TEST FIRES OF A CONTINUOUS DETONATION COMBUSTOR OPERATING ON METHANE–OXYGEN MIXTURE

S. M. Frolov[1,2], V. S. Ivanov[1], I. O. Shamshin[1], and Yu. V. Kozarenko[3]

[1]N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation

[2]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe Sh., Moscow 115409, Russian Federation

[3]Transport of the Future Ltd., Belaya Vezha, Belgorod Region, Russian Federation

Abstract: Test fires of a modified rotating detonation engine (RDE) annular combustor operating on the methane–oxygen mixture have been conducted. Compared to the original RDE combustor tested in 2018, it was modified in terms of changing the scheme of combustor-wall water-cooling, the positions of ports for sensors, and the shape of the supersonic nozzle. The stable operation process with a single detonation wave continuously rotating in the annular gap with the velocity of $\sim$ 1900 m/s (rotation frequency of $\sim$ 6 kHz) has been obtained in the wide range of flow rates of fuel components. This is the important distinguishing feature of the present RDE combustor as compared to the analogs known from the literature, which usually exhibit the increase in the number of simultaneously rotating detonation waves with the increase in the flow rates of fuel components. Compared with the original RDE combustor, the maximum duration of operation and the specific impulse on the sea level have been increased from 1 to 30 s and from 250 to 277 s, respectively. The thermal states of all heat-stressed elements of the RDE construction are obtained: the maximum heat fluxes are registered in the cooling jackets of the central body and the outer wall of the combustor and heat losses in the cooling system increase with an increase in the average pressure in the combustor. The maximum value of the average heat flux over 20 MW/m^2 was achieved on the outer wall of the combustor. The average heat flux into the outer wall of the combustor was approximately 20% higher than into the central body. The average heat flux into the nozzle was several times lower than similar values for the outer wall and the central body of the combustor. The total heat losses into the water-cooled walls of the combustor reached about 10% of the total thermal power of the combustor.

Keywords: rotating detonation engine; methane; oxygen; test fires; specific impulse; thermal state

DOI: 10.30826/CE25180205 **EDN:** LTOMOV

Figure Captions

Figure 1 Schematic (*a*) and photograph (*b*) of an RDE combustor

Figure 2 Video frames of test fires #4 (*a*), #5 (*b*), and #6 (*c*) during normal operation of the RDE combustor

Figure 3 Video frames of test fire #6 at the moment of burnout of the outer wall of the RDE combustor (*a*) and after the emergency shutdown of fuel supply (*b*)

Figure 4 Measured time histories of oxygen and methane pressures at the inlet of the RDE combustor: (*a*) test fire #4; (*b*) #5; and (*c*) test fire #6 (STOP corresponds to an emergency shutdown of fuel supply)

Figure 5 Measured time histories of the thrust produced by the RDE combustor: (*a*) test fire #4; (*b*) #5; and (*c*) test fire #6 (STOP corresponds to an emergency shutdown of fuel supply)

Figure 6 Fragments of records of the pressure pulsation sensor in the RDE combustor at the beginning (top), in the middle (center), and at the end (bottom) of test fires #5 (*a*) and #6 (*b*)

Figure 7 Fourier analysis of the record of pressure pulsation sensor in test fires #5 (*a*) and #6 (*b*)

Figure 8 Measured time histories of the cooling-water temperature at the outlet of the cooling circuits of the central body, combustion chamber, and nozzle in test fires #4 (*a*), #5 (*b*), and #6 (*c*)

Figure 9 Comparison of the dependencies of the specific impulse on the average pressure in the RDE combustor obtained in the present work (*1*) and in [4] (*2*)

Figure 10 Video frames of test fire #6: (*a*) normal operation; (*b*) burnout of the combustor wall with water entering the combustor and steam cloud formation; (*c*) burnout of the cooling circuit of the outer wall of the RDE combustor; and (*d*) emergency shutdown

Figure 11 Photographs of the destruction of the RDE combustor after emergency test fire #6: (*a*) top view; and (*b*) side view

