# Researches for Reaching Minimum Thrusts in Regulates Monofuel Micro Liquid Propulsion Thrusters

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## Abstract

A package of experimental studies has been carried out to develop micro thermocatalytic thrusters (micro-TCT) working on hydrazine. A series of engineering models of thrusters with thrust range from 5 to 50 mN has been developed and successfully studied. The possibility to obtain minimal thrust was experimentally demonstrated both by traditional way at the expense of minimization of hydraulic and gas dynamic section of a thruster and at the expense of change-over to pulse propellant supply with simultaneous reduction of the requirements to injection unit hydraulic resistance. The possibility to maintain low thrust value was verified by means of automatic control system with pressure feedback in a thruster chamber.

## Introduction

The problem of micro-TCT development with thrust value of a few tens of mN is, first of all, to settle two conflicting questions:

-on the one hand it is necessary to provide the manufacturing and later stability of hydraulic characteristics of capillary passages for propellant supply into a thruster chamber during long period of its operation;

-on the other hand it is necessary to provide stable operation of the propellant supply unit due to sharp decrease of propellant consumption.

For micro-TCT with the thrust of about 1 N necessary the diameter of the unit for liquid propellant injection into the chamber is very small and this may complicate thruster service because of real possibility of orifice blockade. Therefore, it is assumed that minimal orifice diameter of the elements supplying propellant into the micro-thruster's chamber are limited by dimension of ~ 0.2 mm [1,2]. One way to obtain still lesser thrust is the change-over to the propellant gasification that was realized in a number of thruster designs.

As is generally known that under turbulent mode of liquid flow in contrast to laminar flow, the resistance coefficient value depends not only on Reynolds number but on the relative roughness of the tube wells. With the increase of Reynolds number and the decrease of laminar sublayer depth the roughness begins to play a leading part and in the self-similarity area - the determining part. With the decrease of tube diameter up to ~ 0,2 mm the relative roughness may increase considerable. However the surface finishing requirements for micro-thruster's capillaries of small diameter are usually very high: these capillaries are made with equivalent roughness not greater than 1,5 $\mu$m. It is assumed that tuber are hydraulically smooth if the relative roughness is not greater than 0.007. According to the data [2] the comparison of the resistance coefficient values for glass tubes, being hydraulically smooth, and the same coefficient for steel tubes with relative roughness not greater than 0.007 demonstrated no considerable difference between them.

In practice of micro thruster testing and operation the events of gradual (progressive) decrease of propellant consumption are observed. This happens because of hydraulic resistance of the injection unit owing to obliteration.

There is a well-known cycle of studies performed for different and related with hydraulic characteristics stability of the capillary passages made of stainless and other materials end with inside diameter of 0.18 mm and 0.3 mm and up to 100 mm in length. This studies demonstrated that the obliteration process is not a mechanical blockage of the capillary by particles of contaminated liquid with the dimension commensurable with that of the capillary flow area, but a very complicated process of gradual deposition of mechanical and dissolved contaminants on inside surface of capillary . There was an attempt to estimate the influence of diameter and length of the capillary, pressure drop on the capillary, running-through mode, degree of purity of the liquid and quality of inner surface cleaning on the obliteration. It was demonstrated that the fluoroplastic or glass capillaries were not practically subjected to obliteration during ~ 100 hours of running through mode in contrast to stainless steel capillary.

During these studies it was failed to determine quantitative law of above mentioned factors influence on obliteration process while continuous running-

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through of capillary influence. Only qualitative, more or less obvious results of capillary diameter and length influence were obtained: the smaller diameter and longer capillary the shorter time of running-through needed to determine liquid consumption decrease. However there was a suggestion based on there experiments that inside surface state of susceptible to obliteration capillary differs from the surface state for the rest of capillaries. On the next stage of experiment the running-through were carried out in the pulse mode ($\tau_{pulse}$= 0,1 s, $\tau_{pause}$ = 0,1 s). A distinguishing feature of this experiment was that there was a spasmodic recovery of liquid consumption after some period when obliteration was observed. This corroborates the idea that during obliteration process the layer of substance not strong enough is formed on the inside surface of capillary. This layer of substance is influence comparatively poor connection with the capillary surface, breaks away and flies out of capillary when under some conditions (for example, when pulse fuel supplying).

