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CATAPULT LAUNCHING TESTS OF AN UNMANNED AERIAL VEHICLE WITH A RAMJET PULSED DETONATION ENGINE

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Abstract

The air-breathing ramjet pulsed detonation thrust module (TM) for an unmanned aerial vehicle (UAV) designed for a subsonic flight at a speed of up to 120 m/s when operating on a standard aviation kerosene was developed using the analytical estimates and parametric multivariant three-dimensional (3D) Computational Fluid Dynamics (CFD) calculations. The TM consists of an air intake with a check valve, a fuel supply system, a pre-chamber jet ignition system and a combustion chamber with an attached detonation tube. Experimental samples of TM were fabricated, and their test fires were carried out on test rigs with thrust-measuring tables. In the test fires, TM characteristics were obtained in the form of dependencies of effective thrust, aerodynamic drag and fuel-based specific impulse on the speed of the approaching air flow. It has been experimentally shown that the fuel-based specific impulse of the TM reaches 1000–1200 s, and the effective thrust developed by it reaches 250 N. The results of catapult launching tests of UAVs powered with one and two paired TMs are presented. The autonomous flight of an UAV with a new type of power plant is demonstrated for the first time. The difference from the US flight tests of the piloted Long E-Z aircraft powered by the multitube pulsed detonation engine (PDE), performed in 2008, is the natural (ram) rather than forced air supply into the engine. The results of catapult launching tests of UAVs with a take-off mass of up to 100 kg have shown that the PDE-based TMs provide a subsonic flight with acceleration and climbing. Due to the simplicity of design and low cost, as well as high propulsion performances, such TMs can be considered as an alternative to the propulsion units based on piston and turbojet engines for subsonic UAVs.

Keywords: Pulsed detonation engine; ramjet; kerosene; UAV; flight test

1 Introduction

Improving the efficiency of light UAVs with a take-off mass exceeding 50 kg is one of the current interests in light aircraft industry. As a rule, such UAVs are equipped with small but expensive turbojet or piston engines. As an alternative, electric motors are considered which have a number of limitations and require infrastructure for charging batteries.

Another alternative is ramjet engines: pulsejets and PDEs [1]. Pulsejets were actively developed in the 1930s–1950s. In such engines operating in a self-oscillating combustion mode with an operation frequency of 100–200 Hz the average static pressure in the combustor increases only slightly. A well-known example of such an engine is a German V-1 pulsejet with a fuel-based specific impulse $I_{sp} \approx$ 600–700 s in the cruising flight. In contrast to the pulsejet, combustion of fuel–air mixture in a PDE occurs in the detonation mode at a frequency of up to 20-40 Hz, which makes it possible to significantly increase the average pressure in the combustor and to increase the completeness of combustion, thus improving the overall propulsion performance considerably.

At the Institute of Chemical Physics, dozens of experimental samples of PDEs operating on various standard motor fuels, including aviation kerosene TS-1 (Russian analog of Jet-A), with a fuel-based specific impulse of $I_{sp} \approx$ 1000–1200 s [2–6] have been developed and tested. This value of I_{sp} is almost twice higher than that of pulsejets.

Despite the PDEs have a lower fuel-based specific impulse than turbojets and piston engines, their use as a propulsion unit for UAVs is justified by the extraordinary simplicity of design, low manufacturing cost and the possibility of deep thrust throttling (from 0% to 100%).

The most promising areas of PDE application are the UAVs with low resource requirements (target aircraft, atmospheric probes, etc.). Consideration is also being given to placing the PDEs at the ends of the main rotor blades of an advanced ramjet helicopter, which will significantly increase the weight efficiency and abandon the gearbox [7]. It should be noted that in 2008 the US Air Force announced the first successful flight tests of the PDE-based power plant in piloted Long E-Z aircraft [8]. In this power plant, air was delivered to PDE tubes with the help of turbocharging through the valve block of a gasoline internal combustion engine.

This paper presents the results of catapult launching tests of UAVs with the kerosene-fueled air-breathing PDE-based TMs with natural (ram) rather than forced air supply into the engine. For the first time, an autonomous flight of a UAV with a power plant of a new type with gaining speed and altitude was demonstrated.

