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CHARACTERIZATION OF OPPORTUNITY FOR UPGRADING OF THE SYSTEM BASED ON ARC PLASMA TORCH FOR THERMAL SPAYING OF CERAMIC MATERIALS, BY MEANS OF USE OF FUEL VORTEX INTENSIFIER.

PART II: THERMAL ENGINEERING ESTIMATION AND EXPERIMENTAL TESTING

Abstract. The main trends in the field of improving thermal spraying processes for ceramic coatings formation is, along with enhancement of coating properties, also the reducing the energy consumption for the process. In this regard, one of the important directions for improving these technologies with plasma is the development of their new versions, using the principle of adding inexpensive fuel-oxidizing mixtures based on hydrocarbons (natural gas, liquefied gas) with air. This type of plasma-fuel type of spraying will be promising for application at the present time, first of all, in order to obtain refractory functional coatings. For this purpose, the opportunity for upgrading an industrial unit/system for plasma spraying of powder materials with arc plasma torch of 25–40 kW power was investigated with the use of experimental variant of a fuel gas-vortex intensifier. Herewith the thermal engineering assessment for possible parameters of the generated high-temperature flow from the torch with this intensifier was carried out to compare these with established thermodynamic characteristics on the applicability range of this system for optimization of the oxide and carbide coating spraying process (using the examples of Al_2O_3, Cr_3C_2 and other powders); and gas dynamic and heat transfer calculations of the intensifier operating regimes in this model unit was also performed. New regimes, which were analyzed in our research as the simulants of Al_2O_3 spraying, have the advantage over the N_2-plasma regimes from the point of view of such kinetic parameter of powder processing as ability of heating factor of hot gas medium. Taking into account the calculated data, the experimental system was developed based on the standard spraying unit UPU-3D with a fuel intensifier of the selected design and the preliminary testing of its operation was carried out at the power of 30 ± 2 kW under the following combination of gases in the torch: nitrogen and mixture of liquefied petroleum gas with air. This system has shown the stable operation in certain range of parameters and, according to the zonal calorimetrical measurement and photo-registration of jets, it provides 30–35 % more energy emission from torch generated jet (with attached fuel vortex chamber) in atmospheric conditions, in a comparison with the torch regime with pure N_2-plasma with the same power on the arc of plasma heater. Use of the system creates an opportunity to spray carbide powders as well as oxide ones at improved intensity of coating producing in a comparison with standard regimes of commercial spraying units with N_2 or Ar plasmas.

Keywords: arc torch, combustion assisted-plasma spray, fuel vortex intensifier, ceramic powders, ability of heating factor, gas dynamic calculation, thermal efficiency, experiment

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ОПРЕДЕЛЕНИЕ ВОЗМОЖНОСТИ МОДЕРНИЗАЦИИ СИСТЕМЫ НА ОСНОВЕ ДУГОВОГО ПЛАЗМОТРОНА ДЛЯ ГАЗОТЕРМИЧЕСКОГО НАПЫЛЕНИЯ КЕРАМИЧЕСКИХ МАТЕРИАЛОВ С ИСПОЛЬЗОВАНИЕМ ТОПЛИВНОГО ВИХРЕВОГО ИНТЕНСИФИКАТОРА.
ЧАСТЬ II: ТЕПЛОТЕХНИЧЕСКАЯ ОЦЕНКА И ЭКСПЕРИМЕНТАЛЬНОЕ ТЕСТИРОВАНИЕ

