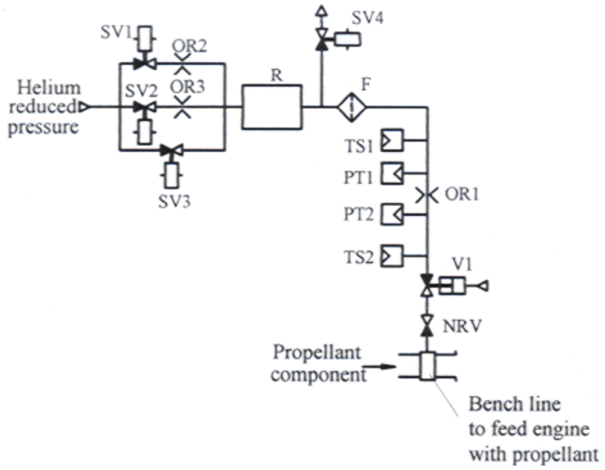
During bench firing tests of RD-8 engine the propellant depletion was simulated by two methods:

1. Propellant depletion from a receiver;
2. Gas (helium) injection into the bench propellant line at the engine's inlet.

The first method allows verification of shutdown's reliability through reproduction of actual propellant depletion from a receiver at specified pressures.

The second method allows reproduction of propellant continuity curves shown in Figure 2. In order to realize this method the firing bench was equipped with specially designed systems of helium injection into the bench oxidizer and fuel lines at the engine's inlet. The principal schematic of the injection system is given in Figure 5.

The helium pressure reduced to the specified level is delivered to the receiver R through three parallel lines with solenoid valves SV1 – SV3 and orifices OR2 and OR3. From receiver the helium passes to the feed line through the valve V1 after its opening. It may also be drained through the solenoid valve SV4. The injection system is equipped with required sensors for measuring gas parameters.



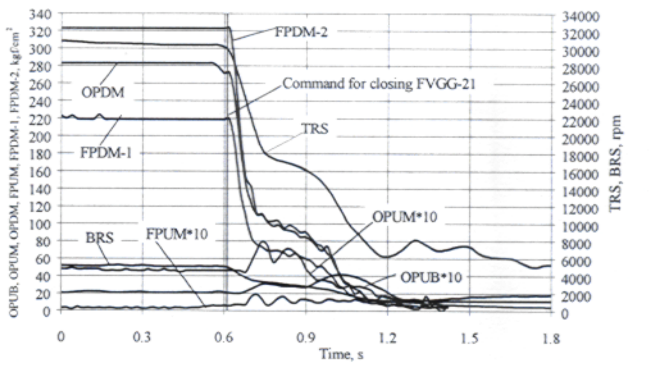
F-filter; NRV-non-return valve; OR1 – OR3-orifice; PT1, PT2-pressure transducer; R-receiver; SV1 – SV4-solenoid valve; TS1, TS2-temperature sensor; V1-pneumatic-driven valve.

Figure 5 – Schematic of helium injection into the feed line of RD-8 engine

The helium flowrate required for reproduction of curves from Figure 2 was provided through selection of orifice internal diameters, specified sequence of actions of valves SV1 – SV4 and helium inlet pressure value. Helium was injected into the propellant line through a hole of 20 mm diameter in the line's wall.

ENGINE'S SHUTDOWN AT FUEL DEPLETION

During bench firing tests, including a phase of RD-8 engine development, at 8 tests the engine's shutdown was performed under simulation of full fuel depletion. The shutdown command was delivered after action of the pressure indicator KDN-21. In general the shutdown was executed in accordance with the normally used sequence. The first command interrupted fuel supply to the gas generator (the valve FVGG-21 was being closed), the second command caused closing of all other valves. During 3 tests the fuel depletion was simulated through full fuel depletion from the inlet receiver, during remained 5 tests – through helium injection into the bench feeding line. In each said test the fuel flowrate through the gas generator declined, gas temperature decreased, and turbopump rotational speed and pressure in combustion chambers fell. At mode falling to 60% from the nominal level the pressure indicator KDN-21 acted, and with delay from 0,1 to 0,19 s a command for engine's shutdown was released. The shutdown on fuel depletion differs from the normal one only by the fact that before the closing of the fuel line the combustion chamber pressure is being decreased to 60% with favorable change of parameters for other engine's units. In all cases the shutdown was going on without any negative remarks as for the engine state. The delay at the command for closing FVGG-21 valve after action of the pressure indicator (τ_2 – up to 0,19 s) did not affected the test result. Figure 6 presents curves of RD-8 basic parameters during the normal shutdown, Figure 7 – the curves of the same parameters at simulation of fuel depletion by helium injection into the feed line and engine's shutdown after action of the pressure indicator KDN-21.



