Synthesis of Nanomaterials in a Coaxial Flame

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Article info	Abstract
	The paper presents the results of experimental studies of the synthesis of fullerenes C_{60} in a coaxial flame of benzene and acetylene at low pressures; of the synthesis of graphene in a coaxial flame of ethanol and propane, benzene, and acetylene; of the soot formation process in the coaxial flame of propane and ethanol. It has been established that the optimum temperature of a coaxial flame for the formation of fullerenes C_{60} is 970–1000 °C with the carbon to oxygen ratio in the internal benzene-oxygen flame $C/O \approx 0.9 \div 1$. The C/O ratio in an external acetylene-oxygen flame was maintained at a stoichiometric ratio. It was found that the preliminary (before feeding into the burner) treatment of the benzene-oxygen mixture using ultraviolet (UV) radiation with a wavelength of 254 nm promotes an increase in the yield of fullerenes. The synthesis conditions were optimized for: 5–10 layers graphene in a coaxial flame of acetylene and ethanol; graphene containing more than 10 layers in a coaxial flame of propane and ethanol; one and two-layer graphene in a coaxial flame of ethanol and benzene. The possibility of a significant reduction of the formation of soot particles in the diffusion flame of propane by organizing its coaxial combustion with ethanol is shown.

1. Introduction

Due to the intensive development of the new technologies and the transport industry, the level of energy consumption is increasing, a significant part of which is produced by burning fossil fuels. In turn, the burning of fossil fuels releases a huge amount of pollutants into the environment. The toxicity of emitted pollutants depends on the type of hydrocarbon fuel burned and the conditions for organizing the combustion process, as a result of this, the study of problems and issues related to combustion does not lose its relevance. According to the theory of chain reactions, developed by academician N.N. Semenov combustion is a reaction with branched chains when one active particle generates several new active particles, each of which generates several newer active particles, etc. and thus there is an avalanche acceleration of the reactions that support the combustion process. In a flame, the development of a chain reaction occurs due to the active intermediate particles, free radicals, atoms, ions and excited molecules formed during combustion. By varying parameters such as the ratio of fuel to oxidizer, pressure, temperature, supply or removal of external energy, it is possible to change the combustion conditions, which in turn leads to a change in the composition of active intermediate particles and their quantitative ratio. This circumstance makes it possible to control the processes of the formation of the final combustion products, which becomes of particular relevance with the development of nanotechnology. Numerous studies on the synthesis of various nanomaterials show that the method of their synthesis in flames is one of the most promising for large-scale production.

Many research groups are conducting intensive research on the synthesis of carbon nanotubes (CNTs) [1, 2] and fullerenes [3, 4] in flames. The authors of [5] studied the formation of fullerenes in a laminar premixed toluene-oxygen flame depending on the pressure in the system, the C/O ratio of the combustible mixture, and the rate of its supply.

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The authors found that the yield of fullerenes decreases with an increase in the C/O ratio in the combustible mixture, regardless of the pressure in the system from 40–100 Torr, and vice versa, the feed rate of the combustible mixture does not affect the mass yield of fullerenes. According to the authors, the method developed by them makes it possible to produce more than one ton of fullerenes per year.

Moreover, methods for the synthesis of graphene in flames have been successfully developed in recent years. In work [6], the authors investigated the synthesis of graphene films in the laminar diffusion flame of pure ethanol and its mixture. The authors associated the impossibility of the graphene synthesis in the pure diffusion flame of ethanol with the flame temperature. The ethanol laminar diffusion flame temperature does not exceed 700 °C, while with an additional supply of hydrogen, the combined flame temperature reaches 1000 °C. High temperature increases the likelihood of dissolution of carbon atoms in the bulk of the nickel film, and the dissolved carbon upon cooling forms graphene in the process of segregation. In [7], the process of graphene synthesis on a nickel substrate in the flame of a premixed butane-oxygen mixture with an addition of benzene under reduced pressures of 40–100 Torr was studied. It was found that the growth of graphene layers on a nickel substrate occurs at flame temperatures of 900–950 °C and an exposure time of 0.5 min. It is shown that, at a pressure in the system of 45–55 Torr, the predominant formation of single-layer graphene is observed. It was determined that with a decrease in the exposure time, the degree of graphene defectiveness decreases and reaches a minimum value equal to $I_D/I_G = 0.36$. The main advantages of the method for the synthesis of graphene in flames include the fact that the synthesis is possible in an open atmosphere, a short growth time, the absence of additional energy costs due to the efficient use of fuel as a heat source, and the ability to scale the process. In one of the latest works [8], the authors, based on an analysis of the latest achievements in the synthesis of nanomaterials in premixed laminar flames, proposed a new model for the formation of soot, carbon nanotubes, fullerenes, single- and multilayer graphene in fuel-rich flames.