As a result of studied carried out was demonstrated that obliteration process depends to a greater degree on the state of capillary inside surface. During experiments, the capillary of 0,3 mm influence diameter turned out to be more susceptible to obliteration than one of 0,18 mm in diameter. The results obtained confirm the consideration that it is appropriate (besides settling the question to make high fuel purity available) to have a method of surface state testing that can identify the differences of inside surface states for different capillary (susceptible to obliteration or not) to make the hydraulic characteristics stable.

The liquid flow influence capillary passage of the operating thruster can be regarded as a flushing liquid for removal of different newly formed contaminants from inside surface of the capillary. In paper [3] it was demonstrated that when changing from the stationary flow to the pulse method of pipeline running through, the intensity of their cleaning increases significantly and the higher speed of liquid flow and amplitude-frequency characteristic the greater intensity. These conditions are best realized in the controlled thruster with pulse-width modulation (PWM) of propellant supply.

Thus, the problem of the 5...50 mN microthruster development is not associated directly with traditional limitation dealing with minimization of the capillary flow area of the thruster, especially in the pulse mode of supply.

## Experimental studies

The engineering model of thermocatalytic thruster КЗШИМ, workings on hydrazine for thrust value of 5...200 mN was developed by FAKEL. This model can throttle the thrust both by changing the propellant pressure at the in bet and by PWM of propellant supply to the decomposition chamber.

The PWM control of continuous thrust is maintained by varying the pulse propellant supply to chamber with period not greater than time constant of propellant decomposition. By doing so, the corresponding relatively constant pressure of decomposition (combustion) products which depends on mean propellant consumption will be maintained in chamber for the given concrete pulse mode of propellant supply.

Almost ultimate thrusts in this thruster were achieved by using propellant supply unit of special design with flow area of ~ $0{,}8 \cdot 10^{-2}$ mm$^2$ pressure. Fig. 1 shows the Experimental relationship between the thrust of (P) and the hydrazine pressure change at the in bet. The thruster operated steadily at all continuous modes with thrust values from 4 to 168 mN, and showed 40-fold change of thrust. The observed spread in thrust values at the level ~ 10 mN was related to increased error of propellant pressure maintenance at the in bet.

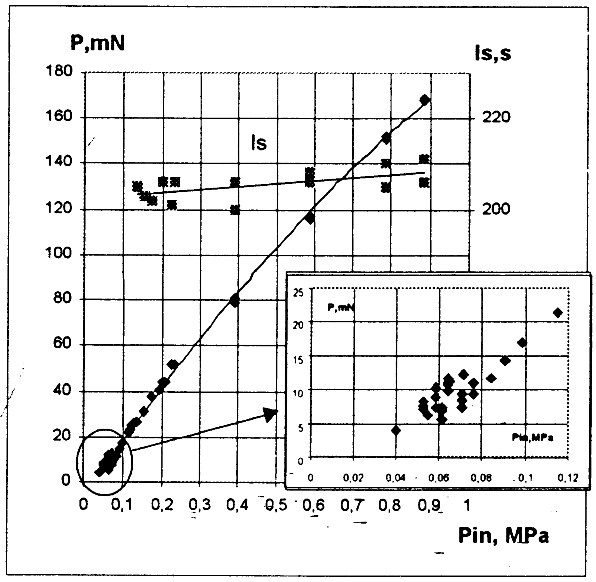

Fig. 1. The thrust and specific thrust impulse of the КЗШИМ thruster # 2 as a function of hydrazine pressure at the input

It should be pointed out that thruster efficiency (Is) remained at relatively high level (Fig. 1) in wide range of thrusts. To solve some problems dealing with the orientation and stabilization of a spacecraft the use of similar thruster with the lesser thrust may be more effective than the use but with short or single switch-on1. That difference in the efficiency according to specific thrust impulse as to developed hydrazine thrusters and conditions of then application may reach the value of up to 15...30%.

