Present Status of Pulse and Rotating Detonation Engine Research

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1. Introduction

A self-sustained detonation wave propagates at the speed of 2–3 km/s, and it induces the exothermic chemical reaction in a tube filled with a premixed gas. An engine with a detonation wave intermittently generated in a straight tube is called a pulse detonation engine (PDE) [1–7], and an engine with a detonation wave rotating continuously in annular gap is called a rotating detonation engine (RDE) [8].

In the detonation combustion process, the reactant is compressed by the shock wave, and it is recombined to be the product at high temperature (the generated entropy for the product is small). Therefore, engines that use a detonation cycle have greater thermal efficiency than engines with constant-pressure combustion cycle. This cycle analysis was done by Zel'dovich [9] and has been confirmed by many researchers using various gaseous models [10–12].

2. Pulse Detonation Engine Research

2.1. Air-Breathing Pulse Detonation Engines and Combustors

There are two types of pulse detonation engines: air-breathing pulse detonation engines (air-breathing PDEs) and pulse detonation rocket engines (PDREs). The former needs an incoming airflow, and the latter does not.

Figure 1 shows the specific impulse dependency on the flight Mach number for an air-breathing PDE using stoichiometric hydrogen and air. According to the analytical calculation reported by Endo et al. [13], the specific impulse of a straight-tube shape PDE at static conditions (M=0) was 4129 s. Experimentally, Schauer et al. [14] confirmed that the specific impulse of a multicycle-operated four-straight-tube PDE at static conditions was almost equivalent to the theoretical value obtained by Endo et al. [13]. The red solid curve in Figure 1 is the specific impulse for a ramjet engine, and the blue dashed curve is that for a constant-volume combustion jet engine (Talley and Coy [15]). Wintenberger and Shepherd [16] calculated the specific impulse for a straight-tube air-breathing PDE system that included an air inlet without nozzle optimization. In their analytical model, a large plenum chamber is located between the inlet and the PDE tube. They assumed that the non-steady flow provided by a PDE supply-valve operation does not affect the air inlet steady-state flow. The analytical results for this PDE system including an inlet are shown in Figure 1 as a black solid curve (sea-level condition) and a black dashed

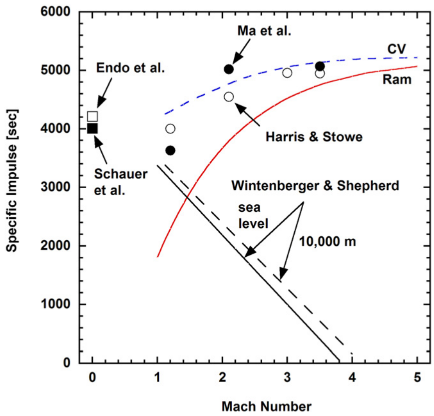

Fig. 1. Specific impulse of air-breathing PDE

Fig. 2. Manned air-breathing PDE airplane [25] (National Museum of the U.S. Air Force)

curve (10,000-m altitude condition). The specific impulse of these cases decreased monotonically when the Mach number increased. If the Mach number increases, the plenum pressure increases and the flow speed from the plenum chamber to a PDE tube also increases. As a result, the pressure of the closed end wall of the PDE tube decreases and the thrust also decreases.

As is also shown in Figure 1, in the case of a straight-tube PDE system without nozzle optimization, when the flight Mach number is below 1.35, its specific impulse is larger than that of a ramjet-engine system.