One of the urgent problems associated with combustion processes is the fight against emissions of pollutants into the environment. Paper [9] presents experimental results for the thermal decomposition of hydroxylammonium nitrate (HAN) in the presence of activated carbon obtained by rice husk. The addition of activated carbon reduces the temperature of the onset of decomposition of HAN from 185 to 86 ± 0.5 °C and reduces the amount of NO_x gases produced by decomposition to 30%. The work [10] presents the results of experimental and numerical studies of the influence of the methanol and ethanol addition on the formation of polycyclic aromatic hydrocarbons (PAHs) and soot in the upstream counterflow diffusion flame of ethylene. Research results have shown that methanol and ethanol have different effects on the formation of PAHs and soot. The addition of a small amount of ethanol (up to 10%) enhances the formation of soot. Using numerical simulations, the authors showed that the decomposition of ethanol produces a relatively large amount of CH_3 methyl radicals, which interact with the C_2 radical and promote the formation of propargyl C_3H_3 and the C_4 radical. As a result, due to the interaction between acetylene C_2H_2 and C_4 and the recombination reaction of C_3H_3, the probability of benzene formation increases, which leads to an increase in the growth of PAHs and the formation of soot. In [11], the effect of adding ethanol to a premixed laminar ethylene-oxygen flame on the formation of soot particles and their size distribution function was studied. The soot particle size distribution did not change significantly with the addition of ethanol compared to the flame of pure ethylene. Based on the results obtained, the authors concluded that in the premixed flame of ethylene, the addition of ethanol has a significant effect on the chemistry of the formation of soot particles and suppresses their growth.

The authors of [12] studied the impact of ethanol vapor additions into the laminar diffusion flame of n-heptane on the mass yield of soot particles, as well as on their structure and morphology. Research results have shown that the addition of ethanol has a direct effect on the flame height and the size of the resulting soot particles. When the ratio of n-heptane to ethanol was 1.5, the flame height increased by 10 mm and the size of soot particles decreased by an average of 34.83% compared with that of pure n-heptane flame. The authors also observed an overall decrease in the mass yield of soot.

After reviewing scientific works, we established that, despite the numerous studies, many questions remain open, related to the control of the formation of intermediate and final combustion products in a flame. The composition, structure and properties of the resulting end products of combustion in a flame depend on the nature of the initial particles
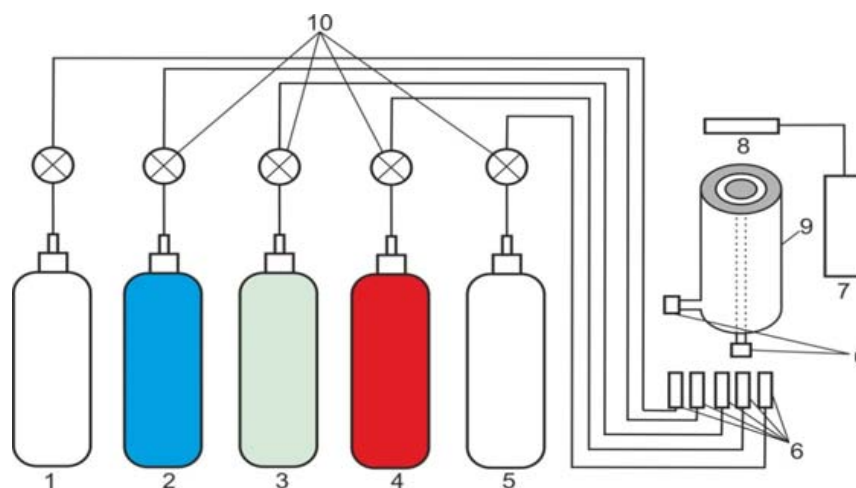
Fig. 1. Scheme of the setup for the study of coaxial flames: 1 – ethanol vapor generator; 2 – compressed air; 3 – acetylene; 4 – propane; 5 – benzene vapor generator; 6 – connecting bushings; 7 – temperature meter; 8 – chromel-alumel thermocouple; 9 – coaxial burner; 10 – flow meters.