Fig. 2 shows the relationship between the thrust of the КЗШИМ thruster and the defining pulse ratio

($K_3$) of a pulse mode at pressure of $P_{in}$=0,17 MPa and frequency of regulating valve switch-on f=20 Hz.

As is known, the slope of adjusting characteristic and smoothness of thrust regulation while changing $K_3$ ratio are first of all determined by gas dynamic quality of the thruster and dynamic parameter of the regulating valve [4]. Gas dynamic quality of the thruster is determined by relationship between pressure drop in the hydraulic passage for propellant supply to the decomposition chamber and pressure proper in the chamber. Gas dynamic quality of K3ШИМ thruster, which was developed first of all as a thruster with the propellant pressure control at the in bet, is relatively low. Therefore, the relationship P = f ($K_3$) in this thruster has a relatively sharp change of thrust in a narrow range of low values of the $K_3$ ratio. However, as will be shown below, any required value of thrust can be available even with this adjusting curve by means of automatic control system.

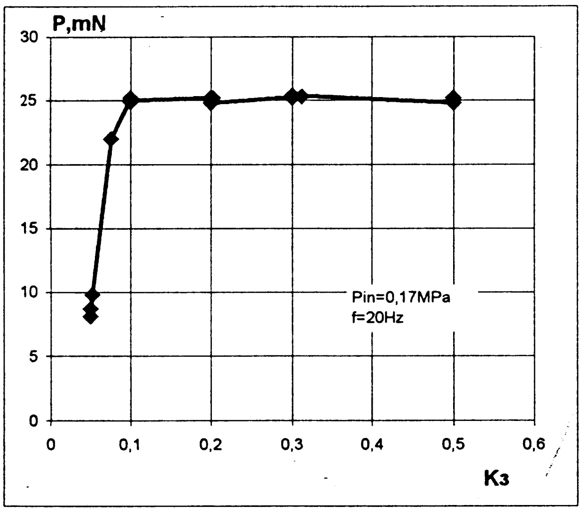

Fig. 2. The relationship between the thrust of K3ШИМ thruster # 2 and $K_3$ ration change

The problem of availability of thrust values not greater than 50 mN can be solved by using PWM thrust control of the thruster with greater values of gas dynamic quality and therefore with more acceptable smoothness of the adjusting curve change. The distinctive features of the K10ШИМ controlled thruster as compared with the K3ШИМ thruster are the wider range of maximum thrusts (up to 1 N) and increased (approximately 5 times as large) gas dynamic quality. A series of experimental curves (pressure as a function of the $K_3$ ratio) of the K10ШИМ thrusters is shown Fig.3 for two constant levels of hydrazine pressure at the inlet. Stable operation of thrusters was observed in the whole range of thrust control action including the range of less than 50 mN.

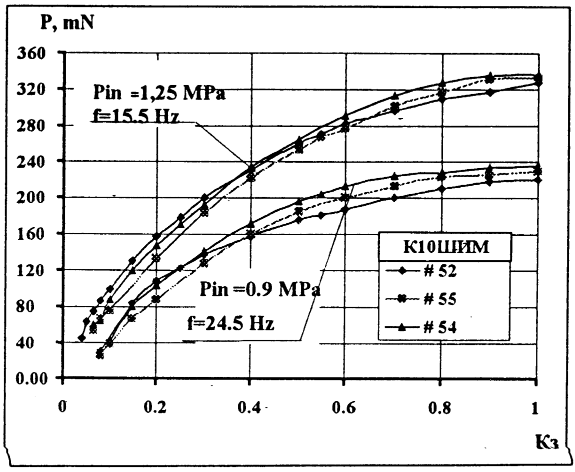

Fig. 3. The relationship between the thrust of thrusters and the $K_3$ ratio under different operating conditions

