

DOI: 10.18721/JPM.13413

THE STABILITY OF FLAME FRONT AND THE COMPOSITION OF COMBUSTION PRODUCTS OF AMMONIA IN OXYGEN IN THE PRESENCE OF HYDROGEN FLUORIDE

*D.S. Pashkevich¹, D.A. Mukhortov², V.V. Kapustin¹, P.S. Kambur¹
E.S. Kurapova³, A.R. Zimin¹, A.S. Maslova¹*

¹ Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation;

² LLC «New Chemical Products», St. Petersburg, Russian Federation;

³ Russian Scientific Center «Applied Chemistry», St. Petersburg, Russian Federation

The authors have proposed a way for producing hydrogen fluoride (the major fluorinating agent in the modern industry) from ammonium bifluoride (by-product in the production of extraction phosphoric acid, tantalum, niobium, etc.) by burning up $\text{NH}_4\text{F}\cdot\text{HF}$ in oxygen. Calculations performed via program complex ASTRA.4 showed that the only fluorine-containing substance was hydrogen fluoride, whereas nitric fluorides and oxyfluorides being absent under the ratio of chemical elements N-1.0; H-5.0; F-2.0; O-1.5 (according to the proposed process), in the temperature range 600 – 2500 K, in thermodynamically equilibrium mixture. The combustion of ammonia in oxygen in the presence of hydrogen fluoride was experimentally investigated and it was found the feasibility of forming a stable flame, where a molar ratio of ammonia/hydrogen fluoride consumptions was 1: 2, only by using methane as a fuel. The conditions for the ratio of component consumptions were determined.

Keywords: ammonium bifluoride, ammonia, hydrogen fluoride, combustion, tunnel burner reactor

Citation: Pashkevich D.S., Mukhortov D.A., Kapustin V.V., Kambur P.S., Kurapova E.S., Zimin A.R., Maslova A.S., The stability of flame front and the composition of combustion products of ammonia in oxygen in the presence of hydrogen fluoride, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 13 (4) (2020) 119–128. DOI: 10.18721/JPM.13413

This is an open access article under the CC BY-NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>)

Introduction

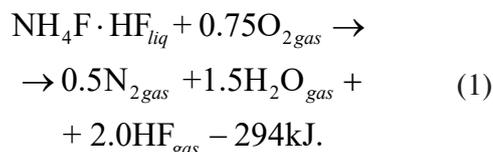
Hydrogen fluoride (HF) serves as the main fluorinating agent in the modern industry producing fluorine compounds. It is used to obtain uranium fluorides in the nuclear fuel cycle, fluoropolymers, ozone-safe freons, electronic gases, etc. [1]. The primary industrial method for producing hydrogen fluoride is sulfuric acid decomposition of natural calcium fluoride concentrate (CaF_2), or fluorspar [2]. The reserves of fluorspar ores, which are a source for obtaining a concentrate with the required composition, are limited. Therefore, developing methods for producing hydrogen fluoride from alternative raw materials is an important task.

Ammonium bifluoride $\text{NH}_4\text{F}\cdot\text{HF}$ (ABF) is a by-product of the production of tantalum, niobium and nitrogen trifluoride [3]. In addition, ABF can be obtained from aqueous solutions of hexafluorosilicic acid (H_2SiF_6), which is a by-product of extraction of phosphoric acid from fluorapatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$) [4, 5]. The market

for H_2SiF_6 is rather small, so it is neutralized and fluorinated waste is disposed of at industrial landfills. The world reserves of fluorapatite (in terms of calcium fluoride content) exceed the reserves of fluorspar by more than 10 times [2, 6]. Therefore, developing science-based approaches to obtaining hydrogen fluoride from ABF will solve two problems: the environmental one, associated with processing fluorine-containing wastes, and the commercial one, associated with scarce reserves and rising prices of natural CaF_2 [7].

While various methods were used to produce hydrogen fluoride from ABF, in particular, sulfuric acid decomposition [8] and catalytic conversion [9], they are not applied industrially.

Hydrogen fluoride can be obtained from ABF via combustion in oxygen:



The subscripts here correspond to the aggregation states of substances: solid (*sol*), liquid (*liq*) and gaseous (*gas*).

The temperature of the products of process (1) can reach about 2400 K. It is known that hydrogen fluoride is one of the most thermally stable fluorides [10].

Combustion of ammonia in oxygen and air is a well-understood phenomenon: the concentration limits of flame propagation are 13–82 and 16–26 vol.%, and the standard velocities are 30–140 and 30–74 cm·s⁻¹, respectively [11].