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2 Operation principle of PDE

The operation principle of the PDE-based TM is described in detail in [6]. The flow-through TM is a tube with the air intake at one end and jet nozzle at the other end. The air intake is equipped with a check valve. Downstream from the check valve, fuel injectors and an igniter are installed. During the atmospheric flight, air enters the TM tube through the open check valve, while fuel injectors supply the atomized liquid fuel (aviation kerosene) into the tube. The resulting fuel–air mixture fills the tube and upon reaching a certain degree of tube filling the control system triggers a signal for ignition.

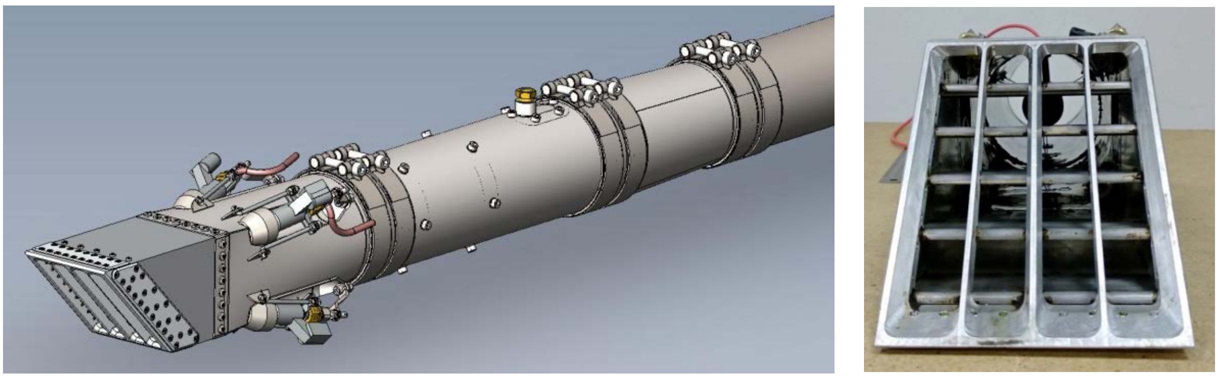
The combustion process in the TM tube is organized in such a way that the pressure increases rapidly in it. When the pressure in the tube exceeds the stagnation pressure of the approaching air flow, the check valve closes and the air supply to the tube stops. The increase in pressure in the TM tube is caused by rapid pre-chamber jet ignition, flame acceleration on special turbulizing obstacles, fast deflagration-to-detonation transition (DDT), and subsequent propagation of the detonation wave towards the nozzle. After the release of the detonation wave from the nozzle, the combustion products expel into the atmosphere, and the pressure in the tube decreases. The thrust is produced due to gas overpressure on the closed check valve which acts as the thrust wall. When the pressure on the valve decreases to the stagnation pressure of the approaching air flow, the valve opens and the TM operation cycle repeats. Thus, the active stage of TM operation with the production of thrust is implemented mainly with the closed check valve.

3 Experimental sample of TM

The TM was developed in several steps. At the first step, the general design of the TM was elaborated based on multivariant 3D CFD calculations. At the second step, an experimental sample of TM was developed, and its primary test fires were performed on a test rig with a free air jet at an approaching air speed ranging from 20 to 80 m/s [5, 6]. According to the results of the primary test fires, the TM design was improved: changes were made in the design of the air intake and some elements of the flow path, aimed at minimizing pressure losses, provided that a stable operation process with the required characteristics is sustained.

The work on the optimization of the TM design resulted in a 3D model shown in Fig. 1a. According to this model a modified experimental sample of the TM was manufactured (Fig. 1b). The air intake is made of a square 100×100-mm tube. The check valve of the air intake is in the normally closed position. The valve grid has five guides with five moving leaves. The square tube couples with a round stainless-steel tube 110 mm in diameter and 3 m long. In the square-to-round tube transition region, four Bosch injectors from a direct-injection gasoline engine are installed. The kerosene injection pressure is 30 atm. The fuel–air mixture is ignited using the pre-chamber jet ignition principle [9]. The pre-chamber with an automotive spark plug is installed on the axis of the TM tube (see Fig. 1b). Along the round tube, turbulizing obstacles are installed. The obstacles ensure the fast DDT according to the concept reported in [10]: the DDT run-up distance is shortened as much as possible due to careful selection of the shape of obstacles and their arrangement, which would provide optimal matching of the flame acceleration rate and shock wave amplification. The turbulizing obstacles are 2-mm thick rings with a blockage ratio varying along the length of the tube from 50% to 20% and installed with a pitch varying along the tube from 40 mm near the pre-chamber to 80 mm near the site of DDT onset. The total length of the tube section with the turbulizing obstacles is 2 m.