OPUB-oxidizer pressure upstream of booster; OPUM-oxidizer pressure upstream of main pump; OPDM-oxidizer pressure downstream of main pump; FPUM-fuel pressure upstream of main pump; FPDM-1-fuel pressure downstream of main pump 1st stage; FPDM-2-fuel pressure downstream of main pump 2nd stage; BRS-booster rotational speed; TRS-turbine rotational speed.

Figure 6 – Change of engine's parameter at normal shutdown

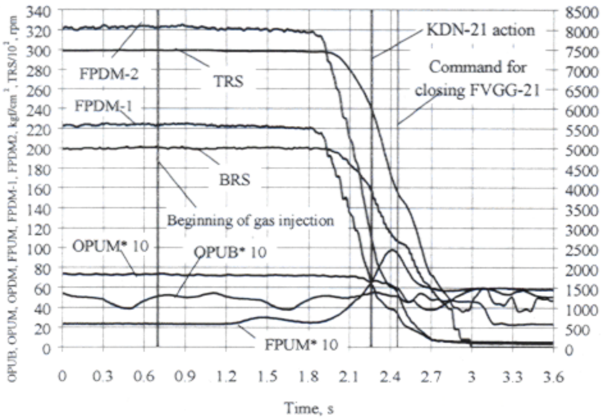


Figure 7 – Change of engine's parameters at shutdown on fuel depletion

ENGINE'S SHUTDOWN AT OXIDIZER DEPLETION

During bench firing tests in the phase of RD-8 development certain circumstances culminated in unsanctioned full depletion of oxidizer from the bench tanks. At this the engine was not equipped with a special system of safe shutdown. The behavior of basic engine parameters for the said case is illustrated in Figure 8.

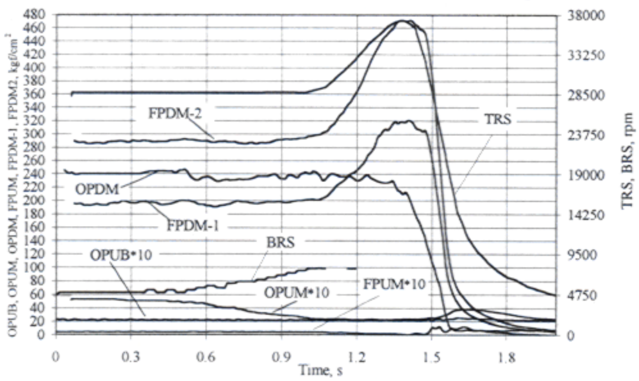


Figure 8 – Change of engine's parameters at shutdown at full oxidizer depletion from the tank

The first reaction to the oxidizer depletion was decline of OBP head (OPUB parameter) and growth of OBP rotational speed (BRS parameter). After 0,2 – 0,4 s (depending on actual continuity decrease gradient) a break-down of oxidizer main pump operation began to come in light. It was revealed through increase of the turbine rotational speed (TRS parameter) and then drop of OMP head (OPDM parameter). The process ended with a burn-out of the gas duct with a sharp fall of the rotational speed and fuel discharge pressure.

In the phase of the safe shutdown system development 14 bench firing tests were performed under simulation of full oxidizer depletion. The shutdown command was released after action of the pressure indicator SDO-21 when the OBP head was lowered to ≈ 60% from the nominal value. The delay of command for closing valve FVGG-21 totaled from 0,1 to ≈ 17s in different tests. The full depletion was simulated both by gas (helium) injection into the feed line and oxidizer depletion from the receiver. At gas injection a reproduction of continuity drop curves was provided (Figure 2). At minimum, as well as at maximum gradients of oxidizer continuity delay (τ_2 = 0,17 s) in releasing command for closing the valve FVGG-21 after action of the pressure indicator SDO-21 the engine's shutdown was going on safely, without negative remarks as for a state of engine's elements.

The typical behavior of engine's parameters at oxidizer depletion from the receiver is shown in Figure 9.

