

Experimental Study of Influence of the Gas Flux on Urotropine Gasification in the Low-Temperature Gas Generator

E.A. Salgansky*, A.Yu. Zaichenko, D.N. Podlesniy, M.V. Tsvetkov

Federal Research Center of Problems of Chemical Physics and Medicinal Chemistry,
Russian Academy of Sciences, Chernogolovka, 142432, Russia

Article info

Received:
14 November 2023

Received in revised form:
12 December 2023

Accepted:
25 January 2024

Keywords:

Hexamethylenetetramine
Gasification
Low-temperature gas generator
Ramjet
High-speed flying vehicle

Abstract

The experimental study was carried out to investigate the gasification of urotropine (hexamethylenetetramine) in a low-temperature solid fuel gas generator under varying inlet gas flows. Nitrogen was applied as the filter gas. The filter gas flow was varied from 0.6 to 1.4 L/s with a step of 0.2 L/s. The inlet gas's initial temperature was equal to 910 K. It was shown that with an increase in the nitrogen flow, the fuel gasification time decreased. Increasing the flux of inlet nitrogen from 0.6 to 1.4 L/s results in an increase in the average urotropine gasification mass rate from 0.63 to 1.61 g/s. When the initial nitrogen flow is raised, the rate of fuel gasification increases almost linearly. Studies have demonstrated that the proportion of mass flows between urotropine gasification products and nitrogen remains constant regardless of the incoming gas flow. The mass flow ratio remains steady at approximately 0.9 g/g when the incoming gas flow is altered. It has been shown that the gaseous products of urotropine gasification consist of nitrogen with a small amount of hydrogen and hydrocarbons. The content of simple gaseous products does not exceed 4% vol.

1. Introduction

The reliability of propulsion devices is crucial for the success of Space missions. New propulsion principles are under investigation at present utilizing the storage of solid fuels and their gasification before injecting into combustion chamber [1–3]. The gas generators for producing low-temperature gas are also used in various extinguishing systems [4–6], for spinning gas turbines [7], in car airbags [8], etc. The high flux gas production, the noncombustible gas products, or the maximum calorific value of gas are imposed depending on the employment of such gas generators.

The solid fuel gas generator for producing low-temperature gas with high caloric value may be implemented in the high-speed flying vehicle engine

[9]. To realize high-speed flying vehicle the ramjet engine is being investigated [10, 11]. Also, liquid fuels [12, 13] gaseous fuels [14] or propellants may be implemented for engine supply [15–17]. The studies of various combustion regimes are carried out using computational programs [18] and experimental setups [19, 20].

The outward air is impossible to use as a cooler in the combustion chamber of high-speed flying vehicle because of the large stagnation of air temperature in the inlet. In this case, the cooler must be placed inside the vehicle [21]. The solid fuel gasification products or liquid fuel may be used as a coolant. The liquid fuel is easy to feed into the combustion chamber cooling system [22]. Unlike solid fuel, liquid fuel has a small volume calorific value due to lower density. In work [23] the possibility of including a solid-fuel low-temperature gas generator in an engine to produce high-calorie gases was demonstrated. An experimental investigation of polypropylene

*Corresponding author.
E-mail address: sea@icp.ac.ru

gasification during filtration of an inert gas with high temperature was carried out [24]. An increase in the inlet gas temperature leads to increases in the gasification rate of polypropylene. It was concluded that by varying the gas flow temperature it is possible to control the rate of gasification of the fuel. The thermal mode and rate of substance decomposition are controlled by the temperature [25, 26].