However, we were unable to uncover any reports on the effect of hydrogen fluoride on the interaction of ammonia with oxygen. It is known that hydrogen fluoride is a polar substance (its dipole moment is $5.78 \cdot 10^{-30}$ C·m [12]) that can have both catalytic and inhibitory effects on chemical reactions [13].

The goal of our study was, firstly, to calculate the thermodynamically stable compositions in the systems of N-H-F-O and C-N-H-F-O elements, and, secondly, to analyze the composition of the products resulting from the interaction of ammonia with oxygen in the combustion mode, in the presence of hydrogen fluoride with methane serving as a fuel.

Experimental methods

Calculations of the thermodynamically stable composition in the system of N-H-F-O and C-N-H-F-O elements were carried out using the ASTRA.4 software package [14]. The

experimental results previously obtained on the laboratory setup constructed for a carbon-containing system indicate that a stable flame can be produced for combustion of ammonia in oxygen in the presence of hydrogen fluoride only if methane is supplied as a fuel to the reaction zone.

The laboratory setup for experimental studies of combustion of ammonia in oxygen in the presence of hydrogen fluoride is shown in Fig. 1. Vertical reactor 1 of the ‘tunnel burner’ type was a steel pipe with an inner diameter $d_1 = 41$ mm and a height of 500 mm. A cable connected to a thermostat was attached to the outer surface of the reactor to heat its wall.

Gases were fed into the reactor through a two-component nozzle assembly 2 installed in the lower part of the reactor.

A separate scheme of reactor 1 and assembly 2 is shown in Fig. 2. The nozzle assembly consists of two coaxial channels: axial (outer diameter 3 mm, inner diameter 2 mm) and annular (outer diameter $d_2 = 8$ mm), with a mixing zone (mixer) with a diameter of 8 mm and variable length h .

The gas flows and the nozzle were heated to a temperature of about 140 °C so that solid ABF would not form upon contact of ammonia with hydrogen fluoride.

The generation and propagation of the flame front was detected using chromel-alumel thermocouples t_1 and t_2 with identical electrode diameters of 200 μm, installed without protective covers so that the thermocouple junctions were



Fig. 1. Schematic of laboratory setup: ‘tunnel burner’ type reactor 1; nozzle assembly 2; polypropylene absorber 3; steel container 4 with pressure sensor for HF and O₂; steel container 5 with pressure sensor for NH₃; gas flow regulator 6 for HF and O₂ supply lines; gas flow regulator 7 for NH₃ supply line

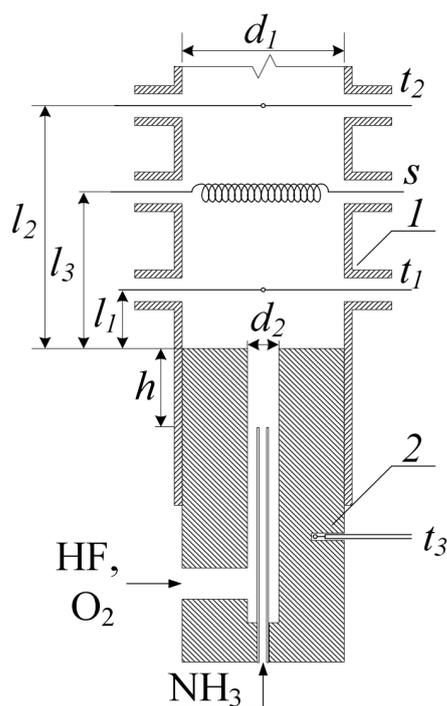


Fig. 2. Schematic of a 'tunnel burner' type reactor and nozzle assembly of the reactor: reactor 1; nozzle assembly 2; coiled filament s ; t_1 , t_2 are the chromel-alumel thermocouples for measuring the temperature in the reactor; t_3 is the chromel-copel thermocouple for measuring the temperature in the nozzle assembly; h , l_1 , l_2 , l_3 , d_1 , d_2 are the geometric parameters

on the reactor axis. Thermocouple t_1 was located at a distance $l_1 = 15$ mm from the nozzle exit, and t_2 at a distance $l_2 = 62$ mm from the exit (see Fig. 2).

The chromel-copel thermocouple t_3 was inserted into nozzle assembly 2 to measure its temperature. Combustion process was initiated by coiled filament s made of nichrome wire 0.3 mm in diameter, placed at a distance $l_3 = 40$ mm from the nozzle exit.

A mixture of oxygen and hydrogen fluoride from the container 4 (see Fig. 1) was fed into the reactor through the annular channel of nozzle assembly 2, and ammonia was fed through the axial channel. The temperature of the mixture components supplied to the nozzle assembly was 25 °C. To prevent ammonium fluoride NH_4F from forming on the inner wall of the reactor upon contact of ammonia with hydrogen fluoride, the reactor wall was thermostated at 300 °C.

