MEASUREMENT OF FLOW RATE CHARACTERISTICS OF FLOW-THROUGH GAS GENERATOR AT GASIFICATION OF LOW-MELTING SOLID MATERIAL BY AMBIENT TEMPERATURE AIRFLOW

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Abstract: A semiempirical method is proposed for determining the flow characteristics of a flow-through gas generator operating on gasification of a solid low-melting material by an ambient temperature airflow. Experimental studies of the gasification of a polypropylene charge are performed to demonstrate the approach. In the test fires, the yield of gasification products ranged from 43 to 120 g/s and the ratio of mass flow rates of air and polypropylene gasification products was 2.3–2.9. The analysis of errors inherent in the approach is carried out.

Keywords: flow-through gas generator; solid low-melting material; polypropylene; flow rate

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Figure Captions

Figure 1 Schematic of the Model Aerodynamic Facity of ITAM SB RAS

Figure 2 Arrangement of the flow-through gas generator with the direct-connect air supply manifold: *1* — electric heater; *2* — gas generator; and *3* — exhaust tube

Figure 3 Gas generator with hydrogen ignition: *1* — air supply; *2* — throttle insert; *3* — hydrogen supply; *4* — pressure measurement; *5* — temperature measurement; *6* — test sample; *7* — spark plug; *8* — measuring nozzle; *9* — exhaust tube; and *10* — thermal insulator

Figure 4 Schematic of sample element. Dimensions are in millimeters

Figure 5 Gas generator with ignition by pyrocharge: *1* — air supply; *2* — pyrocharge; *3* — initiator; *4* — test sample; *5* — $P_{0\mathrm{in}}$ measurement; and *6* — $T_{0\mathrm{in}}$ measurement

Figure 6 Time histories of gas pressure and temperature at the gas generator inlet (*1*) and outlet (*2*) in test fires 1 (*a*), 2 (*b*), and 3 (*c*); *3* is the static pressure in the measuring nozzle

Figure 7 Time histories of gas pressure and temperature at the gas generator inlet (*1*) and outlet (*2*) in test fires 4 (*a*) and 5 (*b*); *3* is the static pressure in the measuring nozzle

Figure 8 Time histories of gas pressure and temperature at gas generator inlet (*1*) and outlet (*2*) in test fires 6 (*a*), 7 (*b*), 8 (*c*), and 9 (*d*); *3* is the static pressure in the measuring nozzle

Figure 9 An example of determining the air flow rate $G_{\mathrm{in}}(t)$ for test fire 4: $P_0 = 3.74$ MPa; $T_0 = 290$ K; $\gamma = 1.4$; $R = 287$ J/kg/K; $m_1 = 0.0404$ (kg·K/J)$^{1/2}$; $d_1^* = 5.15$ mm; $F_1^* = 20.83$ mm^2; $B = 0.002554$ s^{-1}; and $G_0 = 0.181$ kg/s

Figure 10 Coefficient m_2 for calculating the gas flow rate at the gas generator outlet depending on the polypropylene-to-air mass ratio; $P = 1$ MPa

Figure 11 Calculation of the gas flow rate at the gas generator outlet in test fire 9: (*a*) gas flow rate (*1* — inlet; *2* — outlet at $m_2 = 0.0349$ (kg·K/J)$^{1/2}$; and *3* — outlet at $m_2 = 0.0404$ (kg·K/J)$^{1/2}$); and (*b*) yield of gasification products (*1* — yield at $m_2 = 0.0349$ (kg·K/J)$^{1/2}$; *2* — output at $m_2 = 0.0404$ (kg·K/J)$^{1/2}$ with correction; *3* — output at $m_2 = 0.0404$ (kg·K/J)$^{1/2}$; and *4* — difference between outlet and inlet flow rates)

Figure 12 Error in calculating the gas mass flow rate of gasification products with the introduction of a correction for the change in the sample mass

Figure 13 Calculation of gas mass flow rates at the gas generator inlet (*1*) and outlet (*2*) (*a*) and yield of gasification products in test fires 1 to 3 (*b*)

Figure 14 Calculation of gas mass flow rates at gas generator inlet (*1*) and outlet (*2*) (*a*) and yield of gasification products in test fires 4 and 5 (*b*)

Figure 15 Calculation of gas mass flow rates at gas generator inlet (*1*) and outlet (*2*) (*a*) and yield of gasification products in test fires 6 to 9 (*b*)