The low temperature gas generator is divided into two parts. In one part, a self-burning solid propellant may be located, during the combustion of which a gas flow with high temperature is formed. As a rule, this gas has a low calorific value. In the second part, there is a solid porous cooler. The initial section of the gas generator emits hot gas which subsequently passes through a second section and undergoes filtration through a porous cooler. Polymeric material can be used as a coolant. Let's call the polymer material a fuel, and the part of the gas generator with it a gasifier [27–29]. Due to interfacial heat exchange, the inlet gas is cooled, and the fuel is heated. When the fuel is heated, gasification can occur. In this case, the heat of the inlet high-temperature gas is spent on the physical heating of the fuel and its chemical thermal decomposition. Because of the thermal decomposition of the fuel, the gas is enriched with gasification products, while the gas calorific value increases [30]. When heating the fuel, it should not melt, otherwise this will lead to overlapping of the pores. Therefore, fuel gasification should occur in the sublimation mode when the fuel passes from a solid state to a gaseous one. As a result, a gas stream

with a low temperature is obtained at the outlet of the gas generator.

In addition to the inlet gas temperature, the gas flow can also be varied. An experimental study of the effect of gas flow on the gasification characteristics of urotropine has not been carried out. The aim of the current work is the experimental investigation of the gasification regimes of solid fuel under conditions of a low-temperature gas generator varying the inlet gas flow rate.

2. Experimental

Figure 1 shows a diagram of the experimental setup. The cylindrical quartz reactor (2) is the main element of the setup. The wall thickness of the reactor is 2 mm, the inner diameter is 66 mm. To minimize the loss of heat in the lateral direction, thermal insulation (5) is employed to cover the exterior of the reactor. An electric heater (6) is located at the bottom part of the reactor. This part of the reactor is filled with particles of inert firebricks to increase heat exchange with the gas. The length of this part of the reactor is 35 cm. A laboratory autotransformer (4) was used to supply electric current to the heating element. Gas was supplied from a cylinder (7) to the bottom of the reactor. A Bronkhorst "Mass-view" flow meter (8) was used to set the required gas flow. Temperature measurements were made using chromel-alumel thermocouples. Thermocouple TC1 was positioned at the exit of the firebricks layer, while TC2 was located at the exit of the reactor. The sig-

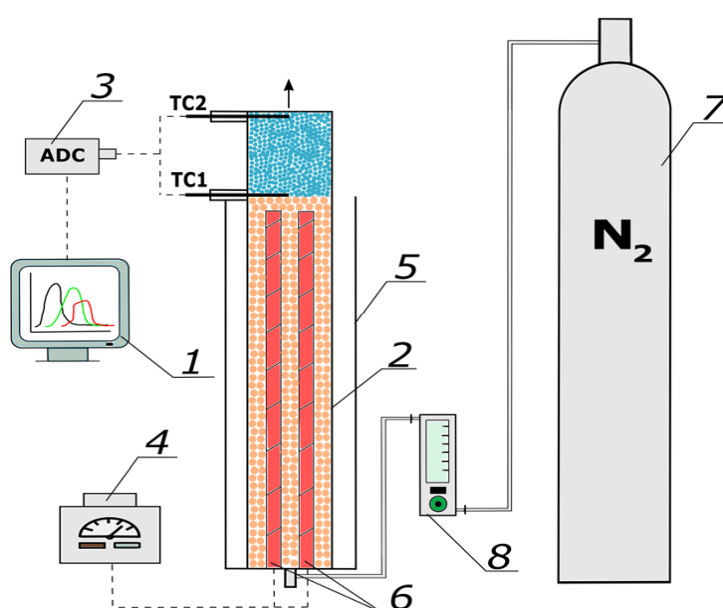


Fig. 1. Diagram of the experimental setup: 1 – PC; 2 – reactor; 3 – ADC; 4 – laboratory autotransformer; 5 – thermal protection shield; 6 – heating elements; 7 – cylinder with nitrogen; 8 – flow meter. TC1, TC2 – thermocouples.

nals from both thermocouples were transmitted to a personal computer (PC) (1) equipped with a ZetLab analog-to-digital converter (ADC) (3) for further processing. The particles of solid fuel were loaded into the gasifier between TC1 and TC2 thermocouples. Gaseous products were analyzed under normal conditions with the "Chromatek Kristal 5000" chromatograph. The error in determining the concentration of gaseous substances is less than 0.01 vol.%.