After the reactor, the products were fed through a heated line into polypropylene vessel 3 filled with water. When the experiment

ended, the contents of hydrogen fluoride and ammonia in the liquid from vessel 3 were analyzed by titration.

Several gas samples were collected the outlet of absorber 3 and analyzed by gas chromatography and infrared Fourier spectroscopy (FTIR). The composition of the gas phase was determined using a Crystal-2000M chromatograph with a thermal conductivity detector. Two packed columns 3 m long each with Porapak Q 80/120 adsorbents were used for detecting hydrogen, nitrogen, oxygen, carbon dioxide, carbon tetrafluoride, methane and nitrogen trifluoride; CaA of 0.25-0.40 fraction was used to detect hydrogen, oxygen, nitrogen and carbon monoxide.

FTIR was used to determine the concentration of carbonyl fluoride COF_2 in gaseous products of the process. A Shimadzu FTIR-8400S spectrometer with a resolution of 0.85 cm^{-1} and a cell size of 200 × 230 × 170 mm was used for this purpose.

The efficiency of the method for producing hydrogen fluoride from ammonium bifluoride in combustion mode is characterized by the conversion of ammonia. This value was determined by the material balance; the basis for the calculations were the flow rates of the initial components, as well as the composition of the liquid in absorber 3 after the experiment, K_{liq} and the composition of the gaseous reaction products K_{gas} :

$$K_{liq} = 100\% \cdot \frac{m(NH_{3gas})_{out}}{m(NH_{3gas})_{in}}, \quad (2)$$

$$K_{gas} = 100\% \cdot \frac{W(N_{2gas})_{out}}{W(NH_{3gas})_{in}}, \quad (3)$$

where $m(NH_3)_{out}$, $m(NH_3)_{in}$, mg, are the masses of ammonia collected in absorber 3 and fed into the reactor, respectively; $W(N_2)_{out}$, $cm^3 \cdot s^{-1}$, is the volumetric flow rate of nitrogen at the reactor outlet under normal conditions; $W(NH_3)_{in}$, $cm^3 \cdot s^{-1}$, is the volumetric flow rate of ammonia at the reactor inlet under normal conditions.

Thermodynamic calculations in the system of N-H-F-O elements

Aside from the target product (HF), a large number of fluorine-containing compounds are known in the system of N-H-F-O elements: NF_3 , N_2F_2 , N_2F_4 , NH_4F , NHF_2 , (NO)F, $(NO_2)F$, NOF_3 , etc. [15]. Calculations of

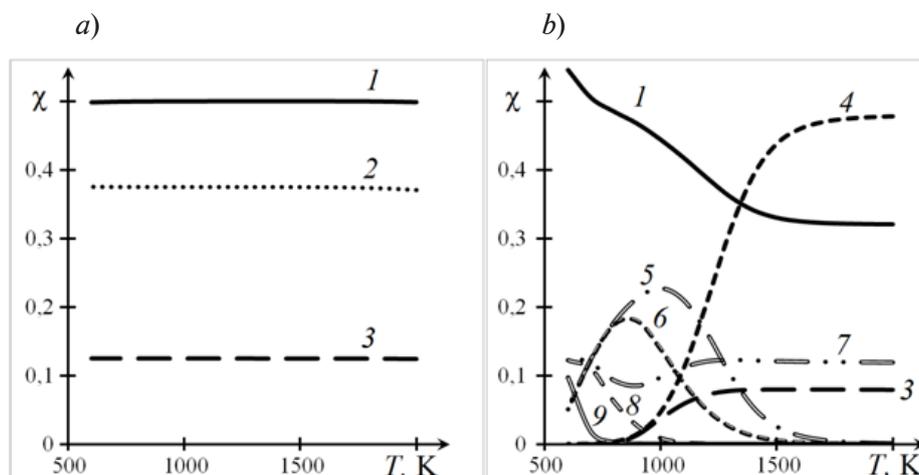


Fig. 3. Temperature dependences of thermodynamically equilibrated composition of substances (in molar fractions) in the system of N-H-F-O elements at various N-H-F-O ratios:

1.0:5.0:2.0:1.5 (a) and 1.0:2.0:5.0:1.5 (b); $n_F > n_H$.

The data are given for HF (1), H₂O (2), N₂ (3), F (4), F₂ (5), (NO)F (6), O₂ (7), NF₃ (8), NOF₃ (9)

the thermodynamically stable composition for the system of N-H-F-O elements at a pressure $P = 0.1$ MPa and in the temperature range 600–2000 K established that the thermodynamically stable composition of the reaction products depends on the atomic ratio between hydrogen and fluorine. If the number of fluorine atoms n_F does not exceed the number of hydrogen atoms n_H , then the only fluorine-containing substance in the equilibrated mixture is hydrogen fluoride, with no fluorides or nitrogen oxyfluorides (Fig. 3,a). If n_F exceeds n_H , then other fluorine-containing substances besides hydrogen fluoride are present in the thermodynamically stable mixture: NF₃, (NO)F, NOF₃, F and F₂ (Fig. 3,b).