The calculations by Harris and Stowe [17] (open circles, Fig. 1) and Ma et al. [18] (closed circles, Fig. 1) showed the specific impulses for the cases of multi-tube PDEs with optimized nozzles. This multi-tube optimized-nozzle PDE's specific impulse was larger than that of a ramjet engine until the flight Mach number was 5. Remeev et al. [19] studied a valveless PDE with a damping compartment. Kojima and Kobayashi [20] studied a pulse detonation ramjet engine with a pre-cooler for the inflow air. A demonstrator of the liquid-fueled (n-heptane) air-breathing PDE with low energy requirements for repeated detonation initiation, with no fuel preconditioning, no use of oxygen, and reasonable geometrical dimensions (~2 m) has been designed and tested by Frolov [21]. The feasibility of a kerosene-fueled PDE was demonstrated by Frolov et al. [22] in a tube 52 mm in diameter comprising a straight section with a Shchelkin spiral and a smooth-walled coil providing cyclic deflagration-to-detonation transition (DDT) at a distance of about 2 m in 5–6 ms at a low ignition energy of 5 J. The feasibility of the innovative natural-gas fuelled pulse-detonation combustor with a cyclic (up to 5 Hz) DDT within a length of ~3.5 m and further detonation propagation at an average velocity above 1600-1700 m/s in a 150-mm-diam tube, with an open end and separate supply of natural gas and air as fuel components, has been demonstrated experimentally by Frolov [23, 24].

The U.S. Air Force Research Laboratory (AFRL) and Innovative Scientific Solutions Inc. (ISSI) conducted a four-tube-PDE-powered and manned flight test in January 2008; the flight model is shown in Figure 2 [25]. This PDE's supply system was composed of a General Motors (GM) quad-four cylinder head. The fuel was propane. The flight-time duration with PDE power was 10 s, and the flight speed was 50 m/s at constant altitude. The thrust at flight was 700 N (the takeoff thrust was 900 N+) and the air flow rate was 770 g/s [25].

2.2. Pulse Detonation Rocket Engines

Thrust augmentation by a nozzle for a PDRE was studied by Morris [26]. He showed that when the ambient pressure around a PDE is extremely low, the performance of a nozzle is almost identical to that of a steady-state nozzle. He also showed that if the ambient pressure of a PDRE is low enough, under the same shape condition the specific impulse of the PDRE is higher than that of a conventional (deflagration combustion) rocket engine [26].

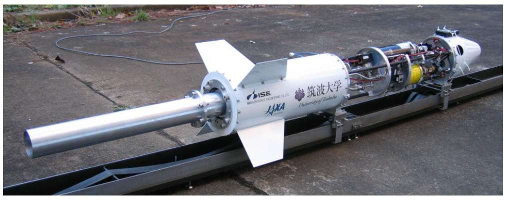

Fig. 3. PDRE Todoroki I [28]

Fig. 4. PDRE flight system model Todoroki II [29, 30]

Kasahara et al. [27, 28] demonstrated the PDRE system Todoroki I by a sliding test (Fig. 3). The fuel was ethylene and the oxidizer was oxygen. The time-averaged thrust was 34.7 N. The fuel and the oxidizer gases were supplied to the PDE tube from self-pressurized cylinders. A pump for supplying gas was not installed in this system. Morozumi et al. [29] and Matsuoka et al. [30] developed a four-cylinder rotary-valved PDRE for flight tests. As illustrated in Figure 4, a vertical flight test was conducted with the PDRE flight system model Todoroki II in November 2013. The fuel was ethylene and the oxidizer was N_2O. The time-averaged thrust and the specific impulse were 270 N and 130 s, respectively. The thrust divided by the total flight-system-model mass was 0.8 [29, 30].

Frolov et al. [31] developed a demonstrator of the operation process of a liquid-fueled PDRE, intended for shaping the future design of a new type of rocket engines for spacecraft control.

2.3. Pulse Detonation Turbine Engines

It is possible to extract work from a high-enthalpy burned-gas jet by attaching a turbine mechanism to a PDE tube's exit. Such a system is called a pulse detonation turbine engine (PDTE). Endo et al. [32] achieved 9.0% thermal efficiency for their PDTE. Velocities at the exit of the PDE tube in a PDTE varies periodically between zero and speed of sound, and the inflow to a turbine is in an extremely unsteady state. Maeda et al. [33] showed that the turbine circumference-direction speed of a single-tube PDTE should be almost the same order as that of speed of sound. Rasheed et al. [34] studied a PDTE using an eight-tube PDE with a single-stage asymmetric-flow turbine. They reported that their PDTE overall efficiency was 25% higher than that of a steady-state combustion case.