The test fires of a modified experimental TM sample in a wind tunnel under conditions simulating a flight at a speed ranging from 27 to 65 m/s showed a significant increase in thrust compared to the TM sample reported in [6].



(a) (b)

Figure 1: The 3D-model of the PDE-based TM (a) and a photograph of the air intake (b)

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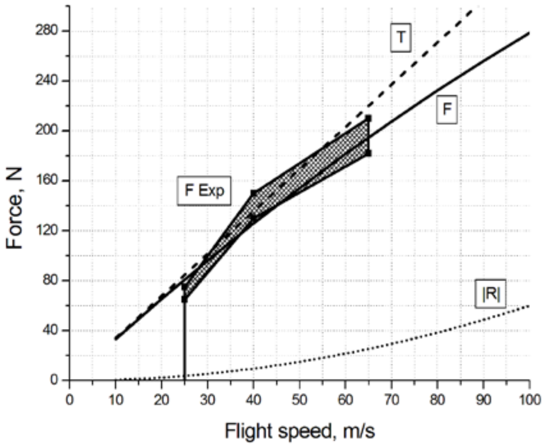

Figure 2: Comparison of the measured (shaded area) and calculated (solid curve) effective thrust of the PDE-based TM at different speeds of approaching air flow. The dashed and dotted curves are the calculated values of the total thrust *T* and the aerodynamic drag force *R* of the TM

The duration of test fires was up to 300 s. During this time, the temperature of the TM wall in the region of the pre-chamber reached a steady-state value not exceeding 200° C, and the maximum temperature of the turbulizing obstacles did not exceed 700° C.

Figure 2 compares the measured (shaded area) and the calculated (solid curve) effective thrust *F* at different speeds of the approaching air flow *V*. Dashed and dotted curves in Fig. 2 correspond to the calculated values of the total thrust *T* and the aerodynamic drag force *R*. The forces *T*, *F* and *R* were calculated using the following relations [6]:

$$T = \dot{m}_f I_{sp} g \qquad (1)$$

$$F = T + R \qquad (2)$$

$$R = -C_X S \rho V^2/2 \qquad (3)$$

$$\dot{m}_f = \rho V S Y_{ST} C_{in} C_f \qquad (4)$$

where g is the acceleration of gravity; ρ is the air density; S is the TM-tube cross-section area; $\dot{m}_f$ is the mass flow rate of fuel; C_X is the aerodynamic drag coefficient; Y_{st} is the fuel mass fraction in the stoichiometric kerosene–air mixture; C_{in} is the discharge coefficient of the TM intake; C_f is the duty ratio of fuel fill. The forces *T*, *F* and *R* are considered positive if they are directed against the approaching air flow. The calculations were made for the following values of the governing parameters: I_{sp} = 1000 s (obtained experimentally in [6]); ρ = 1.2 kg/m^3; S = 0.01 m^2; g = 9.8 m/s^2; C_X = 1.0; Y_{st} = 0.06; C_{in} = 0.5; C_f = 0.8 (i.e., the detonation tube is filled with the fuel mixture during 80% of the cycle time, and during the remaining 20% of the cycle time, the fuel mixture burns and the combustion products expel into the atmosphere).

It follows from Fig. 2 that the experimental values of the effective thrust are in good agreement with the calculated data. The measured effective thrust reaches a maximum value of 180–200 N at an approaching air speed of 65 m/s, while the operation frequency of the TM is 8 Hz. The measured fuel-based specific impulse remained at a level of 1000 s, as in [6].

4 UAV layout

For flight tests, the layout of the UAV with the PDE-based TM equipped with fuel supply, ignition and engine control systems and an onboard power supply battery has been developed. Figure 3 shows the layout of the UAV fuselage with the main systems, while Fig. 4 is a schematic diagram of the TM with fuel supply and control systems.