Given a ratio of chemical elements corresponding to Eq. (1), hydrogen fluoride is the only fluorine-containing substance in the thermodynamically equilibrated mixture in the temperature range of 600–2000 K and at a pressure $P = 0.1$ MPa.

We can conclude from the results of thermodynamic calculations that further experimental studies should be conducted on the stability of interaction of ammonia with oxygen in the presence of hydrogen fluoride in combustion mode.

Results of experiments in the system of NH₃-HF-O₂ elements

The purpose of the laboratory study was to confirm the results of thermodynamic analysis on the composition of substances in the system of N-H-F-O elements, as well as

to determine the effect of hydrogen fluoride on the combustion of ammonia and oxygen.

Hydrogen fluoride was replaced with argon at the first stage of the experiments; this was aimed at determining the conversion of ammonia in combustion mode under standard conditions of the laboratory setup, and, furthermore, at considering the effect that the length h of the mixing zone had on the conversion of ammonia (Table 1).

A stable flame front could be generated at the given concentrations of the initial substances and the flow velocities. The flame front remained in the reactor and did not penetrate into the mixer during the experiments. The thermal diffusivity coefficients are close for gaseous nitrogen and argon (the difference is 3.6% under normal conditions [16]), so it can be assumed that the concentration limits of combustion only change insignificantly if N₂ in the NH₃-O₂-N₂ system is replaced with an equimolar amount of Ar [17]. Therefore, it can be argued that the ammonia concentration was within the concentration limits of combustion for the NH₃+O₂+Ar mixture (Fig. 4). The linear velocity of the gas in the reactor was significantly lower than the normal velocity of flame propagation in the NH₃+O₂+N₂ (Ar) mixture. The degree of ammonia conversion depended on the length of the mixing zone, and the ratio of the component flow rates and, reaching over 95%.

When argon was replaced with an equimolar amount of hydrogen fluoride (corresponding to its content in ABF), a stable flame front could not be produced for component flow rates in the range of 37–64 cm³·s⁻¹ with the length of

Table 1

Composition of products of interaction of NH_3 with O_2 in the presence of Ar in combustion mode (excluding unreacted NH_3) and conversion of NH_3 depending on the flow rate of initial components and mixer length

h , mm	Initial mixture, mol			W , cm ³ /s	V_R , cm/s	V_M , cm/s	Composition of reaction products, mol				K_{gas} , %	K_{liq} , %
	NH_3	O_2	Ar				N_2	Ar	H_2	O_2		
0		1.06		32.0	2.4	–	0.23			0.69	47	56
35		1.20		20.0	1.5	39.5	0.49			0.44	98	93
	1,00	1.20	2.03	20.0	1.5	39.5	0.49	2.03	0.0	0.44	99	89
50		1.03		38.0	2.9	76.3	0.42			0.24	84	88
		0.96		63.0	4.8	124.8	0.41			0.17	83	87

Notations: h is the length of the mixing zone; W is the total volumetric flow rate of components at flow temperature $t = 140^\circ\text{C}$; V_R , V_M are the flow rates in the reactor and in the mixing zone (respectively) at a temperature $t = 140^\circ\text{C}$; K_{gas} , K_{liq} are the ammonia conversion rates, determined from the gaseous reaction products and the composition of the liquid in the absorber, respectively.

the mixing zone varying from 0 to 40 mm. The linear gas velocity in the reactor varied in the range of 2.9–4.9 $\text{cm}\cdot\text{s}^{-1}$ and was lower than the normal flame propagation velocity in the $\text{NH}_3+\text{O}_2+\text{N}_2$ mixture. The concentration of ammonia in the experiments was within the concentration limits of flame propagation in the $\text{NH}_3+\text{O}_2+\text{N}_2$ mixture (see Fig. 4).

The absence of a stable flame front may be due to the inhibitory effect of hydrogen fluoride on the rate of ammonia oxidation or to the formation of liquid ABF upon contact of ammonia with hydrogen fluoride in a mixer.

To generate a stable flame front of ammonia and oxygen in the presence of hydrogen fluoride, fuels such as methane can be added to the

initial system and oxygen consumption can be increased for complete oxidation of methane.

Our further goal was to determine the minimum amount of methane at which the flame front would be stable and ammonia conversion would be close to 100%.