2.4. Pulse Detonation Thermal Spraying and Micro-Pulse Detonation Engines

A pulse detonation tube was practically applied to a thermal spraying gun in which small particles of metal or another material were rapidly heated and accelerated toward a target material for coating [35]. The Super D-Gun [36], a product offered by Union Carbide Coating Service, is one of the detonation combustion thermal spraying guns available. Endo et al. [37] performed a detonation combustion thermal spraying gun experiment in a 250-Hz operation using cobalt nickel chromium aluminum yttrium (CoNiCrAIY) as the spraying material. As a result of pulse-detonation thermal spraying new material layers with a high content of alloying elements up to 5 μm thick and hardness up to10 500MPa were formed on the surface of stamp steel samples in experiments of Vasilik et al. [38]. After modification, thus conducted wear resistance of stamp steel tools tested industrially increased up to 2–4 times. A small-sized micro-PDE was thoroughly investigated by Wu [39].

3. Rotating Detonation Engine Research

Figure 5 is a schematic picture of a rotating detonation engine (RDE). In a typical RDE, fuel and oxidizer are injected into the space between two annular tubes (cylinders, Fig. 5). The detonation wave propagates in the circumferential direction of the annular tubes. The RDE can obtain thrust from a burned-gas jet in an axial direction (Fig. 5). The RDE's merits are the continuous propagation of the

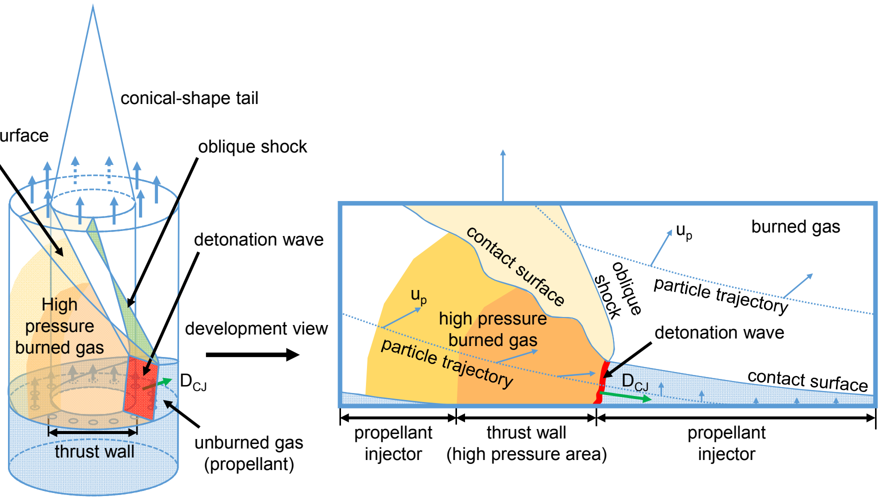

Fig. 5. Schematics of rotating detonation engine

detonation wave, single detonation initiation, high mass flow rate, and high thrust density. The RDE's problems are its high heat transfer rate (a cooling device is needed for long-duration operation), a large pressure loss during injection, and mixing of the fuel and oxidizer.

In 2013, the existing RDE research was reviewed in detail by Wolanski [8]. Bykovskii et al. [40] visualized the RDE combustion process in detail. They revealed that for a successful run, the RDE's filling length was 17±7 times greater than the characteristic time which is the summation of the atomization, vaporization, diffusion, mixing and chemical reaction times. A thrust experiment using an RDE rocket was performed by Kindracki et al. [41], and their results confirmed that the thrust performance of an RDE can be comparable to that of a conventional rocket engine.