and the chemical kinetics of these processes. Hydrocarbons can be roughly divided into four main classes: iso- and normal- paraffins, naphthenes and aromatic ones. They differ in the physicochemical characteristics of molecules and thus have individual kinetic characteristics in the course of oxidation reactions, the production of radicals and products. Precursors (building material) of aromatic molecules are especially sensitive to the reaction process of C_3H_3, C_4H_3, C_4H_5, C_2H_2, C_3H_2, C_4H_2 and C_4H_4. Their formation and growth depend on the concentration of active radicals OH, H, O, HO_2, CH_3, C_2H, HCO, C_2H_3. Thus, the composition, structure and properties of the forming first aromatic molecules, their growth to poly-aromatic combustion products in a flame depend on the composition and concentration of the formed intermediate particles and aromatic precursors. By combining the compositions of the intermediate components and the density of aromatic precursors, it is possible to create the most favorable conditions for the growth of poly-aromatic molecules. In this regard, it seems effective to use a combination of intermediate oxidation products of various types of hydrocarbons in order to obtain aromatic molecules of specified sizes. Fundamental studies of the structures of such flames are practically unknown. The scientific novelty of the presented study is the experimental study of the possibilities to use the advantages of coaxial combustion of different fuels to control the formation of combustion products.

The experimental setup consists of two coaxial burners for producing laminar premixed flames, the reaction zones of which can be brought into contact to produce a combined coaxial flame reaction zone. The burners are installed in such a way that they allow mixing flames at different heights from the burner surfaces, i.e. at various stages of the development of the reaction. This condition makes it possible to regulate the formation of stabilizing combustion products by selecting fuels and changing the concentration density and composition of intermediate particles in the combined reaction zone of the flames. The synthesis of fullerenes C_{60} in a coaxial flame of benzene and acetylene at low pressures, the synthesis of graphene in a coaxial flame of ethanol with benzene, and the process of soot formation in a coaxial flame of propane and ethanol are studied in this present work.

2. Experimental part

Figure 1 shows a scheme of an experimental setup for studying the process of coaxial combustion of various fuels with the formation of a combined reaction zone of flames.

The main unit of the setup is a burner with a coaxial arrangement of two nozzles (Fig. 2).

The design of the burner allows feeding different types of fuel to each nozzle separately and controlling the ratio of oxidizer to fuel in the combustible mixture and creating flames from very rich in fuel to the stoichiometric ratio. It is possible to move the nozzles relative to each other along the vertical axis, which allows mixing flames at different stages of the development of combustion reactions. This makes it possible to study the effect of mixing of intermediate particles (radicals, ions, fragments of molecules, etc.) formed during the combustion of different fuels on the formation of nuclei of the final combustion products.
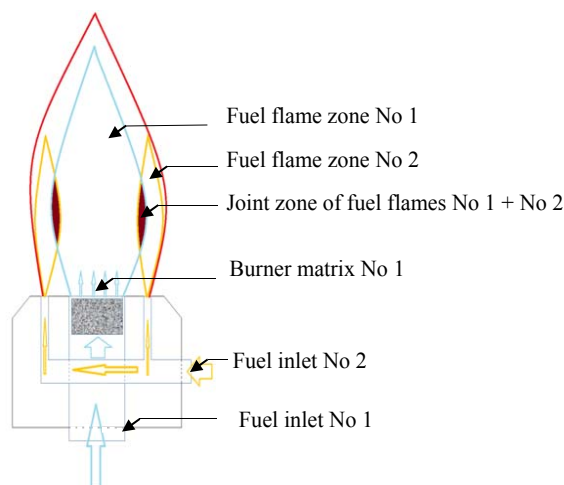
Fig. 2. Diagram of a coaxial burner.

Figure 3 shows a schematic representation of a setup on which fullerene-containing soot was synthesized during coaxial combustion of an external acetylene-oxygen mixture and an internal benzene-oxygen mixture at low pressure.

The coaxial flame was created by encircling an internal premixed benzene-oxygen flame with an annular external flame of an acetylene-oxygen mixture. The gas flow rate was controlled by Alicat Scientific flow meters. Benzene vapors were obtained by bubbling oxygen gas through benzene, the flow rate of which was controlled by changing its temperature. The coaxial flame burned under the following conditions: consumption of benzene (C_6H_6) – 140–150 cm³/min, oxygen consumption (O_2) – 440–460 cm³/min, which ensured the ratio of carbon to oxygen in the combustible mixture C/O ≈ 0.9÷1. Argon consumption Ar = 60 cm³/min. The acetylene-oxygen flame burned at the follow-

ing flow rates: acetylene (C_2H_2) – 200–220 cm³/min, oxygen (O_2) – 1100–1150 cm³/min, which ensured close to stoichiometric combustion of the acetylene-oxygen mixture. For 60 min of combustion, up to 500 mg of fullerene-containing soot was formed. The temperature of the coaxial flame was 970–1000 °C. The collected soot was subjected to cold extraction in benzene for 48 h at room temperature. The obtained extracts for the identification of dissolved soot products were investigated on a Fourier-transform infrared spectroscopy (FTIR) spectrophotometer.