Fuel supply system

The fuel supply system is of displacing type. It contains two tanks, each with a volume of 1.6 L. The tanks are installed in the fuselage of the UAV at an angle of 10º to its longitudinal axis and connected in their upper parts by a 6-mm i.d. tube. One tank is partially filled with fuel, and the other tank is used as an expansion volume. The fuel tank in its lower part has baffles with openings to reduce fuel overflow during multidirectional overloads and to

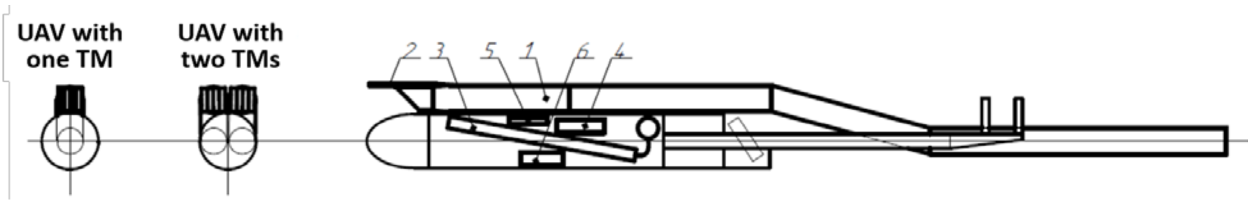

Figure 3: The layout of the UAV with the PDE-based TM: *1* – PDE, *2* – total pressure sensor, *3* – fuel tank, *4* – control unit, *5* – ignition coil, *6* – power supply battery

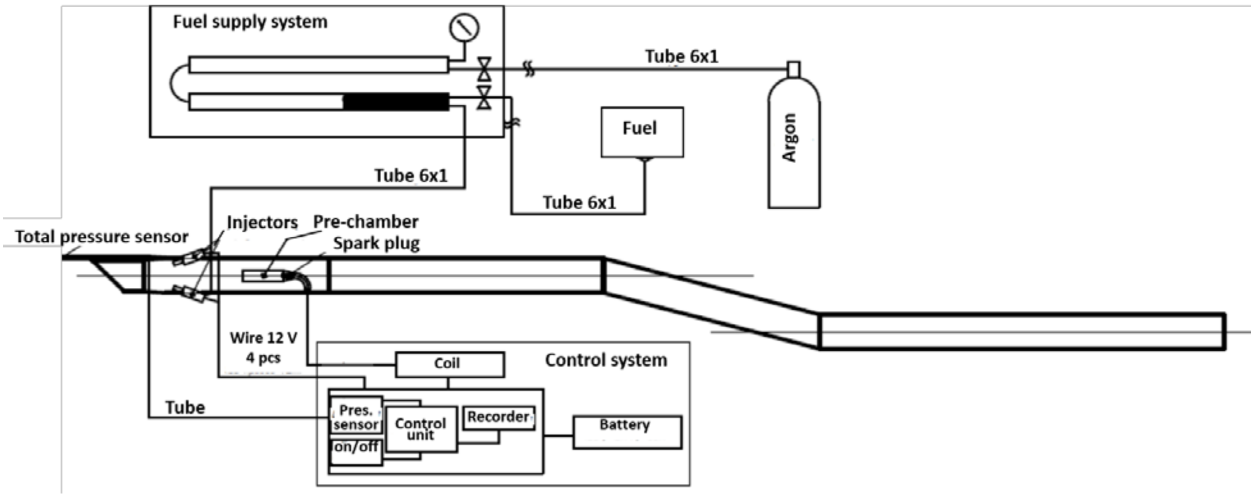

Figure 4: Schematic diagram of the TM control system

prevent gas bubbles from entering the fuel injection system. Before the catapult launching tests, the fuel tank is filled with liquid kerosene in a volume of ~ 0.8 L. Further, the expansion tank is pressurized with an inert gas (argon) under a pressure of 30 atm, and the fuel supply system is disconnected from the fuel and inert gas mains. The pressure drop in the tanks is determined only by a decrease in the fuel level and expansion of the displacing gas.

Control system

The control system of the TM is developed on the basis of *Arduino* hardware and software tools. Electric power is provided by a 12 V battery. The control system applies a predetermined algorithm and allows changing the engine operation mode depending on the speed of approaching air flow *V*. Speed *V* is measured using a total pressure sensor installed on the TM and a static pressure sensor mounted in the control unit. The control system algorithm has been worked out during test fires at the aerodynamic test benches and is optimized for engine thrust. The engine operation mode is determined by the mass flow rate of the fuel and by the cycle diagram. The mass flow rate of fuel is controlled by the number of activated fuel injectors: from one to four. The cycle diagram of the engine determines the time of filling the tube with the fuel mixture and the instant of ignition of the fuel mixture (Fig. 5). The main parameters of the cycle diagram are: *T1* is the time of the active stage (during this time the combustion of fuel–air mixture takes place with an increase in pressure at the closed check valve of the TM intake, a decrease in pressure at the closed valve due to the expelling of combustion products into the atmosphere and the opening of the valve); *T2* is the time of filling the TM tube with the fuel–air mixture; *T3* is the ignition time; *T4* is the ignition advance time (compensates for the ignition delay in the pre-chamber). The Table shows the values of *T1* to *T4* and the number of activated fuel injectors used in the TM control system algorithm.