Zhdan et al. [42] and Hishida et al. [43] obtained a numerical solution for a two-dimensional RDE. An idealized specific impulse was obtained by Shwer and Kailasanath [44–46]. They investigated the RDE pressure loss dependency on the injector and its shape [46]. Nordeen et al. [47] performed a thermodynamic analysis on each particle path in an RDE. Uemura et al. [48] explained an RDE transverse wave generation mechanism. Naples et al. [49] observed self-luminescence in a quartz-glass cylinder RDE. Gawahara et al. [50] studied an RDE using oval-type annular tubes. Nakayama et al. [51, 52] and Kudo et al. [53] showed experimentally that the detonation wave curvature radius must be > 10 times the cell size or stable-shape propagation. MBDA Missile Systems in France, Poiter University (Institute Pprime), and Aerojet Rocketdyne [54] have also performed active RDE experiments. Ishihara et al. [55] performed experiments with the RDE equipped with a conical plug nozzle.

Frolov et al. [56] and Dubrovskii et al. [57] performed three-dimenstional computational fluid dynamics (CFD) calculations of RDE operation with due regard for turbulent and molecular mixing of fuel and air. They revealed the complex three-dimensional structure of the rotating detonation waves in RDEs and compared their calculations with available experiments. Frolov et al. [58–60] also performed extensive experimental studies of hydrogen–air and hydrogen–oxygen RDEs and proved experimentally the advantage of the detonation cycle over the constant-pressure combustion cycle in terms of energy efficiency by about 6% to 8%.

Nordeen et al. [61] permormed a thermodyamic analysis of two-dimentional RDEs including a mixing model. They showed that mixing has a minimal impact on performance; however, mixing was a factor in the control of the stability and the existence of rotating detonation.

References

[1] Kailasanath, K., *AIAA J.* 38: 1698-1708 (2000).
[2] Kailasanath, K., *AIAA J.* 41: 145-159 (2003).
[3] Bazhenova, T. V., and Golub, V. V., *Combust. Expl. Shock Waves* 39: 365-381 (2003).
[4] Nikolaev, Yu. A., Vasil'ev, A. A., and Ul'yanitskii B. Yu., *Combust. Expl. Shock Waves* 39: 382-

410. (2003)

[5] Roy, G. D, Frolov, S. M., Borisov, A. A., and Netzer, D. W., *Prog. Energy Combust. Sci.* 30: 545-672 (2004).

[6] Kasahara, J., Matsuo, A., and Endo, T., *Nagare* (in Japanese) 26: 205-213 (2007).

[7] Kailasanath, K., in 47th AIAA Aerospace Sciences Meeting, AIAA 2009-631 (2009).

[8] Wolanski, P., *Proc. Combust. Inst.* 34: 125-158 (2013).

[9] Zeldovich, Ya. B., *J. Propulsion Power* 22: 588-592 (2006). (originally published in *Zhurnal Tekhnicheskoi Fiziki* 10: 1453-1461 (1940)).

[10] Heiser, W. H., and Pratt, D. T., *J. Propulsion Power* 18: 68-76 (2002).

[11] Wu, Y., Ma, F., and Yang, V., *J. Propulsion Power* 19: 556-567 (2003).

[12] Endo, T., Yatsufusa, T., Taki, S., and Kasahara, J., *Sci. Tech. Energetic Materials* (in Japanese) 65: 103-110 (2004).

[13] Endo, T., Kasahara, J., Matsuo, A., Inaba, K., Sato, S., and Fujiwara, T., *AIAA J.* 42: 1921-1930 (2004).

[14] Schauer, F., Stutrud, J., and Bradley, R., in 39th AIAA Aerospace Sciences Meeting, AIAA 2001-1129 (2001).

[15] Talley, D. G., and Coy, E. B., *J. Propulsion Power* 18: 400-406 (2002).

[16] Wintenberger, E., and Shepherd, J. E., *J. Propulsion Power* 22: 593-603 (2006).

[17] Harris, P. G., Stowe, R. A. Ripley, R. C. and Guzik, S. M., *J. Propulsion Power* 22: 462-473 (2006).