Research on the synthesis of graphene in coaxial flames of ethanol with benzene, propane, and acetylene has been carried out. Ethanol and benzene vapors were obtained by bubbling oxygen gas through ethanol or benzene the concentration of which was controlled by changing their temperature. In all experiments, the coaxial flame burned when the ethanol-oxygen combustible mixture was fed into the inner flame. The ratio of carbon to oxygen in the ethanol-oxygen combustible mixture in all experiments was maintained at the level of C/O ≈ 0.9. The ratio in the supplied hydrocarbon combustible mixtures varied within C/O ≈ 0.7–0.8, the flame temperature varied in the range of 970–1200 °C. As substrate used nickel foil from company Goodfellow with 0.2 mm thickness, the synthesis time ranged from 60 to 180 sec. In experiments on the synthesis of graphene's, the used substrates were installed at angles of inclination relative to the flame from 45 to 80 ° in the region of the combined reaction zone of the coaxial flame. In total, more than 150 carbon-coated samples were obtained under various experimental condi-
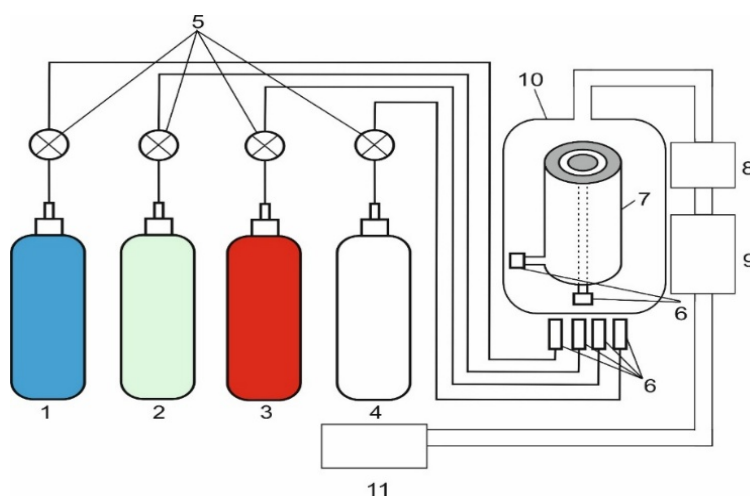

Fig. 3. Schematic representation of a plant for the synthesis of fullerene-containing soot: 1 – oxygen; 2 – argon; 3 – acetylene; 4 – benzene vapor generator; 5 – flow meters; 6 – connecting bushings; 7 – coaxial burner; 8 – nitrogen trap; 9 – soot collector; 10 – sealed quartz reactor; 11 – vacuum pump.

tions and examined by Raman spectroscopy. Suppression of soot formation in flames remains one of the urgent problems. The article presents the results of studies of the process of soot formation in a diffusion flame of propane during its coaxial combustion with an ethanol-air flame. The coaxial flame was created by encircling an internal premixed ethanol-air flame with an annular external propane diffusion flame. The external diffusion flame burned at a propane flow rate of 65 cm³/min. A combustible ethanol-air mixture with different C/O ratios was obtained by bubbling air through liquid ethanol. The supply of clean airflow to the internal burner promotes complete after burning of the fuel and, as a result, the process of soot formation is reduced. Therefore, in experiments, a combustible ethanol-air mixture was obtained by bubbling a strictly fixed volume of air at 150 cm³/min. To change the C/O ratio in the ethanol-air flame, the concentration of the ethanol vapor volume was controlled by heating from 25 to 55 °C, which ensured the ethanol consumption in the range of 0.035–0.75 g/min.

3. Results and discussion

3.1. Fullerene synthesis

The main condition for the formation of fullerenes is the presence in the system not only of structures containing a six-membered ring (hexagon C_6), but also the obligatory presence of a structure with a five-membered ring (pentagons C_5). It is the combination of the pentagon with the hexagon that leads to the curvature and subsequent folding of the resulting structure into a fullerene nucleus. In a benzene flame, structures containing six-membered benzene rings are constantly present in suf-

ficient quantities and a very low probability of the formation of a structure with a five-membered ring. Based on the foregoing, in our research, we have developed a technique for forcing a structure containing a five-membered ring into the flame. It is known that short-term irradiation of benzene with short-wave UV radiation with a wavelength of 254 nm leads to benzene isomerization with the formation of fullerene, a structure with a five-membered ring.