Table Captions

Table 1 List of measured parameters

Table 2 Main results obtained in test fires #4, #5, and #6

Table 3 Data on the thermal state of the walls of the RDE combustor

References

1. Belov, E. A., V. Yu. Bogushev, I. A. Klepikov, and A. M. Smirnov. 2000. Rezul'taty eksperimental'nykh rabot v NPO Energomash po osvoeniyu metana kak komponenta topliva dlya ZhRD [Results of experimental work at NPO Energomash on the development of methane as a fuel component for liquid-propellant rocket engines]. *Trudy NPO Energomash* [NPO Energomash Proceedings] 18:86–89.
2. Zel'dovich, Ya. B. 1940. K voprosu ob energeticheskom ispol'zovanii detonatsionnogo goreniya [On the energy use of detonation combustion]. *J. Techn. Phys.* 10(17):1453–1458.
3. Frolov, S. M., A. E. Barykin, and A. A. Borisov. 2004. Termodinamicheskii tsikl s detonatsionnym szhiganiem topliva [Thermodynamic cycle with detonation combustion of fuel. *Khim. Fizika* 23(3):17–25.
4. Frolov, S. M., V. S. Aksenov, V. S. Ivanov, S. N. Medvedev, I. O. Shamshin, N. N. Yakovlev, and I. I. Kostenko. 2018. Rocket engine with continuous detonation combustion of the natural gas – oxygen propellant system. *Dokl. Phys. Chem.* 478(2):31–34. doi: 10.1134/S001250161802001X.
5. Chvanov, V. K., S. M. Frolov, and L. E. Sternin. 2012. Zhidkostnyy detonatsionnyy raketnyy dvigatel' [Liquid detonation rocket engine]. *Trudy NPO Energomash* [NPO Energomash Proceedings] 29:4–14.
6. Frolov, S. M., V. S. Aksenov, P. A. Gusev, V. S. Ivanov, S. N. Medvedev, and I. O. Shamshin. 2014. Experimental proof of the energy efficiency of the Zel'dovich thermodynamic cycle. *Dokl. Phys. Chem.* 459(2):207–211.
7. Frolov, S. M., V. S. Aksenov, and V. S. Ivanov. 2015. Experimental proof of Zel'dovich cycle efficiency gain over cycle with constant pressure combustion for hydrogen–oxygen fuel mixture. *Int. J. Hydrogen Energ.* 40(21):6970–6975.
8. Frolov, S. M., V. S. Aksenov, A. V. Dubrovskii, V. S. Ivanov, and I. O. Shamshin. 2015. Energy efficiency of a continuous-detonation combustion chamber. *Combust. Explo. Shock Waves* 51(2):232–245.
9. Kindracki, J., P. Wolanski, and Z. Gut. 2011. Experimental research on the rotating detonation in gaseous fuels–oxygen mixtures. *Shock Waves* 21:75–84.
10. Bykovsky, F. A., and S. A. Zhdan. 2013. *Nepreryvnaya spinovaya detonatsiya* [Continuous spin detonation]. Novosibirsk: SB RAS Publs. 423 p.
11. Frolov, S. M., V. S. Aksenov, P. A. Gusev, V. S. Ivanov, S. N. Medvedev, and I. O. Shamshin. 2015. Eksperimental'nye issledovaniya stendovykh obraztsov malorazmernykh raketnykh dvigatelei s nepreryvno-detonatsionnymi kamerami sgoraniya [Experimental studies of small-size bench rocket engines with continuous-detonation combustors, *Goren. Vzryv (Mosk.) — Combustion and Explosion* 8(1):151–163.
12. Ivanov, V. S., V. S. Aksyonov, S. M. Frolov, and I. O. Shamshin. 2016. Eksperimental'nye issledovaniya stendovogo obraztsa raketnogo dvigatelya s nepreryvno-detonatsionnym goreniem smesi prirodnogo gaza s kislorodom [Experimental studies of a stand sample of rocket engine with continuous-detonation combustion of natural gas – oxygen mixture]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 9(2):51–64.
13. Goto, K., R. Yokoo, J. Kim, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, D. Nakata, M. Uchiumi, and K. Higashino. 2019. Experimental performance validation of a rotating detonation engine toward a flight demonstration. *AIAA Scitech 2019 Forum*. San Diego, CA. doi: 10.2514/6.2019-1501.
14. Dvigatel' RD-107A [RD-107A engline]. Available at: https://www.uecrus.com/products-and-services/products/raketnye-dvigateli/dvigatel-rd-107a/ (accessed May 12, 2025).
15. Ivanov, V. S., S. M. Frolov, S. S. Sergeev, Yu. M. Mironov, A. E. Novikov, and I. I. Schultz. 2021. Pressure measurements in detonation engines. *P. I. Mech. Eng. G — J. Aer.* 235(14):2113–2134. doi: 10.1177/0954410021993078.

Received December 26, 2024
After revision January 24, 2025
Accepted February 4, 2025

Contributors

Frolov Sergey M. (b. 1959) — Doctor of Science in physics and mathematics, head of department, head of laboratory, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin

Str., Moscow 119991, Russian Federation; professor, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe Sh., Moscow 115409, Russian Federation; smfrol@chph.ras.ru

Ivanov Vladislav S. (b. 1986) — Doctor of Science in physics and mathematics, deputy director, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; ivanov.vls@gmail.com

Shamshin Igor O. (b. 1975) — Candidate of Science in physics and mathematics, leading research scientist, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str.,Moscow 119991, Russian Federation; igor_shamshin@mail.ru

Kozarenko Yurii V. (b. 1990) — director, Transport of the Future Ltd., Belaya Vezha, Belgorod Region, Russian Federation; info@tb-drone.ru