[18] Ma, F., Choi, J.-Y., and Yang, V., *J. Propulsion Power* 22: 1188-1203 (2006).

[19] Remeev, N. Kh, Vlasenko, V. V., Khakimov, R. A., *Deflagrative and Detonative Combustion*, ed. by G.D. Roy and S.M. Frolov, Torus Press, Moscow, 313-328 (2010).

[20] Kojima, T., and Kobayashi, H., *Uchu-Gizyutsu* (in Japanese) 4: 35-42 (2005).

[21] Frolov S. M. *J. Propulsion and Power,* 23(6): 1162-1169 (2006).

[22] Frolov S. M., Aksenov V. S. *Doklady Physical Chemistry*, 416(1): 261–264 (2007).

[23] Frolov S. M. *J Propulsion and Power*, 30 (1): 41-46 (2014).

[24] Frolov S. M., Aksenov V. S., Avdeev K. A., Borisov A. A., Ivanov V. S., Koval' A. S., Medvedev S. N., Smetanyuk V. A., Frolov F. S., Shamshin I. O. *Rus. J. Physical Chemistry B*, 7(2): 137–141 (2013).

[25] Hoke, J. L., Bradley, R. P., Brown, A. C., Litke, P. J., Stutrud, J. S., and Schauer, F. R., in Symposium on Shock Waves in Japan, Saitama, Japan, 239-246 (2010)

[26] Morris, C. I., *J. Propulsion Power* 21: 527-538 (2005).

[27] Kasahara, J, Hirano, M., Matsuo, A., Daimon, Y., and Endo, T., *J. Propulsion Power* 25: 1281-1290 (2009).

[28] Kasahara, J., Hasegawa, A., Nemoto, T., Yamaguchi, H., Yajima, T., and Kojima, T., *J. Propulsion Power* 25: 173-180 (2009).

[29] Morozumi, T., Sakamoto, R., Kashiwazaki, T., Matsuoka, K., Takagi, S., Kasahara, J., Matsuo, A., Funaki, I., in 52nd AIAA Aerospace Sciences Meeting, AIAA (2014) 1317.

[30] Matsuoka, K., Takagi, S., Kasahara, J., Morozumi, T., Kashiwazaki, T., Fujiwara, Y., Matsuo, A., Funaki, I., in 52nd AIAA Aerospace Sciences Meeting, AIAA (2014) 1319.

[31] Frolov S. M., Aksenov V. S., Ivanov V. S. *Rus. J. Physical Chemistry B*, 5(4): 664–667 (2011).

[32] Endo, T., Susa, A., Akitomo, T., Okamoto, T., Kanekiyo, K., Sakaguchi, Y., Yokoyama, H., Kato, S., Mitsunobu, A., Takahashi, T., Hanafusa, T., and Munehiro, S., in Proc. 23rd International Colloquium Dynamics Expl. Reactive Systems, Irvine, USA, 190, (2011) (USB flash drive).

[33] Maeda, S., Kasahara, J., Matsuo, A., and Endo, T., *Transaction Japan Soc. Aeronautical Space Sci.* 53: 192-206 (2010).

[34] Rasheed, A., Furman, A. H., and Dean, A. *J. Propulsion Power* 27: 586-596 (2011).

[35] Ul'yanitskii V.Yu., Prokhorov E.S., Nikolaev Yu.A., Gavrilenko T.P. Combustion, Explosion,