Table Captions

Table 1 Characteristics of gas generator operation with hydrogen ignition

Table 2 Characteristics of gas generator operation with pyrocharge ignition

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References

1. Kondratova, O. A. 2007. Issledovanie rabochikh protsessov tverdotoplivnykh gazogeneratorov podushek bezopasnosti [Study of working processes of solid-fuel gas generators of airbags]. Tomsk. PhD Thesis.
2. Karabeyoglu, A., G. Zilliac, B. J. Cantwell, S. DeZilwa, and P. Castellucci. 2004. Scale-up tests of high regression rate paraffin-based hybrid rocket fuels. // J. Propul. Power 20:1037–1045.
3. Encinar, J. M., and J. F. González. 2008. Pyrolysis of synthetic polymers and plastic wastes. Kinetic study. *Fuel Process. Technol.* 89:678–686.
4. Aboulkas, A., K. El harfi, and A. El Bouadili. 2010. Thermal degradation behaviors of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms. *Energ. Convers. Manage.* 51:1363–1369.
5. Mazzetti, A., L. Merotto, and G. Pinarello. 2016. Paraffin-based hybrid rocket engines applications: A review and a market perspective. *Acta Astronaut.* 126:286–297.
6. Srivastava, Diksha. 2021. Advances in biofuel technology: A review. *IOSR J. Engineering* 11(4):32–41.
7. Rashkovskiy, S. A., and S. E. Yakush. 2020. Numerical simulation of low-melting temperature solid fuel regression in hybrid rocket engines. *Acta Astronaut.* 176:710–716. doi: 10.1016/j.actaastro.2020.05.002.
8. Salgansky, E. A., and N. A. Lutsenko.2021. Effect of solid fuel characteristics on operating conditions of low-temperature gas generator for high-speed flying vehicle. *Aerosp. Sci. Technol.* 109:106420.
9. Bobrov, A. N., D. A. Yagodnikov, and I. V. Popov. 1992. Ignition and combustion in a two-component powder suspension in a gas. *Combust. Explo. Shock Waves* 28(5):453–457. doi: 10.1007/BF00755713.
10. Glotov, O. G., D. A. Yagodnikov, V. S. Vorob'ev, *et al.* 2007. Ignition, combustion and agglomeration of encapsulated aluminum particles in a composite solid propellant. II. Experimental studies of agglomeration. *Combust. Explo. Shock Waves* 43(3):320–333. doi: 10.1007/s10573-007-0045-y.
11. Krasil'nikov, A. V., G. A. Makarevich, and A. V. Mikhailov. 2008. Stend dlya eksperimental'nogo issledovaniya sverkhzvukovogo goreniya uglevodorodnykh topliv [A facility for an experimental research in supersonic hydrocarbon fuels combustion]. *Kosmonavtika i raketostroenie* [Cosmonautics and Rocket Manufacturing] 1(50):35–42.
12. DeLuca, L. T., L. Galfetti, G. Colombo, F. Maggi, A. Bandera, M. Boiocchi, G. Gariani, L. Merotto, C. Paravan, and A. Reina. 2011. Time-resolved burning of solid fuels for hybrid rocket propulsion. *Progress in propulsion physics*. Eds. L. DeLuca, C. Bonnal, O. Haidn, and S. Frolov. EUCASS advances in aerospace sciences book ser. EDP Sciences – TORUS PRESS. 2:405–426.
13. Shabunin, A. I., S. V. Kalinin, V. I. Sarab'ev, D. A. Yagodnikov, and A. R. Polyanskii. 2012. Rezul'taty issledovaniya i razrabotki nizkotemperaturnykh bystrogoryashchikh gazogeneriruyushchikh topliv dlya sistem peremeshcheniya elementov ispolnitel'nykh mekhanizmov [The results of research and development of low-temperature, fast-burning, gas-generating fuels for systems moving elements of actuators]. *Science and Education* 02. 13 p. Available at: http://technomag.edu.ru/doc/299736.html (accessed August 15, 2021).
14. Wang, L. H., Z. W. Wu, H. W. Chi, *et al.* 2015. Numerical and experimental study on the solid-fuel scramjet combustor. *J. Propul. Power* 31(2):685–693. doi: 10.2514/1.B35302.
15. Lv, Zhong, Zhi-xun Xia, Bing Liu, and Li-ya Huang. 2017. Preliminary experimental study on solid-fuel rocket

scramjet combustor. *J. Zhejiang University — SCIENCE A* 18(2):106–112.

16. Shiplyuk, A. N., V. I. Zvegintsev, S. M. Frolov, D. A. Vnuchkov, T. A. Kiseleva, V. A. Kislovsky, S. V. Lukashevich, A. Yu. Melnikov, and D. G. Nalivaychenko. 2020. Gasification of low-melting hydrocarbon material in the airflow heated by hydrogen combustion. *Int. J. Hydrogen Energ.* 45:9098–9112.
17. Shiplyuk, A. N., V. I. Zvegintsev, S. M. Frolov, D. A. Vnuchkov, V. A. Kislovsky, N. A. Kiseleva, S. V. Lukashevich, A. Yu. Melnikov, and D. G. Nalivaychenko. 2021. Gasification of low-melting fuel in a high-temperature flow of inert gas. *J. Propul. Power* 37(1):20–28. doi: 10.2514/1.B37780.
18. Arkhipov, V. A., S. A. Basalaev, V. T. Kuznetsov, V. A. Poryazov, and A. V. Fedorychev. 2021. Modeling of ignition and combustion of boron-containing solid propellants. *Combust. Explo. Shock Waves* 57(3):308–313.
19. Zarko, V., V. Perov, A. Kiskin, and D. Nalivaichenko. 2019. Microwave resonator method for measuring transient mass gasification rate of condensed systems. *Acta Astronaut.* 158:272–276. doi: 10.1016/j.actaastro.2019.03.028.
20. Evans, B. N., A. Favorito, and K. Kuo. 2005. Study of solid fuel burning-rate enhancement behavior in an X-ray translucent hybrid rocket motor. AIAA Paper No. 2005-3909. doi: 10.2514/6.2005-3909.
21. Zvegintsev. V. I. 2014. *Gazodinamicheskie ustanovki kratkovremennogo deystviya. Chast' 1. Ustanovki dlya nauchnykh issledovaniy* [Short-duration gasdynamic facilities. Part 1. Facilities for scientific research]. Novosibirsk: Parallel. 551 p.
22. Trusov, B. G. 1991. *Modelirovanie khimicheskikh i fazovykh ravnovesiy pri vysokikh temperaturakh "Astra 4"* [Modeling of chemical and phase equilibria at high temperatures "Astra 4"]. Moscow: N. E. Bauman Moscow State Technical University Publs. 40 p.

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