Thermodynamic calculations in the system of N-H-F-O elements

Calculations of the thermodynamic equilibrated composition for the system of N-H-F-O-C elements at a pressure $P = 0.1$ MPa in the system and in the temperature range of 600–2000 K confirmed that the only fluorine-containing substance at $n_H \geq n_F$ was hydrogen fluoride, the same as for the system of N-H-F-O

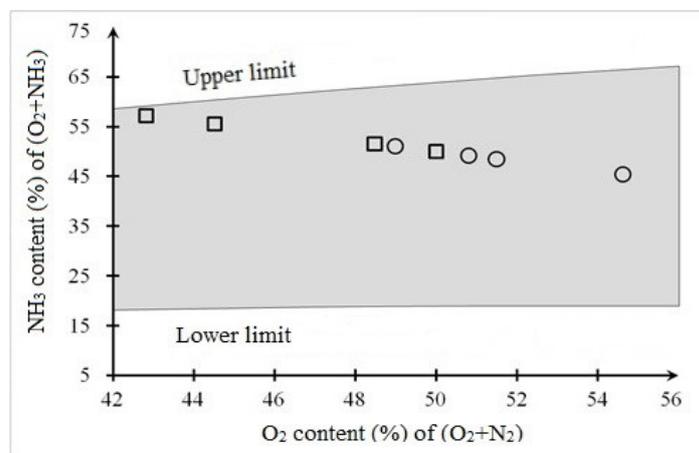


Fig. 4. Propagation region of $\text{NH}_3\text{-O}_2$ flame (shaded trapezoid), its concentration limits (upper and lower border lines) and O_2/NH_3 ratios in the experiments; the data are given for experiments with Ar (circles) and HF (squares)

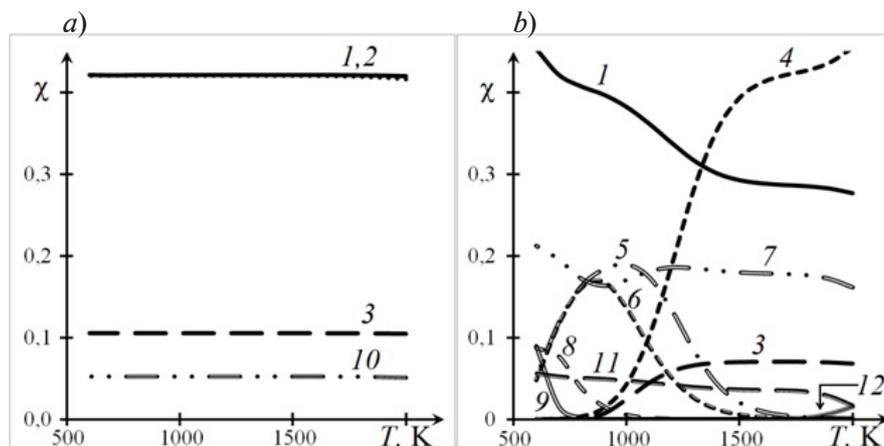


Fig. 5. Temperature dependences of thermodynamically equilibrated composition of substances (in molar fractions) in the system of N-H-F-O-C elements at various N-H-F-O-C ratios: 1.00:6.00:2.00:2.50:0.25 (a) and 1.00:2.00:6.00:2.50:0.25 (b); $n_F > n_H$.

The data are given for HF (1), H₂O (2), N₂ (3), F (4), F₂ (5), (NO)F (6), O₂ (7), NF₃ (8), NOF₃ (9), CO₂ (10), CF₄ (11), COF₂ (12)

elements, (Fig. 5,a). If $n_H < n_F$, then other fluorine-containing substances besides hydrogen fluoride are present in the thermodynamically equilibrated mixture: NF₃, (NO)F, NOF₃, F, F₂, CF₄ и COF₂ (Fig. 5,b).

Results of experiments in the NH₃-HF-O₂-CH₄ system

Methane was used to stabilize the flame front in the NH₃-HF-O₂ system, with a mixture of ammonia and methane supplied to the reaction zone. The oxygen content in the system corresponded to the minimum amount necessary

for complete combustion of ammonia producing nitrogen and water vapors, and for complete combustion of methane producing water vapors and carbon dioxide. To prevent liquid ABF from forming upon contact of ammonia with the hydrogen fluoride in the mixer, the experiments were carried out at $h = 0$ mm. The results of experiments are given in Table 2.