The experimental procedure included the following stages: supplying gas to the reactor, heating the gas with an electric heater to a given temperature, filling a fuel sample, measuring the temperature of gas at the reactor outlet, and taking and analyzing samples of gas products. The time of loading the fuel into the reactor was taken as the beginning of the experiment. The time of complete fuel gasification was set as the end of the experiment. The margin of error in determining the overall fuel gasification time was within 5%.

The overlapping of the fuel pores and stoppage of the gas filtration may be caused by the melting of the fuel. The urotropine ($C_6H_{12}N_4$), under heating, sublimates and turns into the gas phase without melting. Therefore, the urotropine was used as a model fuel. The length of the sample fuel filling was 20 cm. The mass of urotropine in one experiment was 250 g. The density of urotropine (as material) is 1144 kg/m^3 . The urotropine was crushed and dispersed on sieves with an average particle size of 5–10 mm. Nitrogen (N_2) was taken as an inert filter gas. The nitrogen purity in the cylinder is 99.5%. The filter gas flow was varied from 0.6 to 1.4 L/s with a step of 0.2 L/s. The inlet gas's initial temperature was equal to 910 K.

The temperature at the outlet of the gasifier was measured, and a sample of gas was taken during the experiment. The time of fuel gasification was measured.

3. Results and discussion

The dependence of the temperature of the gas at the outlet of the reactor on time for several gas flow rates is shown in Fig. 2. The inlet gas flow was varied from 0.6 to 1.4 L/s with a step of 0.2 L/s. On the graph, the numbers indicate the values of the nitrogen flow (1 – 0.6, 2 – 0.8, 3 – 1.0, 4 – 1.2, 5 – 1.4 L/s). The experiment began after the inlet temperature of gas was equal to 910 K. At the beginning of the experiment, fuel with a temperature of 298 K was loaded into the reactor. The gas temperature at the outlet of the gasifier begins to rise from the initial temperature of urotropine. As a result of heat

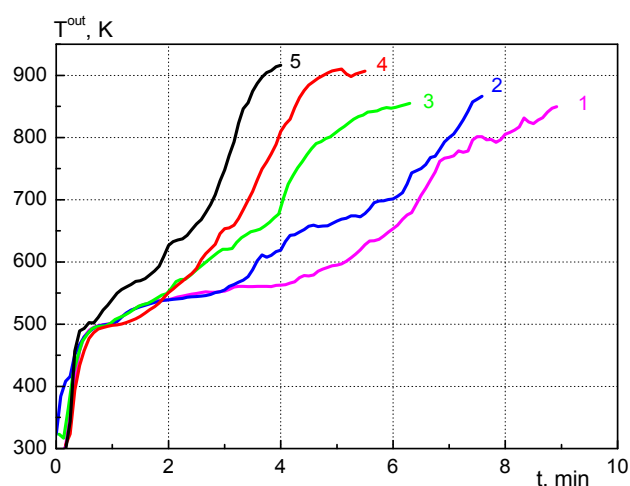


Fig. 2. The dependence of the temperature of gas at the outlet of the reactor on time for several gas flow rates (1 – 0.6, 2 – 0.8, 3 – 1.0, 4 – 1.2, 5 – 1.4 L/s).

exchange with gas, the temperature of urotropine rises, which in turn causes the temperature of the outgoing gas to increase due to a reduction in the interfacial heat exchange intensity. In the interval of 500–550 K the temperature of the outgoing gas changed slightly due to an intensive gasification of urotropine. This is due to the fact that the melting point of urotropine is 553 K. As the urotropine was consumed, the gas temperature at the outlet of the gasifier increased. As a result, the temperature of the gas phase at the outlet of the reactor becomes equal to 910 K. Determining the fuel gasification time, its average gasification rate was calculated.

The data presented in Fig. 2 indicates that as the nitrogen flow increases, the fuel gasification time decreases. In work [31], similar numerical predictions were obtained. The reason for this is that as the nitrogen flow increases, there is a corresponding increase in the intensity of interfacial heat exchange. As a result, the gas generator's operating time decreases with an increase in the incoming gas flux.