Thus, if benzene is irradiated with UV radiation before it is fed to the burner, it is possible to artificially create structures containing five-membered rings, which, falling into the flame, will participate in the reactions of formation of a fullerene nucleus. For this purpose, the installation for the synthesis of fullerene-containing soot was additionally equipped with a system for irradiating the supplied benzene-oxygen mixture with UV radiation with a wavelength of 254 nm. A bactericidal irradiator Generis 2-15-01 was used as a source of UV radiation. The rapid breakthrough of the benzene-oxygen combustible mixture through the quartz tube ensures a short duration of UV treatment. The synthesis of fullerenes in a coaxial flame was carried out at a pressure in the system of 60–100 Torr. Figure 4 shows the IR spectrum of a carbon black extract obtained at a pressure of 90–95 Torr.

Figure 5 shows the IR spectrum of a soot extract obtained at a pressure of 60–65 Torr.

In the IR spectra, there are 4 peaks in the region of 528, 577, 1183, 1429 cm⁻¹, corresponding to fullerene C_{60}. Comparative analysis of the IR spectra of soot extracts obtained in the coaxial flame of benzene and acetylene at a pressure in the system of 90–95 Torr and 60–65 Torr shows that in the IR spectra with a decrease in pressure by 30 Torr, the intensity of the peaks corresponding to
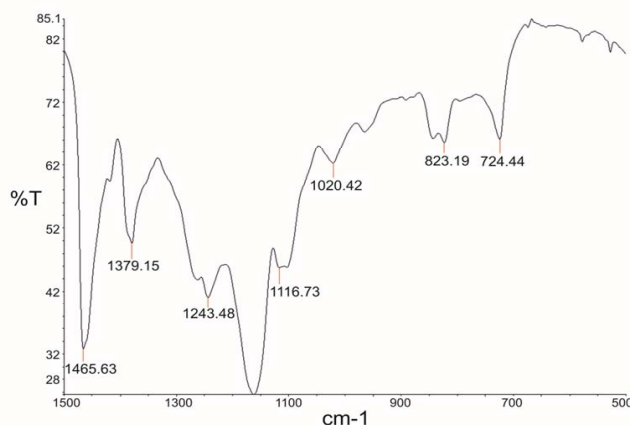

Fig. 4. IR spectrum of the carbon black extract obtained in a coaxial flame of acetylene and benzene at a pressure of 90–95 Torr.
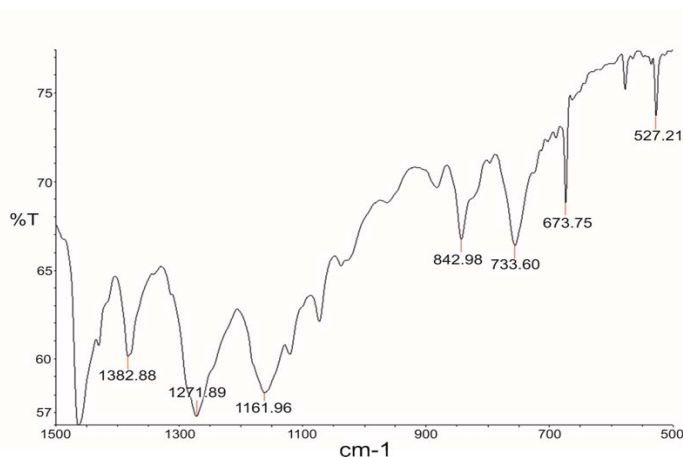
Fig. 5. IR spectrum of the soot extract obtained in a coaxial flame of acetylene and benzene at a pressure of 60–65 Torr.

fullerene C_{60} increases approximately four times, and as a consequence, according to the Bouguer-Lambert-Beer law, the concentration of fullerene C_{60} in soot also approximately quadruples.

Thus, studies have been carried out and the conditions for the formation of fullerenes in a coaxial flame of benzene with acetylene have been optimized. It was found that the optimal flame temperature for the formation of fullerenes C_{60} is 970–1000 °C. It was found that for the formation of fullerenes the optimal ratio of carbon to oxygen C/O in an internal benzene-oxygen flame is C/O $\approx 0.9 \div 1$. The ratio of carbon to oxygen, C/O, in an external acetylene-oxygen flame was maintained close to stoichiometric. Studies have shown that the most effective option for the formation of fullerenes in a coaxial flame is coaxial combustion of an acetylene-oxygen mixture with a benzene-oxygen combustible mixture, which is pretreated before being fed into the burner with UV radiation at a wavelength of 254 nm.