The pulse mode tests of a thruster with switch-on time of $\tau_{pulse}$= 1 s, $\tau_{pause}$= 3 s were carried out in order to estimate the operating stability margin of the K10ШИМ thruster in PWM control mode in the range of low thrust values with f = 20 Hz valve switch-on frequency. In this case with thruster operation at 0,1 N thrust mode the temperature of external body of the regulating valve and consequently the propellant temperature was positively increased up to 96°C. In this conditions there was no tendency toward the appearance of the propellant supply "lock out effect" by the injection unit. This effect is always a problem for monopropellant micro-thrusters. The point of this phenomenon is that "thermal lock out" of the injection unit due to boiling and decomposition of propellant takes place at certain modes of thrusters switching on with additional warming up of injection unit in pauses between switchings on. And therefore this can lead to limitations of thruster operation modes and thermal conditions of thruster usage during operation. The problem of stable operation of the other Fakel's thrusters with PWM control did not arise too. Although it should be mentioned that as to thermal condition when changing from continuous propellant supply to pulse propellant supply the operation continuous of propellant supply unit become worse and can be accompanied by some temperature increase of the unit. However this temperature increase had no effect on thruster capacity for work. This is a consequence that due to pulse injection the ingress of propellant into the decomposition chamber of a thruster with throttling rate increase takes place in more favorable conditions as compared to traditional way of propellant pressure decrease the thruster inlet. So, under - identical operation conditions and mean propellant consumption with regulating valve operation mode of $K_3$ = 0.1 the instantaneous velocity of propellant injection into the chamber of a thruster with PWM control is significantly higher them the injection velocity for continuous supply.

Using the K10ШИМ thruster serial # 55 as an example, Figure 4 shows the possibility to throttle the thrust for propellant pressure at the inlet with the constant values of $K_3$ ratio, al no in the interval of high thrust throttling. The thruster operated in stable mode without any remarks with thrust values less then 0.1 N.

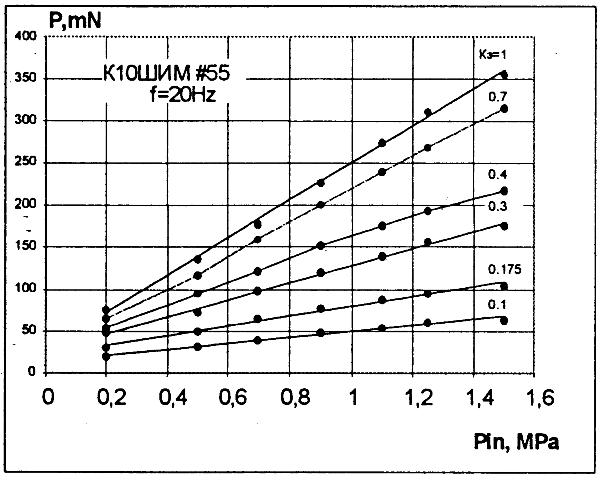

Fig. 4. The relationship between the thrust of a thruster and hydrazine pressure at the inlet for different values of $K_3$

It should be mentioned that the slope of $P=f(P_{in})$ curves decreases (i. e. the relationship between the thrust and pressure oscillation on the inlet becomes less fast) when $K_3$ value decreases. This is essential for providing of low thrust since this confirms the circumstance that pulse mode of propellant supply, in fact, creates "an additional equivalent hydraulic resistance" in the injection unit as compared to continuous injection of propellant into the chamber. Thus when developing such type of thruster with low thrust the requirement of hydraulic chamber dimension minimization can be reduced providing, at the same time hydraulic resistance required.

When providing throttleable thrust in the PWM mode of control the peculiarity of thrust start-up dynamics should be meant. This peculiarity can be illustrated as follows. At the first moment, when mean starting propellant consumption is proportional to the $K_3$ ratio, it can be represented as follows:

$$m_{start} = (P_{in}/C) \cdot K_3,$$

were $m_{start}$ - starting consumption;
$C$ - hydraulic resistance of the valve and injection unit which depends on its geometrical dimensions and physical properties of a propellant.

This equation can be written in another way:

$$\tau \sim (m_{start})^{-1} = (P_{in} \cdot K_3), \qquad (1)$$

which describes the time of "start-up" portion of fuel supply into a thruster to provide its start-up. Equation (1) shows that the time needed for a thruster with PWM controlled thrust to reach steady mode will be the smaller, the lover the hydraulic resistance of valve and injection unit, the greater propellant pressure at the inlet and the $K_3$ ratio. This conclusion is well coordinated with experimental data FAKEL received for different controlled thruster.