The dependence of the gasification of urotropine mass rate on the gas flow rates is shown in Fig. 3. The error in measuring the gasification rate did not exceed 10%. Increasing the flux of inlet nitrogen from 0.6 to 1.4 L/s results in an increase in the average urotropine gasification mass rate from 0.63 to 1.61 g/s. Figure 3 illustrates that the fuel gasification rate almost linearly increases as the initial nitrogen flow increases. This can be attributed to the heightened intensity of interfacial heat exchange that occurs with an increase in nitrogen flow. Additionally, the rate of temperature increase in urotropine also rises, increasing its gasification rate. In work [32], the gas-

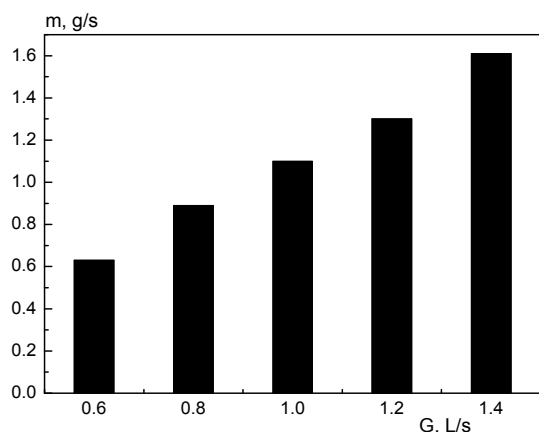


Fig. 3. The dependence of the gasification of urotropine mass rate on the gas flow rates.

ification of urotropine in a CO_2 flow was experimentally studied. The gasification rate of urotropine was 1.2 g/s at a flow and gas temperature of 0.8 L/s and 920 K, respectively. In the case of a CO_2 flow, the rate of urotropine gasification is higher than in a nitrogen flow under the same conditions. This is because CO_2 has a higher density and specific heat capacity than nitrogen. In this case, the CO_2 flow carries more heat at the same temperature than the nitrogen flow. The greater heat content of the CO_2 flow leads to a greater degree of gasification of urotropine.

Varying the flow rate of the incoming gas leads to a change in the flow of fuel gasification products. This can allow controlling the parameters of the engine operating regime.

The gas coming out of the gasifier enters the engine combustion chamber cooling system. Therefore, it must have a low temperature to function as a cooler. Additionally, this gas needs to have a signif-

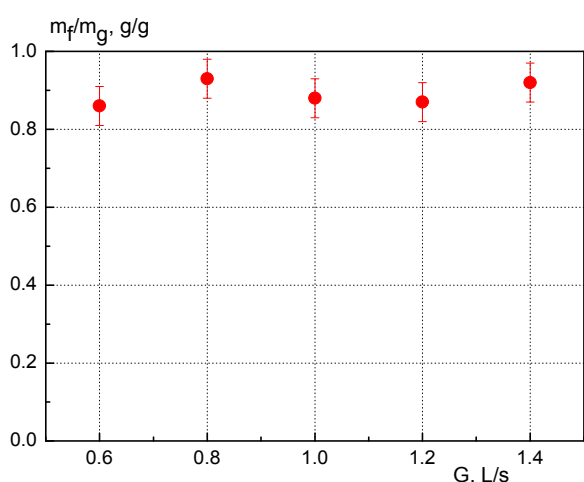


Fig. 4. The dependence of the mass flows ratio of gasification products of fuel (m_f) and inlet nitrogen (m_g) on the inlet gas flow rates.

icant caloric content to generate thrust for the engine when it burns out in the combustion chamber. Figure 4 demonstrates how the ratio of the mass flows of the gasification products of urotropine (m_f) and inlet nitrogen (m_g) relate to the inlet gas flow. This mass flow ratio demonstrates how many urotropine gasification products there are for each unit of inlet gas mass. It can be seen from Fig. 4 that the mass flow ratio is independent of the inlet gas flow. When varying the inlet gas flow from 0.6 to 1.4 L/s, the value of the ratio of m_f/m_g is constant and equals approximately 0.9 g/g. Thus, we can conclude how many times the flux of inlet gas has increased, so many times the gasification products of urotropine flow increased at a given inlet gas temperature. In work [32], the gasification of urotropine in a CO_2 flow was experimentally studied. The ratio of mass flows was 0.8 g/g at a flow and gas temperature of 0.8 L/s and 920 K, respectively. In the case of a CO_2 flow, the mass flow ratio is smaller than in a nitrogen flow under the same conditions.