3.2 Graphene synthesis

The process of formation of graphene on the surface of a nickel substrate during coaxial combustion of ethanol with acetylene, propane, and benzene was studied. In all experiments, the synthesis time was 90 sec, and in an ethanol-oxygen combustible mixture, the ethanol vapor consumption was 170 cm³/min at an oxygen consumption of 420 cm³/min. Figure 6 shows the Raman spectrum of a carbon film obtained on the surface of a nickel substrate in a coaxial flame of ethanol and acetylene. In an acetylene-oxygen combustible mixture, the acetylene consumption is 90 cm³/min, the oxygen consumption is 380 cm³/min. The flame
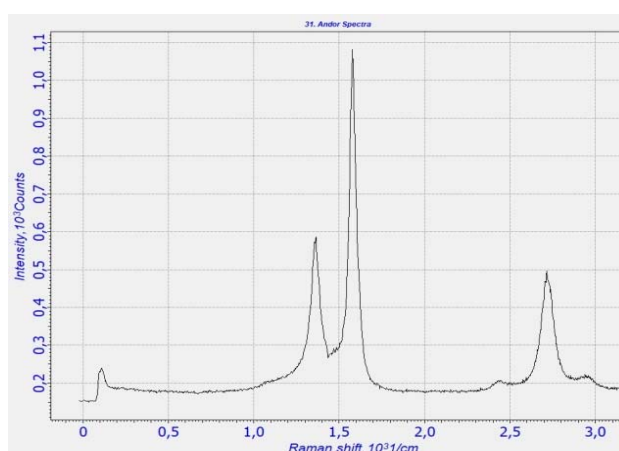

Fig. 6. Raman spectrum of a carbon film obtained on the surface of a nickel substrate in a coaxial flame of ethanol and acetylene.

temperature in the combined reaction zone of the coaxial flame reached 1150 °C, the substrate temperature 1100 °C. The angle of inclination of the substrate relative to the flame vertically is 80 °.

Figure 7 shows the Raman spectrum of a carbon film obtained on the surface of a nickel substrate in a coaxial flame of ethanol and propane. In a propane-oxygen combustible mixture, the propane consumption was 130 cm³/min, and the oxygen consumption was 560 cm³/min. The temperature in the combined reaction zone of the coaxial flame reached 1050 °C, the temperature of the substrate is 1000 °C. The angle of inclination of the substrate relative to the flame vertically is 80 °.

Figure 8 shows the Raman spectrum of a carbon film obtained on the surface of a nickel substrate in a coaxial flame of ethanol and benzene. In a benzene-oxygen combustible mixture, benzene vapor consumption is 160 cm³/min, oxygen consumption is 600 cm³/min. The temperature in the combined
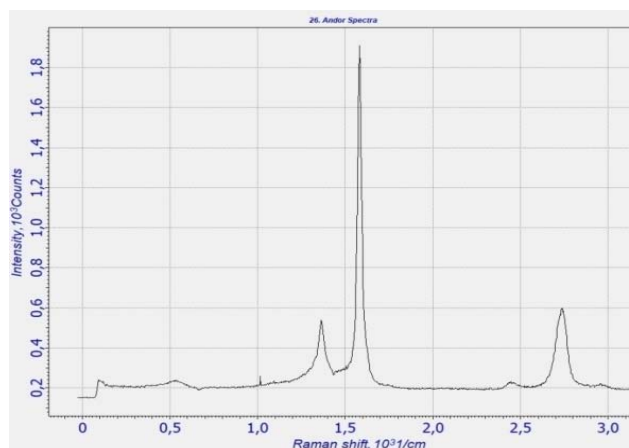
Fig. 7. Raman spectrum of a carbon film obtained on the surface of a nickel substrate in a coaxial flame of ethanol and propane.

reaction zone of the coaxial flame reached 1200 °C, the temperature of the substrate – 1150 °C. The angle of inclination of the substrate relative to the flame is 80 °.

As a result of the experimental studies, it was found that the exposure time of 90 sec is optimal for the growth of graphene layers on the surface of a nickel plate. In the first 15 sec, the substrate heats up to 950–1150 °C, depending on the flame used, and then the substrate temperature is stabilized and maintained until the end of the experiment. An increase in the exposure time over 90 sec does not affect the number of layers of the formed graphene.