It was established that a stable flame front could be formed successfully at the concentrations of methane and oxygen in the initial mixture above 5.6 and 27.8 vol.%, respectively. Neither methane nor carbon

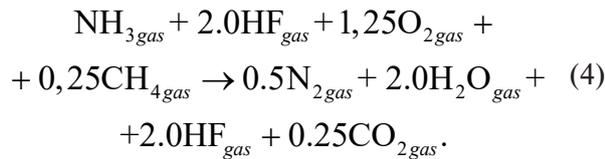
Table 2

Composition of reaction products of NH₃, O₂ and CH₄ in the presence of HF in combustion mode and NH₃ conversion depending on the flow rates of the initial components

Initial mixture, mol				W , cm ³ /s	V_R , cm/s	V_{RC} , cm/s	V_{AC} , cm/s	Composition of reaction products, vol.%				K_{gas} , %	K_{liq} , %
NH ₃	HF	O ₂	CH ₄					H ₂	N ₂	O ₂	CO ₂		
1,00	2,00	0.97	0.11	51.0	3.8	85.5	439.4	Impossible to form a stable flame front					
		1.25	0.25	50.0	3.7	82.7	437.5	0	0.50	0.01	0.25	95	97
		1.65	0.42	52.0	4.0	87.2	466.2		0.50	0.07	0.42	98	98
		1.59	0.42	53.0	4.0	88.4	480.7		0.03	0.50	0.02	0.42	96
	1.99	1.70	0.48	52.0	4.0	82.6	475.2	0	0.49	0.01	0.48	98	98

Notations: W is the total volumetric flow rate of components at the flow temperature $t = 140$ °C; V_R , V_{RC} , V_{AC} are the flow rates in the reactor, annular channel and axial channel (respectively) at a temperature $t = 140$ °C; K_{gas} , K_{liq} are the ammonia conversion rates, determined from the composition of gaseous reaction products and the composition of the liquid in the absorber after the experiment, respectively.

monoxide were found in the reaction products (within to $10^{-2}\%$). Conversion of ammonia in combustion mode reached 98% and practically did not depend on the concentration of methane in the mixture. The minimum contents of methane and oxygen in the mixture, at which it was possible to carry out the reaction in combustion mode correspond to the equation:



To reduce the flow rate of methane and the water content in the products of process (4), gaseous fluorine F_2 can be used to initiate reaction chains, stabilizing combustion. Elemental fluorine is known

to have a low dissociation energy equal to $\Delta H_{\text{dis}} = 157.5 \text{ kJ}\cdot\text{mol}^{-1}$, and the presence of fluorine radicals in the reacting mixture can stabilize the flame front [1]. Therefore, gaseous fluorine mixed with oxygen and hydrogen fluoride was fed into the reaction zone in an amount corresponding to a concentration of 0.5–1.3 vol.% in a $\text{NH}_3 + \text{HF} + \text{O}_2 + \text{CH}_4 + \text{F}_2$ mixture. However, a stable flame front could not be formed in the presence of gaseous fluorine without methane (Table 3). The flame front was stable in the presence of methane in an amount corresponding to a concentration of 2.7 vol.% and gaseous fluorine in an amount corresponding to a concentration of 0.5%; ammonia conversion reached 98% in this mode. Thus, using gaseous fluorine allows to reduce the concentration of methane at which the flame front is stable.

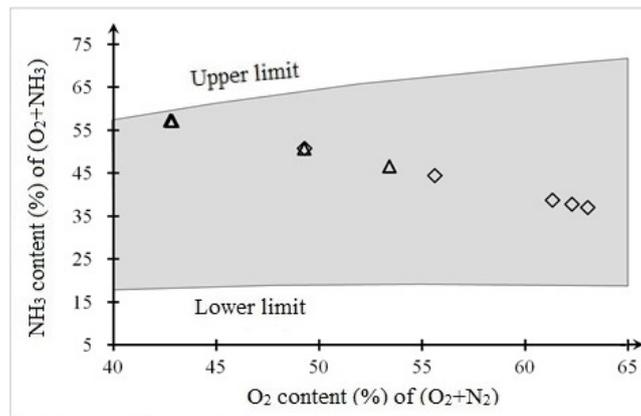


Fig. 6. Propagation region of $\text{NH}_3\text{-O}_2$ flame (shaded trapezoid), its concentration limits (upper and lower border lines) and O_2/NH_3 ratios in the experiments; the data are given for experiments with CH_4 (triangles) and F_2 (diamonds)

Table 3

Composition of reaction products of NH_3 , O_2 , CH_4 and F_2 in the presence of HF in combustion mode and NH_3 conversion depending on the flow rates of initial components

Initial mixture, vol.%					W , cm^3/s	V_R , cm/s	V_{RC} , cm/s	V_{AC} , cm/s	Composition of reaction products, vol.%			K_{gas} , %	K_{liq} , %
NH_3	HF	O_2	CH_4	F_2					N_2	O_2	CO_2		
1.00	2.00	0.97	0.11	0.02	50.0	3.8	84.2	430.0	0.49	0.03	0.11	97	98
		0.75	—	0.03	51.0	3.8	86.4	427.3	Impossible to form a stable flame front				
		0.75	—	0.04	50.0	3.8	85.0	419.1					
		0.75	—	0.05	50.0	3.8	84.9	416.8					
		1.15	—	0.04	47.0	3.6	82.7	356.6					

The notations are identical to those given in Table 2.