The control system is activated before the launch of the UAV. After activation, the system is in standby mode and requests data to determine the speed *V* with a frequency of 20 Hz. When *V* increases to a value above 8 m/s, the control system activates the corresponding mode of engine operation (see Table). To exclude off-design operation modes at random casts of *V* values, the control system prohibits abrupt transitions between various modes. The control system is equipped with a built-in recorder which records the time, flight speed and mode number in each operation cycle of the TM.

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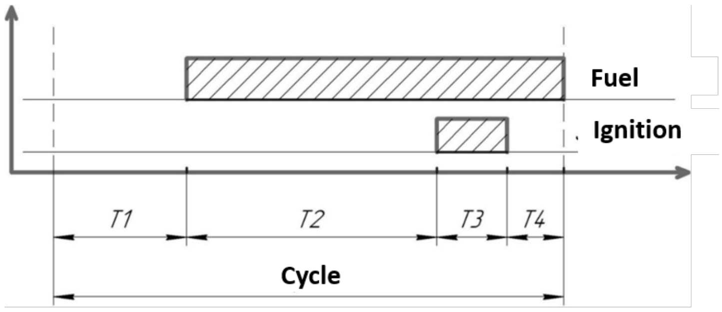

Figure 5: Cycle diagram of TM operation

Table: The values of governing parameters in control system algorithm

Mode No.	*V* m/s	*T1* ms	*T2* ms	*T3* ms	*T4* ms	Number of injectors
1	<8	50	0	0	0	0
2	8-10	280	20	10	100	1
3	10-15	280	20	10	100	1
4	15-20	280	20	10	100	2
5	20-25	280	20	10	100	2
6	25-30	240	20	10	100	2
7	30-35	190	20	10	100	2
8	35-40	170	20	10	100	2
9	40-45	150	20	10	100	2
10	45-50	140	20	10	100	2
11	50-55	130	20	10	90	2
12	55-60	130	20	10	70	3
13	60-65	120	20	10	60	3
14	65-70	120	20	10	50	3
15	70-75	110	20	10	50	3
16	75-80	110	20	10	50	3

5 Assembling of TM on UAV

In accordance with the developed layout and schematic diagrams of the TM, the UAVs powered with one and two paired TMs have been assembled (Fig. 6 to 8).

6 Catapult launching tests

The catapult launching tests were performed on the test field of Rotor R&D Ltd. (Togliatti) using the available UAVs with a take-off mass of up to 100 kg and a pneumatic catapult. The catapult is equipped with an accelerating pneumatic cylinder and air receivers with a maximum operation pressure of 16 atm and allows the UAV to be launched with an initial speed of 30 to 70 m/s. The speed of the UAV launching by the catapult is determined by the air pressure in the air receivers and their volume, as well as the mass of the aircraft. In the conducted catapult launching tests, the catapult operated in the launching mode with a speed of 40–45 m/s, however due to the cold winter conditions, the actual launching speed was 30–35 m/s. Figure 9 shows photographs of UAVs powered with one and two paired TMs mounted on the catapult and prepared for the launching test. Figure 10 shows the video frames of the UAV powered with one TM in the flight. Figure 11 shows some video frames from other cameras used in the tests. In particular, Fig. 11a catches the moment when the luminous detonation products expel from one of the paired TMs in the UAV powered by two TMs.

7 Results of catapult launching tests

Catapult launching tests have shown that the UAVs powered by TMs are gaining speed and altitude. As an example, Fig. 12 shows the time histories of the flight speed measured using the onboard control system for testing UAVs with one (Run 1) and two paired TMs (Run 2). After starting the TMs the flight speed increases (“active phase” in Fig. 12), which indicates a positive effective thrust of the TMs mounted on the UAVs.