Raman spectroscopy is an effective technique for determining the structural characteristics of allotropic forms of carbon. The peak at 1350 cm⁻¹ corresponds to the vibrations of the D mode, which is interrelated with the presence of vacancies and distortions of grain boundaries; with structural de-
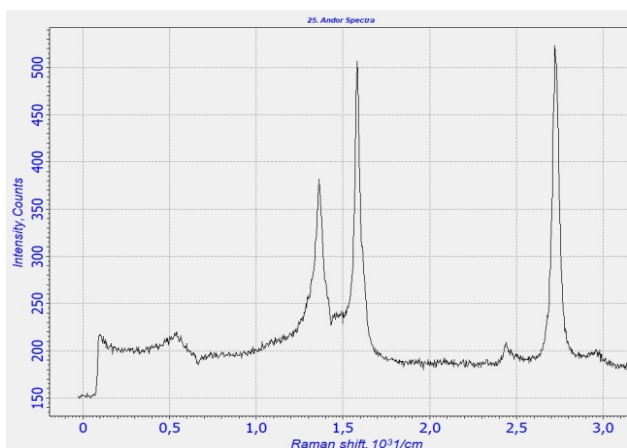
fects. The second peak at 1582 cm⁻¹ corresponds to G mode vibrations and shows the degree of graphitization. The third peak at 2710 cm⁻¹ is called the 2D mode, because of the position and shape that can be estimated for the graphene layer. Thus, the intensity of the D peak in the Raman spectra can be used to analyze the structural imperfection in graphene, and from the ratio of the intensity of the 2D peak to the intensity of the G peak, one can approximately estimate the number of graphene layers [13].

An analysis of the Raman spectra obtained for carbon coatings shows the possibility of synthesizing graphenes on the surface of a nickel substrate in all three studied types of coaxial flames. In a coaxial flame: propane with ethanol, graphene is formed, containing from 10 layers or more, acetylene with ethanol, graphene is formed, containing from 5 to 10 layers, in a coaxial flame of benzene with ethanol, one and two-layer graphene.

There are two possible mechanisms of graphene formation on the surface of metal substrates, which are considered in [14, 15]. First, at high temperatures in a hydrocarbon gas medium, carbon atoms dissolve in the surface layer of a metal plate, and graphene grows due to the process of carbon segregation on its surface when the substrate is cooled. In the second case, the dissolution of carbon in the surface layer of the metal does not occur, and the growth of graphene occurs due to the process of dissociation of gas molecules and the subsequent alignment of atomic carbon into the graphene structure on the substrate surface. The dissolution of carbon in nickel is possible at temperatures above 1000 °C, which are achieved in our investigated coaxial flames. In the ethanol flame, OH radicals are formed in high concentrations, the concentration of which decreases during the coaxial combustion of ethanol with all the hydrocarbons used. We assume that OH radicals, getting into the combined zone of the coaxial flame, react with the oxidation products of the second hydrocarbon, and in view of their activity, they break C–C and C–H bonds, promoting the formation of free carbon atoms. The formed carbon atoms diffuse into the surface layer of the nickel substrate, and the growth of graphene layers occurs already in the process of carbon segregation upon cooling the nickel substrate. The reason for the change in the number of graphene layers in the synthesized graphene can be explained by a change in the concentration density of free carbon atoms, which are formed in a coaxial flame as a result of combustion of the used hydrocarbon.

Fig. 8. Raman spectrum of a carbon film obtained on the surface of a nickel substrate in a coaxial flame of ethanol and benzene

In a coaxial flame of propane with ethanol, the process of soot formation is sharply reduced, and it can be assumed that this leads to a high concentration of free carbon atoms in the flame, because they do not have time to condense into soot particles. As a result, a larger amount of carbon dissolves on the nickel substrate, which form a larger number of graphene layers during segregation upon cooling. In the coaxial flame of acetylene with ethanol, a sufficient amount of soot is formed, which settles on the top of the nickel substrate, set at an angle into the flame. The process of condensation of free carbon atoms in the flame into soot particles leads to a decrease in their concentration, and a smaller amount of carbon dissolves on the surface of the nickel substrate. Accordingly, in the process of segregation, when the substrate is cooled, a smaller number of graphene layers are formed. The coaxial flame of benzene with ethanol, in comparison with the coaxial flame of propane and acetylene, is the most soot-forming. The intensive process of the formation of soot particles significantly reduces the concentration of free carbon atoms; accordingly, a small amount of carbon has time to dissolve on the surface of the nickel substrate, and only one or two-layer graphene can form during the segregation process.