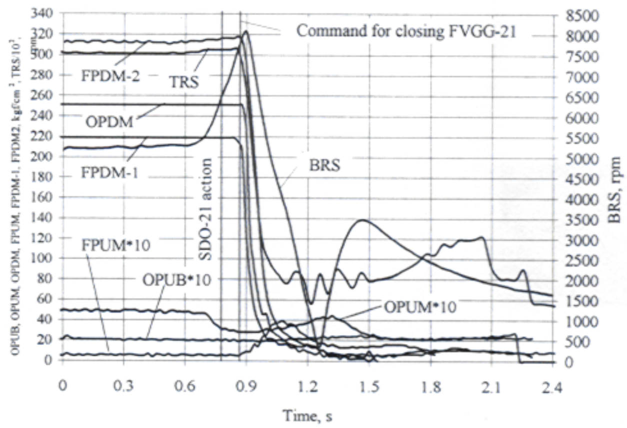


Figure 9 – Change of engine's parameters at shutdown on oxidizer depletion from receiver

The parameters behavior at engine's shutdown under simulation of oxidizer depletion through gas injection is shown in Figure 10.

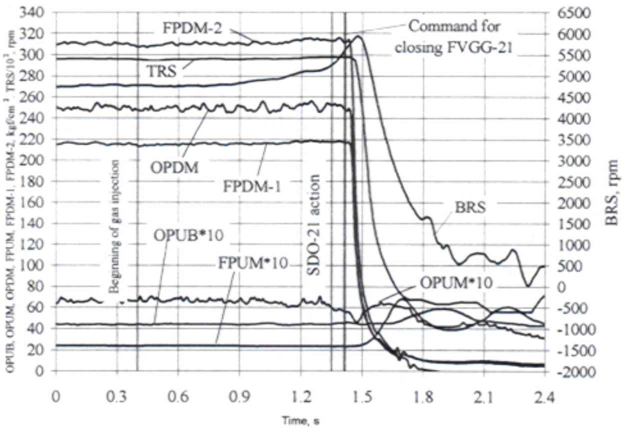


Figure 10 – Change of engine's parameters at shutdown on oxidizer depletion

In the last figures the moments of action are marked for both pressure indicator SDO-21 and valve FVGG-21. The figures show that during shutdown the turbine rotational speed (TRS parameter), Ox/Fu pump discharge pressures (parameters OPDM, PFPDM-1, FPDM-2) are practically at the same level, as before onset of the depletion. This means that the engine's shutdown is performed timely, before development of destructive events because of oxidizer continuity decline owing to the depletion.

ENGINE'S SHUTDOWN AT SIMULTANEOUS DEPLETION OF OXIDIZER AND FUEL

In the phase of engine's shutdown development under propellant depletion 2 bench firing tests were performed with simulation of simultaneous depletion of oxidizer and fuel. It was realized by simultaneous injection of gas (helium) into Ox/Fu feed lines at the engine inlet. At this the maximum gradients of continuity decline were reproduced. The behavior of engine's parameters at simulation of propellants depletion and engine's shutdown is shown in Figure 11.

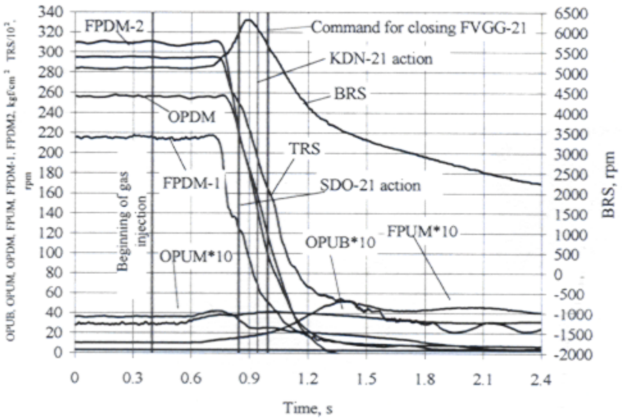


Figure 11 – Change of engine's parameters at shutdown on depletion of oxidizer and fuel

The beginning of the injection causes decline of the turbine rotational speed and pumps discharge pressure. The OBP head also drops, and its rotational speed rises. The first action was made by the pressure indicator KDN-21 with following shutdown command release.

Temperature increase of the generator's gas was not detected.

CONCLUSION

The performed bench firing tests of RD-8 engine have confirmed reliability of developed by experts of Yuzhnoye SDO system of the engine's safe shutdown at full propellant depletion from tanks of Zenit-3SL LV 2nd stage.