Flame propagation was possible in the experiments carried out, both in a mixture of ammonia with oxygen and in a mixture of methane with oxygen. The concentration of ammonia was within the concentration limits of flame propagation of ammonia and oxygen (Fig. 6) in all experiments, and the concentration of methane was within the concentration limits of flame propagation of methane and oxygen [18]. The normal velocity of flame propagation in the $\text{CH}_4 + \text{O}_2$ mixture was $330 \text{ cm}\cdot\text{s}^{-1}$, which is 2.4 times higher than that for the $\text{NH}_3 + \text{O}_2$ mixture. Therefore, it can be assumed that methane oxidation is the main stage of wave process (4) [19].

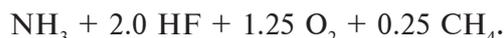
Main results and conclusions

Calculations via the ASTRA.4 software package have confirmed that hydrogen fluoride is the only fluorinated substance in a thermodynamically stable mixture in the system of N-H-F-O elements in the temperature range from 600 to 2000 K, given a ratio of chemical elements corresponding to Eq. (1), while other nitrogen fluorides and oxyfluorides are absent.

It was established in experiments with a laboratory reactor of the ‘tunnel burner’ type and a nozzle assembly that it was impossible to generate a stable combustion front of ammonia in oxygen with hydrogen fluoride present in the reaction zone, with ammonia concentrations varying from 25.0 to 27.5%, hydrogen fluoride from 50.0 to 55.1% and oxygen from 17.4 to 25.0%, i.e., when the molar ratio is $\text{NH}_3\text{-}2\text{HF}\text{-}\text{O}_2$

and the concentration of ammonia is within the concentration limits of flame propagation, if hydrogen fluoride is replaced by nitrogen.

For methane used in a mixture with ammonia, when the concentration of methane in a four-component mixture $\text{CH}_4\text{-}\text{NH}_3\text{-}\text{HF}\text{-}\text{O}_2$ was not less than 5.6%, the molar ratio $\text{NH}_3\text{-}\text{H}$ corresponded to $\text{NH}_4\text{F}\cdot\text{HF}$, and the amount of oxygen was sufficient for complete oxidation of both ammonia and methane:



A stable combustion front could be maintained under these conditions. The conversion of ammonia in combustion mode reached 98%.

Using fluorine in the amount corresponding to about 1% concentration in the mixture did not allow to generate a stable combustion flame of ammonia in oxygen in presence of hydrogen fluoride. Using fluorine in the amount corresponding to a concentration of about 0.5% made it possible to reduce the concentration of methane providing a stable flame front to 2.7%.

The method proposed can be used as a basis for obtaining hydrogen fluoride from ammonium fluorides, which are by-products in some industries.

This study was supported by the Ministry of Science and Higher Education of the Russian Federation (grant No. 05.608.21.0277, project ID RFMEFI60819X0277).

REFERENCES

1. Maksimov B.N., Barabanov V.G., Serushkin I.L. et al., Promyshlennye ftororganicheskie produkty. Spravochnik [Industrial fluoroorganic products. Handbook], Khimiya, Leningrad, 1990.
2. Tumanov V.V., Ostrovskij S.V., Starostin A.G., The mineral resource fluorine base of Russia and other countries, Vestnik of Perm National Research Polytechnic University, Chemical Technology & Biotechnology. (4) (2015) 124–136.
3. Pashkevich D.S., Mukhortov D.A., Alexeev Yu.I., et al., New aspects of waste-free technology for producing high-purity nitrogen trifluoride by fluorination of a melt of acidic ammonium bifluoride with fluorine, Proceedings of 2nd International Siberian Seminar “Modern Inorganic Fluoride” (Intersibfluorine-2006), June 11–16, 2006, Tomsk, TPU (2006) 222–225.
4. Dahlke T., Ruffiner O., Cant R., Production of HF from H_2SiF_6 , Procedia Engineering. 138 (2016) 231–239.
5. Pashkevich D.S., Mukhortov D.A., Kambur P.S., et al., Method of obtaining hydrogen fluoride, Pat. No. 2669838, Russian Federation, MPK C 01 B 7/19; SPb., “New Chemical Product” LLC is a declarant and a patentee, No. 2018101617; declar. 16.01.18; publ. 16.10.18, Bull. No. 29, 9 p.
6. Mineral commodity summaries 2019: U.S. Geological Survey, United States Government Printing Office (2019).
7. Pashkevich D.S., Mamaev A.V., Production of hydrogen fluoride by processing fluorine-containing wastes and by-products of modern industries, WIT Transactions on Ecology and the Environment, 231 (2019) 111–123.
8. Rodin V.I., Kharitonov V.P., Seredenko V.A., Hydrogen fluoride technology by sulfuric acid decomposition of ammonium bifluoride, Russian Chemical Industry. 76 (12) (1999) 753–757 (in Russian).