Salganskaya et al. [3] demonstrated that there is a correlation between an increase in the inlet gas temperature and an increase in the mass flow ratio. From the ratio of mass flows of fuel gasification products and inlet gas, it is possible to calculate the calorific value of the gas leaving the reactor. In these experiments, it was found that the outlet gas calorific value can be two times lower than the calorific value of the original fuel.

The result of the analysis of gaseous products leaving the gasifier is shown in Table 1. The table shows that the gaseous products of urotropine gasification consist of nitrogen with a small amount of hydrogen and hydrocarbons. The nitrogen in the gaseous products of urotropine gasification comes from the nitrogen cylinder. That is at this temperature (910 K) urotropine is not only sublimated, but also decomposed to simpler gaseous products. When urotropine is heated, it evaporates into the gas phase in the form of initial molecules. When cooled to room temperature, urotropine molecules condensed from the gas phase. The decomposition of urotropine molecules into simple substances at this temperature is very slow. The content of simple gaseous products does not exceed 4% vol.

Table 1. Composition of gaseous products of urotropine gasification (under normal conditions)

N_2 , % vol.	H_2 , % vol.	CH_4 , % vol.	C_2H_4 , % vol.	Other, % vol.
96.7	1.5	0.6	0.5	0.7

In works [33, 34], similar results were obtained on the formation of urotropine decomposition products. The authors have shown that pyrolysis of hexamethylenetetramine occurs at a low temperature, while hydrogen and a small amount of gaseous hydrocarbons are formed.

4. Conclusion

1. It was shown that with an increase in the nitrogen flow, the time of urotropine gasification decreases. When the flux of incoming nitrogen was increased from 0.6 to 1.4 L/s, the average mass rate of urotropine gasification rose from 0.63 to 1.61 g/s. The fuel gasification rate showed an almost linear increase with a rise in the inlet nitrogen flow.

2. It has been shown that the ratio of mass flows of fuel gasification products and inlet gas does not depend on the value of inlet nitrogen flow. When varying the inlet gas flow from 0.6 to 1.4 L/s, the value of the mass flow ratio is constant and equals approximately 0.9 g/g.

3. It has been shown that the gaseous products of urotropine gasification consist of nitrogen with a small amount of hydrogen and hydrocarbons. That is at this temperature (910 K) urotropine is not only sublimated but also decomposed to simpler gaseous products. The decomposition of urotropine molecules into simple substances at this temperature is very slow. The content of simple gaseous products does not exceed 4% vol.

Acknowledgments

This work was supported by the Russian Science Foundation (Project No. 21-79-20008).