3. Soot formation

To reduce the process of soot formation during combustion of hydrocarbons, the method of adding various alcohols to fuels is used. In [16], a detailed chemical kinetic model of ethanol oxidation was developed and tested on a variety of experimental data. The author of the work claims that the content of hydroxyl groups in the ethanol molecule promotes the intensive formation of active oxygen-containing radicals HCCO, CHO, OH during its combustion. An increase in the concentration of these components contributes to a decrease in the concentration of CH_3 and C_2H_2, which are the main components of PAH formation through methylation, cyclization, and dehydrogenation. Thus, the low PAH content in the ethanol flame leads to an additional decrease in the overall soot formation process. Ethanol is one of the most promising for practical application of oxygenates, now produced on an industrial scale. We investigated the effect on the process of soot formation in a diffusion flame of propane during its coaxial combustion with a premixed ethanol-air mixture. What is the difference between the process of coaxial combustion? This is primarily that in the external diffusion

flame of propane and the internal flame of ethanol at the beginning of the flame front, intermediate particles of different composition are formed, which are mixed at a certain height from the burner matrices and change the course of the reactions of formation of combustion products. The external diffusion propane flame burned at a propane flow rate of 65 cm^3/min. The internal flame of the ethanol-air mixture burned at an air flow rate of 150 cm^3/min with different contents of ethanol vapors. The supply of ethanol vapors into the combustible mixture was carried out by passing an air flow through a bubbler filled with ethanol, which was heated to a certain fixed temperature. At ethanol temperatures of 25–55 °C, the equivalence coefficient of the combustible ethanol-air mixture varied within the range $\phi = 0.9$–2.26. The resulting soot particles were collected on the surface of the stainless steel plate for 5 min. The soot mass was measured on an analytical balance together with the plate. Table presents the results of the effect of changing the concentration of ethanol vapors of the internal ethanol-air flame on the mass yield of soot particles during coaxial combustion.

The obtained results show a sharp decrease in the formation of soot particles in the diffusion flame of propane during the organization of its coaxial combustion with a premixed ethanol-air flame. An increase in the concentration of ethanol vapors in a combustible ethanol-air mixture above the equivalence coefficient $\phi = 1.21$ does not lead to a further decrease in the formation of soot particles. As noted in [15], the ethanol flame contains increased concentrations of HCCO, CHO, OH radicals, which during coaxial combustion, mixing with the combustion products of the propane flame, lead to intensification of oxidation processes and complete combustion of the fuel, and as a result, the probability of PAH and soot formation decreases. Thus, the results of experimental studies have shown the possibility of reducing the process of soot formation by organizing the coaxial combustion of propane with ethanol.

4. Conclusion

The results obtained show the promise of using the process of coaxial combustion of various fuels to reduce the process of soot formation and controlled synthesis of nanomaterials in a flame. Comparative analysis of the IR spectra of soot extracts obtained in a coaxial flame of benzene and acetylene at a pressure in the system of 90–95 Torr and 60–65 Torr shows that in the IR spectra with

Table

Results of the influence of changes in the concentration of ethanol vapors of the internal ethanol-air flame
on the mass yield of soot particles during coaxial combustion

#	Air flow, m^3/min	Ethanol temperature, °C	Ethanol consumption, g/min	Equivalence coefficient, ϕ	The mass of the formed soot, mg
1	150	-	-	-	0.1053
2	150	25	0.034	0.90	0.0086
3	150	30	0.056	1.05	0.0092
4	150	35	0.046	1.21	0.0040
5	150	45	0.060	1.57	0.0041
6	150	55	0.086	2.26	0.0041

a decrease in pressure by 30 Torr, the intensity of the peaks corresponding to fullerene C_{60} increases approximately four times. It was found that when organizing coaxial combustion, changing the types of fuels, it is possible to achieve conditions for obtaining graphene with a given number of layers. In a coaxial flame of propane with ethanol, graphene containing 10 or more layers were synthesized; graphene containing from 5 to 10 layers were synthesized with acetylene with ethanol; in a coaxial flame of benzene with ethanol, one and two-layer graphene. It was found that organizing the coaxial combustion of ethanol and propane can significantly reduce the process of soot formation. This result can be of practical importance not only in terms of ensuring environmental safety, but also for increasing the efficiency of combustion processes in internal combustion engines, gas turbines and boiler units.

Acknowledgments

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