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Figure 6: Assembly of the UAV with the PDE-based TM: general view

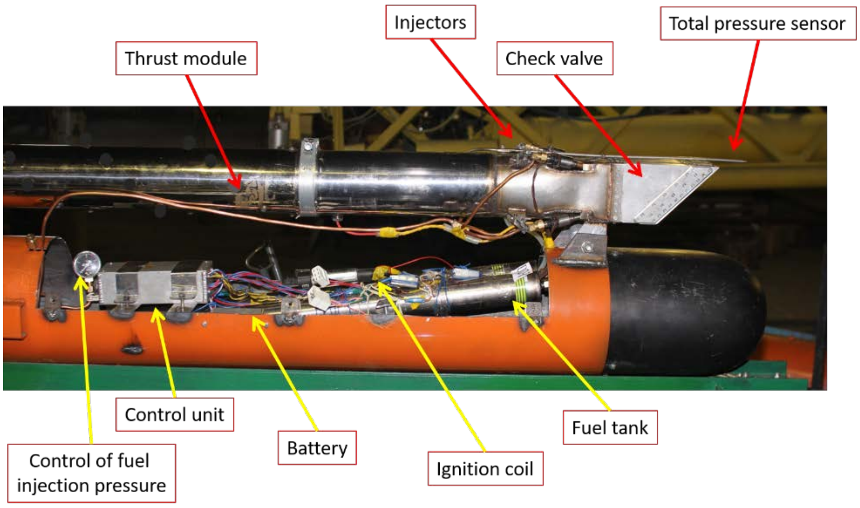

Figure 7: Assembly of the UAV with the PDE-based TM: details

Figure 8: Assembly of the UAV with two paired PDE-based TMs:
1 – TM, 2 – UAV

DOI: 10.13009/EUCASS2019-178

(a)

(b)

Figure 9: Photos of the UAV (1) on the catapult (2): (a) UAV with one PDE-based TM, (b) UAV with two paired PDE-based TMs