References

- [1]. N.N. Smirnov, *Acta Astronaut.* 204 (2023) 679–681. DOI: [10.1016/j.actaastro.2022.10.028](https://doi.org/10.1016/j.actaastro.2022.10.028)
- [2]. I. Remissa, H. Jabri, Y. Hairch, et al., *Eurasian Chem.-Technol. J.* 25 (2023) 3–19. DOI: [10.18321/ectj1491](https://doi.org/10.18321/ectj1491)
- [3]. M.V. Salganskaya, A.Yu. Zaichenko, D.N. Podlesniy, et al., *Acta Astronaut.* 204 (2023) 682–685. DOI: [10.1016/j.actaastro.2022.08.039](https://doi.org/10.1016/j.actaastro.2022.08.039)
- [4]. A.I. Karpov, A.Y. Leschev, A.M. Lipanov, G.A. Leschev, *J. Loss. Prev. Process Ind.* 26 (2013) 338–343. DOI: [10.1016/j.jlp.2011.10.007](https://doi.org/10.1016/j.jlp.2011.10.007)
- [5]. R. Srinivasan, B.N. Raghunandan, *Exp. Therm Fluid Sci.* 44 (2012) 323–333. DOI: [10.1016/j.expthermflusci.2012.07.004](https://doi.org/10.1016/j.expthermflusci.2012.07.004)
- [6]. S. Krishnan, K.K. Rajesh, *Int. J. Energetic Mater. Chem. Propul.* 5 (2002) 316–329. DOI: [10.1615/IntJEnergeticMaterialsChemProp.v5.i1-6.340](https://doi.org/10.1615/IntJEnergeticMaterialsChemProp.v5.i1-6.340)
- [7]. S. Yang, G.Q. He, Y. Liu, J. Li, *Applied Mechanical and Materials* 152–154 (2012) 204–209. DOI: [10.4028/www.scientific.net/AMM.152-154.204](https://doi.org/10.4028/www.scientific.net/AMM.152-154.204)
- [8]. A. Kim, Z. Liu, G. Crampton, Explosion suppression of an armoured vehicle crew compartment. *Progress in Safety Science and Technology: Proc. 2004 International Symposium on Safety Science and Technology, Vol. 4*, 1070–1074.
- [9]. V.N. Avrashkov, E.S. Metelkina, D.V. Meshcheryakov, *Combust. Explos. Shock Waves* 46 (2010) 400–407. DOI: [10.1007/s10573-010-0054-0](https://doi.org/10.1007/s10573-010-0054-0)
- [10]. Yu.V. Tunik, G.Ya. Gerasimov, V.Yu. Levashov, V.O. Mayorov, *Acta Astronaut.* 198 (2022) 495–501. DOI: [10.1016/j.actaastro.2022.06.027](https://doi.org/10.1016/j.actaastro.2022.06.027)
- [11]. E.A. Salgansky, N.A. Lutsenko, *Aerosp. Sci. Technol.* 109 (2021) 106420. DOI: [10.1016/j.ast.2020.106420](https://doi.org/10.1016/j.ast.2020.106420)
- [12]. D.O. Glushkov, G.V. Kuznetsov, A.G. Nigay, V.A. Yanovsky, *Acta Astronaut.* 177 (2020) 66–79. DOI: [10.1016/j.actaastro.2020.07.018](https://doi.org/10.1016/j.actaastro.2020.07.018)
- [13]. E.V. Matus, S.A. Yashnik, A.V. Salnikov, L.M. Khitsova, et al., *Eurasian Chem.-Technol. J.* 23 (2021) 267–275. DOI: [10.18321/ectj1130](https://doi.org/10.18321/ectj1130)
- [14]. X. Li, J. Cao, J. Du, *Aerosp. Sci. Technol.* 127 (2022) 107737. DOI: [10.1016/j.ast.2022.107737](https://doi.org/10.1016/j.ast.2022.107737)
- [15]. S. Barbarossa, M. Murgia, R. Orrù, G. Cao, *Eurasian Chem.-Technol. J.* 23 (2021) 213–220. DOI: [10.18321/ectj1104](https://doi.org/10.18321/ectj1104)
- [16]. D.B. Lempert, A.I. Kazakov, E.M. Dorofeenko, et al., *Russ. J. Phys. Chem. B* 14 (2020) 579–586. DOI: [10.1134/S1990793120040090](https://doi.org/10.1134/S1990793120040090)
- [17]. A.G. Korotkikh, I.V. Sorokin, E.A. Selikhova, et al., *Russ. J. Phys. Chem. B* 14 (2020) 592–600. DOI: [10.1134/S1990793120040089](https://doi.org/10.1134/S1990793120040089)
- [18]. S. Luo, Y. Feng, J. Song, D. Xu, K. Xia, *Aerosp. Sci. Technol.* 128 (2022) 107798. DOI: [10.1016/j.ast.2022.107798](https://doi.org/10.1016/j.ast.2022.107798)
- [19]. D.A. Vnuchkov, V.I. Zvegintsev, D.G. Nalivaichenko, et al., *Thermophys. Aeromech.* 25 (2018) 605–611. DOI: [10.1134/S0869864318040121](https://doi.org/10.1134/S0869864318040121)
- [20]. G.A. Tarasov, A.A. Molokanov, N.A. Plishkin, et al., *J. Phys.: Conf. Ser.* 1891 (2021) 012056. DOI: [10.1088/1742-6596/1891/1/012056](https://doi.org/10.1088/1742-6596/1891/1/012056)
- [21]. N.K. Gopinath, K.V. Govindarajan, D.R. Mahapatra, *Int. J. Heat Mass Transf.* 194 (2022) 123060. DOI: [10.1016/j.ijheatmasstransfer.2022.123060](https://doi.org/10.1016/j.ijheatmasstransfer.2022.123060)
- [22]. C. Qiu, W. Zhou, L. Long, et al., *Appl. Therm. Eng.* 197 (2021) 117333. DOI: [10.1016/j.applthermaleng.2021.117333](https://doi.org/10.1016/j.applthermaleng.2021.117333)
- [23]. V.Yu. Aleksandrov, M.V. Ananyan, K.Yu. Arefyev, et al., Investigation of the process sublimation for solid hydrocarbons in permanent section