This circumstance can be very important during start up mode with $K_3$ = const to provide very low thrust by means of PWM control. However it can be easily parried by regulating valve control system, for instance, by prolonging the propellant supply during first switching-on of the valve.

To provide on accuracy requirements for spacecraft control regarding thrust and thrust impulse (given thrust level or given time of switching-on) in the main range of PWM thrust throttling it is advantageous to use automatic control systems. In this case, for instance pressure in a the star chamber, spacecraft orientation sensor readings, e to can be used as parameters of control.

In order to confirm the possibility of given thrust maintenance on relatively fast regulating curve $P=f(K_3)$, studies of the K10ШИМ thruster serial #3 functioning in the hydrazine decomposition product pressure feed back control system have been carried out. Electric power supply of the regulating valve has been performed at frequency of 50 Hz with $K_3$ ratio automatically changed. Firing tests results of the system are shown in Fig. 5.

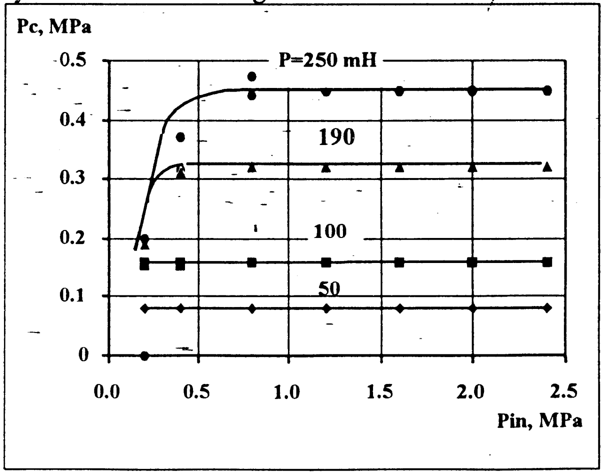

Fig. 5. Given thrust (pressure Pc in the chamber) maintenance in automatic mode of the K10ШИМ thruster control when changing the hydrazine pressure at the inlet

The maintenance of given thrust levels was stable provided during repeated change of propellant pressure at the inlet. In this case the maximum degree of thrust throttling (at the level of 50 mN) compared to maximum possible thrust for this thruster (1 N at Pin=2.2 MPa) accounted for not less than 20. Since main hydraulic resistance of supply unit thruster was only the resistance 0.3 mm diameter regulating valve inlet, the thruster had fast P = f ($K_3$) curve. In order to maintain the given thrust when increasing propellant pressure at the inlet, the $K_3$ values tended not only decrease (as it should be expected for ideal case) but slightly to increase due to changing dynamic parameters of regulating valve (Fig. 6).

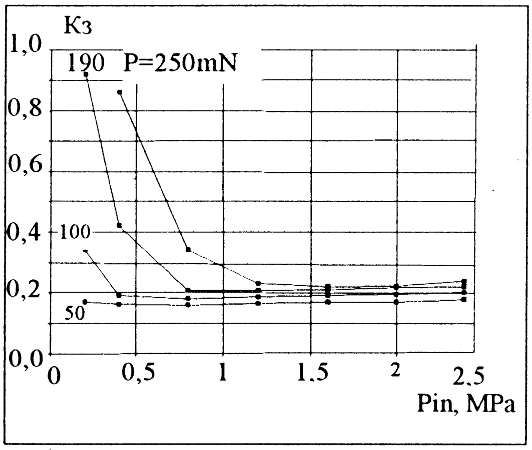

Fig. 6. The $K_3$ ratio change by control system when changing propellant pressure at the inlet

## Conclusion

Experimental studies carried out at FAKEL to attain minimal thrust in the controlled micro-TCT on hydrazine allow to make the following conclusions:

1. The microthrusters with the thrust of 5...50 mN both with pulse and with continuous propellant supply to the decomposition chamber have been developed.
2. The increased stability of thruster with pulse propellant supply was shown.
3. Using PWM mode of control in thruster allows to throttle practically any thrust beginning from maximum thrust which depends on propellant pressure level at the inlet.
4. The possibility and prospects to use the controlled thruster in the automatic control systems with feed back from the thruster or spacecraft sensors were shown.

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