9. **Kurapova E., Mukhortov D., Pashkevich D., et al.**, Production of hydrogen fluoride using fluorine-containing waste of manufacturing phosphate fertilizers, *Chimica Oggi – Chemistry Today*. 35 (3) (2017) 24–26.
10. **Pashkevich D.S.**, Regeneration of fluorine in the form of hydrogen fluoride from volatile fluorine-containing wastes in a hydrogen-containing fuel-oxygen-containing oxidant flame, *Russian Journal of Physical Chemistry B: Focus on Physics*. 13 (6) (2019) 993–1003.
11. **Shebeko Yu.N., Trunev A.V., Tsarichenko S.G., Zaitsev A.A.**, Investigation of concentration limits of flame propagation in ammonia-based gas mixtures, *Combustion, Explosion and Shock Waves*. 32 (5) (1996) 477–480.
12. **Morrison R., Boyd R.**, *Organic chemistry*, 2nd Ed., Allyn and Bacon Inc., Boston, 1970.
13. **Pashkevich D.S., Kostyaev R.A.**, Rol' fluorovodoroda i diflorida kopal'ta v protsessakh fluorirovaniya uglevodorodov trifloridom kopal'ta [The role of hydrogen fluoride and cobalt difluoride in the processes of fluorination of hydrocarbons with cobalt trifluoride], *Russian Journal of Applied Chemistry*. 67 (12) (1994) 2012–2017 (in Russian).
14. **Trusov B.G.**, Programmnyaya sistema modelirovaniya fazovykh i khimicheskikh ravnovesiy pri vysokikh temperaturakh [Code system for simulation of phase and chemical equilibriums at higher temperatures], *Herald of the Bauman Moscow State Technical University, Series Instrument Engineering, Special Iss. 2: Software Engineering* (2012) 240–249 (in Russian).
15. **Pankratov A.V.**, *Khimiya fluoridov azota* [Chemistry of the nitrogen fluorides], Khimiya, Moscow, 1973 (in Russian).
16. **Grigoriev I.S., Meilikhov E.Z.** (Eds.), *Fizicheskie velichiny* [Handbook of Physical Quantities], Energoatomizdat, Moscow, 1991 (in Russian).
17. **Snegiryov A.Yu.**, *Osnovy teorii goreniya* [Principles of combustion theory], Polytechnical University Publishing, St. Petersburg, 2014 (in Russian).
18. **Antonov V.N., Lapidus A.S.**, *Proizvodstvo atsetilena* [Acetylene production], Khimiya, Moscow, 1970 (in Russian).
19. **Han J.W., Lee C.E., Kum S.M., Hwang Y.S.**, Study on the improvement of chemical reaction mechanism of methane based on the laminar burning velocities in OEC, *Energy & Fuels*. 21 (6) (2007) 3202–3207.

Received 11.09.2020, accepted 21.09.2020.

THE AUTHORS

PASHKEVICH Dmitrii S.

Peter the Great St. Petersburg Polytechnic University
29, Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
pashkevich-ds@yandex.ru

MUKHORTOV Dmitrii A.

LLC «New chemical products»
11, A, Moyka River Emb., St. Petersburg, 191186, Russian Federation
dmukhortov@mail.ru

KAPUSTIN Valentin V.

Peter the Great St. Petersburg Polytechnic University
29, Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
valentin.kapustin.2014@yandex.ru

KAMBUR Pavel S.

Peter the Great St. Petersburg Polytechnic University
29, Politechnicheskaya St., St. Petersburg, 195251, Russian Federation
pavel.kambur@mail.ru

KURAPOVA Ekaterina S.

Russian Scientific Center «Applied Chemistry»

26, Bolshieviki Ave., St. Petersburg, 193232, Russian Federation

e_kurapova@mail.ru

ZIMIN Arsenii R.

Peter the Great St. Petersburg Polytechnic University

29, Politechnicheskaya St., St. Petersburg, 195251, Russian Federation

fz1min@yandex.ru

MASLOVA Anastasiia S.

Peter the Great St. Petersburg Polytechnic University

29, Politechnicheskaya St., St. Petersburg, 195251, Russian Federation

anastasiiamaslova5@gmail.com