- channels, 31st Congress of the International Council of the Aeronautical Sciences, (2018) 143115.
- [24]. A.N. Shipliyuk, V.I. Zvegintsev, S.M. Frolov, et al., *J. Propuls. Power* 37 (2021) 20. DOI: [10.2514/1.B37780](https://doi.org/10.2514/1.B37780)
- [25]. Z.A. Mansurov, *Eurasian Chem.-Technol. J.* 23 (2021) 235–245. DOI: [10.18321/ectj1127](https://doi.org/10.18321/ectj1127)
- [26]. G. Rao, W. Feng, J. Zhang, et al., *J. Therm. Anal. Calorim.* 135 (2019) 2447–2456. DOI: [10.1007/s10973-018-7359-8](https://doi.org/10.1007/s10973-018-7359-8)
- [27]. E.A. Salganskii, V.P. Fursov, S.V. Glazov, et al., *Combust. Explos. Shock Waves* 39 (2003) 37–42. DOI: [10.1023/A:1022193117840](https://doi.org/10.1023/A:1022193117840)
- [28]. E.A. Salgansky, A.Yu. Zaichenko, D.N. Podlesniy, et al., *Fuel* 210 (2017) 491–496. DOI: [10.1016/j.fuel.2017.08.103](https://doi.org/10.1016/j.fuel.2017.08.103)
- [29]. E.A. Salganskii, V.P. Fursov, S.V. Glazov, et al., *Combust. Explos. Shock Waves* 42 (2006) 55–62. DOI: [10.1007/s10573-006-0007-9](https://doi.org/10.1007/s10573-006-0007-9)
- [30]. I.I. Amelin, E.A. Salgansky, N.N. Volkova, et al., *Russ. Chem. Bull.* 60 (2011) 1150–1157. DOI: [10.1007/s11172-011-0180-1](https://doi.org/10.1007/s11172-011-0180-1)
- [31]. E.A. Salgansky, N.A. Lutsenko, *Russ. J. Phys. Chem. B* 16 (2022) 278–282. DOI: [10.1134/S1990793122020117](https://doi.org/10.1134/S1990793122020117)
- [32]. E.A. Salgansky, A.Yu. Zaichenko, D.N. Podlesniy, et al., *Thermophys. Aeromech.* 30 (2023) 339–345. DOI: [10.1134/S0869864323020142](https://doi.org/10.1134/S0869864323020142)
- [33]. M. Nomoto, T. Komoto, T. Yamanobe, *Bunseki Kagaku* 59 (2010) 1013–1020. (in Japan). DOI: [10.2116/bunsekikagaku.59.1013](https://doi.org/10.2116/bunsekikagaku.59.1013)
- [34]. M. Leidl, C. Schwarzingler, *J. Anal. Appl. Pyrol.* 74 (2005) 200–203. DOI: [10.1016/j.jaap.2004.11.001](https://doi.org/10.1016/j.jaap.2004.11.001)