Shock Waves, 1990, No.2.
[36] Gill, B. J., *Aircraft Eng. Aerospace Tech.* 62, 8: 10-14 (1990)
[37] Endo, T., in 2013 International Workshop on Detonation for Propulsion, Tainan, Taiwan, (2013) (USB flash drive).
[38] Vasilik N. Ya., Tyurin Yu.N., Kolisnichenko O. V., Kovaleva M.G., Prozorova M. S., Arseenko M. Yu. *Goren. Vzryv (Mosk.)— Combustion and Explosion*, 8(2): 85–93 (2015).
[39] Wu, M.-H, in 2013 International Workshop on Detonation for Propulsion, Tainan, Taiwan, (2013) (USB flash drive).
[40] Bykovskii, F. A., Zhdan, S. A., and Vedernikov, E. F., *J. Propulsion Power* 22: 1204-1216 (2006).
[41] Kindracki, J., Wolanski, P., and Gut, Z., *Shock Waves* 21: 75-84 (2011).
[42] Zhdan S. A., Bykovskii F. A., Vedernikov E. F. *Combust. Explos., Shock Waves* 43:449 (2007).
[43] Hishida, M., Fujiwara, T., and Wolanski, P., *Shock Waves* 19: 1-10 (2009).
[44] Schwer, D., and Kailasanath, K., *Proc. Combust. Inst.* 33: 2195-2202 (2011).
[45] Schwer, D., and Kailasanath, K., *Proc. Combust. Inst*. 34: 1991-1998 (2013).
[46] Schwer, D., and Kailasanath, K., in 51st AIAA Aerospace Sciences Meeting, AIAA 2013-1178, (2013).
[47] Nordeen, C. A., Schwer, D., Schauer, F., Hoke, J., Barber, T., and Cetegen, B., in 51st AIAA Aerospace Sciences Meeting, AIAA 2013-1175, 2013.
[48] Uemura, Y., Hayashi, A. K., Asahara, M., Tsuboi, N., and Yamada, E., *Proc. Combust. Inst.* 34: 1981-1989 (2013).
[49] Naples, A., Hoke, J., Karnesky, J., and Schauer, F., in 51st AIAA Aerospace Sciences Meeting, AIAA 2013-0278, (2013).
[50] Gawahara, K., Nakayama, H., Kasahara, J., Matsuoka, K., Tomioka, S., Hiraiwa, T., Matsuo, A., and Funaki, I., in 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2013-3721, (2013).
[51] Nakayama, H., Kasahara, J., Matsuo, A., and Funaki, I., *Proc. Combust. Inst.* 34: 1939-1947 (2013).
[52] Nakayama, H., Moriya, T., Kasahara, J., Matsuo, A., Sasamoto, Y., and Funaki, *Combust. Flame* 159: 859-869 (2012).
[53] Kudo, Y., Nagura, Y., Kasahara, J., Sasamoto, Y., and Matsuo, A., *Proc. Combust. Inst.* 33: 2319-2326 (2011).
[54] Claflin, S, in 2013 International Workshop on Detonation for Propulsion, Tainan, Taiwan, 2013 (USB flash drive).
[55] Ishihara, K., Matsuoka, K., Kasahara., J., Matsuo, A., Funaki, I., in 53rd AIAA Aerospace Sciences Meeting, AIAA 2015-0630, (2015).
[56] Frolov, S. M., Dubrovskii, A. V., Ivanov, V. S., *Russian Journal of Physical Chemistry B*, 7: 35-43 (2013).
[57] Dubrovskii, A. V., Ivanov, V. S., Frolov, S. M. *Russian Journal of Physical Chemistry B*, 9: 104-119 (2015).
[58] Frolov, S. M., Aksenov, V. S., Gusev, P. A., Ivanov, V. S., Medvedev, S. N., Shamshin, I. O., *Doklady Physical Chemistry*, 459 part 2: 207-211 (2014).
[59] Frolov, S. M., Aksenov, V. S., Ivanov, V. S., Shamshin, I. O., *International Journal of Hydrogen Energy,* 40: 1616-1623 (2015).
[60] Frolov, S. M., Aksenov, V. S., Ivanov, *International Journal of Hydrogen Energy,* 40 (21): 6970-6975 (2015).
[61] Nordeen, C. A., Schwer, D., Schauer, F., Hoke., J., Barber, T., Cetegen B. M., *Shock Waves*, in press.