

## THRUST CHARACTERISTICS OF MICROTHRUSTERS WITH NANOTHERMITE-BASED FUEL

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**Abstract:** The possibility of using Al/CuO nanothermite (NT) as a propellant for a microthruster has been investigated. To change the characteristics of combustion and ignition of an NT mixture of various densities, the influence of a gas-generating additive, nitroguanidine, was studied. It was found that introducing up to 16,5 % (wt.) nitroguanidine into a stoichiometric NT Al/CuO mixture more than doubles its combustion rate and nearly quadruples its specific impulse. The influence of microthruster design features on their thrust characteristics has been also studied.

**Keywords:** microthruster; nanothermite; burning rate; nitroguanidine; specific impulse; Laval nozzle

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### Figure Captions

**Figure 1** Schematic diagram of the setup for measuring the thrust characteristics of a microthruster: 1 — control computer; 2 — digital oscilloscope; 3 — pyrometer; 4 — laser; 5 — lens; 6 — protective glass; 7 — mirror; 8 — light guide; 9 — microthruster; 10 — thrust force sensor (TFS); 11 — TFS power supply; and 12 — Phantom Miro LC310 video camera

**Figure 2** Diagram of the setup for calibrating the pressure sensor for force measurement: 1 — electromagnet; 2 — steel ball; 3 — ball guide tube; 4 — video recording window; 5 — extension rod; 6 — rod guide cylinder; 7 — M109C11 PCB pressure sensor; and 8 — Phantom Miro L310 video camera

**Figure 3**  $x-\tau$  diagram of ball movement:  $u_1 = 1.29 \pm 0.01$  m/s;  $u_2 = -(0.45 \pm 0.01)$  m/s;  $v = -(0.22 \pm 0.01)$  m/s; and  $\Delta P = 15.38$  N·ms

**Figure 4** Oscillogram of the force profile  $F(\tau)$  recorded by the sensor, integral from 0 to 0.14 ms:  $I_F = 13.91$  mV·ms

**Figure 5** Microthruster design: 1 — Laval nozzle; 2 — straight tube; 3 — NT fuel; and 4 — engine housing

**Figure 6** A film sequence of a microthruster in operation with a flying Laval nozzle (interval between frames is 4.16  $\mu$ s)

**Figure 7** A film recording of a steel microthruster with a Laval nozzle in operation (interval between frames is 7.14  $\mu$ s)

**Figure 8** Dependence of thrust pulse  $I_\Sigma$  of microthruster with nozzle on fuel weight  $W$ : 1 —  $I_{sp} = 30 \pm 4$  s at 0% NQ; 2 —  $I_{sp} = 48 \pm 2$  s at 5% NQ; 3 —  $I_{sp} = 80 \pm 3$  s at 15% NQ; 4 —  $I_{sp} = 86 \pm 3$  s at 16.5% NQ; and 5 —  $I_{sp} = 156 \pm 4$  s at 15% NQ (with flying-off nozzle)

**Figure 9** Dependence of specific impulse of NT mixture with addition of 15% NQ on its porosity

**Figure 10** Typical thrust profiles of microthrusters (NT without additives): 1 — top-axis ignition:  $I_{sp} = 22 \pm 2$  s; and 2 — bottom-axis ignition:  $I_{sp} = 17 \pm 2$  s

**Figure 11** Experimental assembly: (a) diagram (dimensions are in millimeters); and (b) photograph

**Figure 12** A film recording of fuel combustion propagation during ignition from below (interval between frames is 7.14  $\mu$ s)

**Figure 13** Distribution of copper drops along the length of the glass tube after the test. The scale is in millimeters

**Figure 14** A fragment of a film recording of NT combustion in a straight glass tube

**Figure 15** Thrust profile of a quartz glass microthruster with fuel ignited from below

**Figure 16** Dependence of the specific impulse of NT with 5% NQ on the length of the combustion chamber of a microthruster

### Table Caption

Effect of NQ additive on nanothermite burning rate in a steel tube

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