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t = -0,18 s

t = -0,15 s

t = -0,12 s

t = 0,00 s

t = 0,09 s

t = 0,24 s

t = 0,54 s

t = 0,84 s

t = 1,44 s

t = 1,74 s

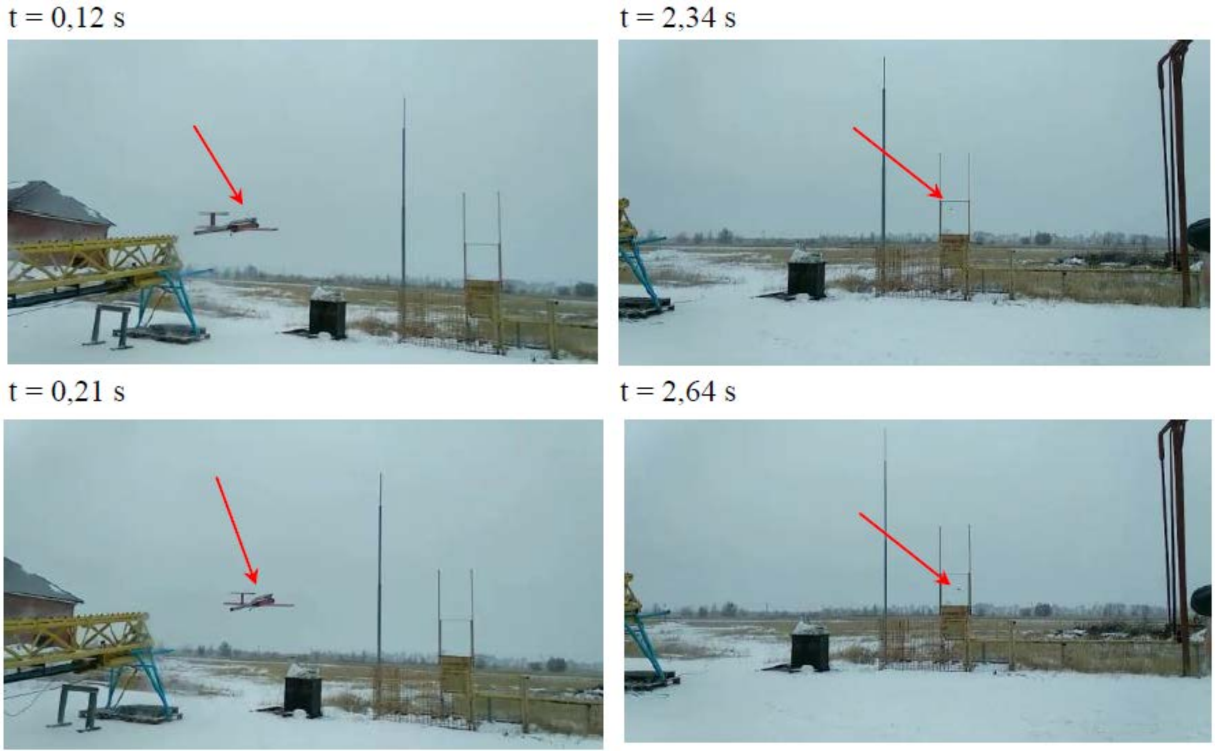

Figure 10: Video frames of the UAV powered with one TM in the flight. Arrows shows the position of the UAV. Time is counted from the instant of UAV separation from the catapult.

(a)

(b)

Figure 11: Video frames of catapult launching tests of UAVs with (a) one and (b) two paired PDE-based TMs

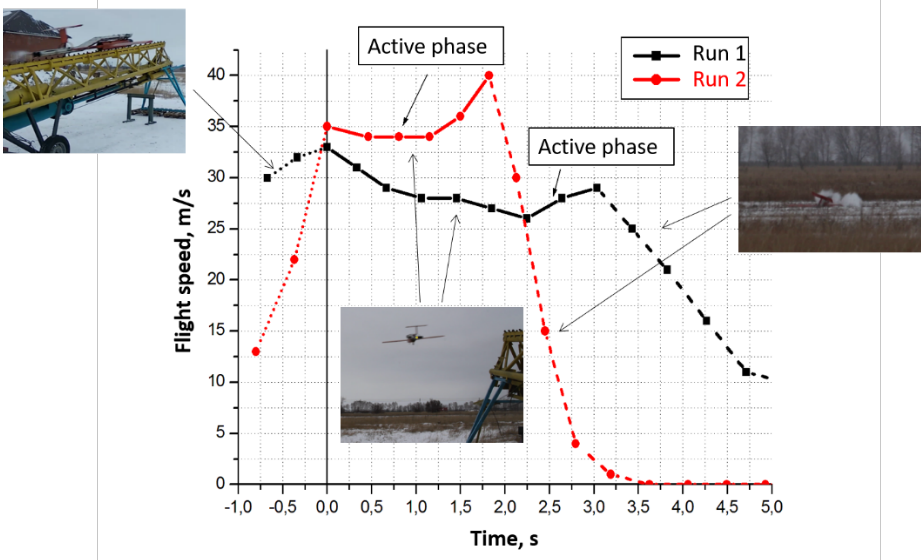

Figure 12: Examples of UAVs' flight speed records by onboard control system: Run 1 is the catapult launching test of the UAV with one TM. Run 2 is the catapult launching test of the UAV with two paired TMs

Thus, for the first time we demonstrated an autonomous flight of a UAV with a PDE-based TM with gaining speed and altitude. The most important difference from the flight tests of the PDE-based power plant reported in [8] is the use of the ram air flow in the engine path instead of forced air supply due to turbocharging.

8 Conclusions

Experimental samples of PDE-based TMs were developed and tested on a test rig with a free air jet, in a wind tunnel, and in catapult launching tests as power plants of UAVs. The TM includes the air intake with a check valve and a detonation tube and runs on various hydrocarbon fuels, including standard aviation kerosene. When the speed of approaching air flow ranges from 30 to 120 m/s, the TM provides an effective thrust of up to 250 N with a fuel-based specific impulse of 1000–1200 s.

As a result of test fires on a test rig with a free air jet, the predicted thrust performances of the experimental engine samples were confirmed. For the first time, an autonomous subsonic flight of a UAV with a PDE-based TM with gaining speed and altitude was demonstrated in the catapult launching tests of UAVs with a take-off mass of up to 100 kg powered by one and two paired TMs.

The most important difference from the flight tests of the PDE-based power plant performed by the US Air Force in 2008 is the use of the ram air flow in the engine path instead of forced air supply due to turbocharging. Due to the simplicity of the design and low cost of such TMs, as well as high fuel-based specific impulse, they can be considered as an alternative to the power plants based on piston and turbojet engines for subsonic UAVs. The most promising areas of application of such TMs are the UAVs with low resource requirements (target aircraft, atmospheric probes, etc.), as well as advanced ramjet helicopters.

Acknowledgments

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