Аннотация. К основным тенденциям в технологиях газотермического напыления керамических покрытий, наряду с оптимизацией их свойств, относится и снижение энергоемкости процесса. При этом одно из направлений в данных процессах с плазмой – это разработка новых их вариантов с использованием введения в теплоноситель недорогих смесей углеводородов с окислителем. Для решения этой задачи рассмотрена возможность модернизации промышленной системы для напыления порошковых материалов на основе дугового плазмотрона на 25–40 кВт путем применения пробного варианта топливного газо-вихревого интенсификатора. При этом сделана упрощенная теплотехническая оценка возможных параметров генерируемой высокотемпературной струи плазмотрона с данным интенсификатором для сравнения с термодинамическими данными по применимости данных систем с целью формирования оксидных и карбидных покрытий (на примере Al_2O_3, Cr_3C_2 и других порошков), а также газодинамический и тепловой расчет режимов плазменно-топливного интенсификатора в такой системе. Изученные новые режимы – имитаторы напыления Al_2O_3, имеют преимущество над азотно-плазменными режимами с точки зрения кинетического параметра нагрева порошков – фактора нагревательной способности (ability of heating factor, *AHF*) газовой среды. С учетом полученных данных выполнена разработка экспериментальной системы на базе стандартной установки напыления УПУ-3Д с интенсификатором выбранной конструкции и проведено тестирование ее работы при мощности 30 ± 2 кВт и сочетании газов: азота и смеси сжиженного газа (пропан-бутана) с воздухом. Система показала стабильную работу в определенном интервале параметров и, согласно результатам предварительных калориметрических измерений и фоторегистрации струй, обеспечивает внешнее энерговыделение от выходящей из плазмотрона с топливной насадкой струи больше на 30–35 % по сравнению с вариантом работы данного нагревателя с азотной плазмой при той же мощности на дуге. Использование системы открывает возможность для напыления как карбидных, так и оксидных порошков при повышенной производительности получения покрытий в сравнении с традиционными режимами промышленных установок на азотной или аргоновой плазме.

Ключевые слова: плазмотрон, ассистируемое горением плазменное напыление, топливный интенсификатор, керамические порошки, фактор нагревательной способности, газодинамический расчет, тепловой КПД, эксперимент

Для цитирования: Определение возможности модернизации системы на основе дугового плазмотрона для газотермического напыления керамических материалов с использованием топливного вихревого интенсификатора. Часть II: Теплотехническая оценка и экспериментальное тестирование / О. Г. Девойно [и др.] // Вес. Нац. акад. навук Беларусі. Сер. фіз.-тэхн. навук. – 2022. – Т. 67, № 1. – С. 7–16. https://doi.org/10.29235/1561-8358-2022-67-1-7-16

Introduction. During the last decade, the new group of promising technologies of surface engineering sector have been actively developing in a number of countries [1–6] for electric arc spraying (at atmospheric pressure, APS) and for melting/spheroidizing of ceramic (refractory oxides and carbides) and metal (copper and nickel alloys) powder materials, as with the use of hydrocarbon based gas combinations (including “liquefied petroleum gas (LPG) + air” and “methane + CO_2” mixtures) to enhance plasma jet parameters in order to intensify the material melting in them, as well as with carbonaceous additives injection into the jets for improved control of the structure of sprayed coatings [7–11].

Preliminary the thermodynamic assessment was performed for a group of the parameters of mixed high-enthalpy flow after the conventional type DC arc plasma torch with assisted fuel intensifier of our design for establishing the potential of this prospective combined plasma-fuel system to modify the technology of ceramic oxide and carbide coatings formation [12]. For this task the cases of two main C–H–O–N–Ar–Me-systems (Me = Al, Cr) and one comparative C–H–O–Al-system (all at the pressure p = 0.101 MPa) were analyzed, with taking account of possible variants of combustion assisted APS (CA-APS) and partial oxidation APS (POX-APS) regimes. Based on these results, the task for current investigation can be assumed: to obtain (with use of thermal engineering estimation and experimental testing) the data on possible parameters of high-enthalpy flow after the plasma torch of 25–40 kW with the fuel intensifier (described in [12]) in order to compare them with previously found thermodynamic characteristics of this system on its applicability range for optimization of the ceramic coating spraying process (using the examples of Al_2O_3 and other powders) to a level suitable for machine industry applications.

Estimation of the effect of kinetic parameter of the powder heating in the analyzed spray system. Taking into account the fact that the levels of efficiency parameters, found in our thermodynamic modeling of this spray system [12], are relatively close both for the C–H–O–N–Ar–Me-systems investigated and for the auxiliary "basic" (N_2–MeO_x)-systems (as the simulants of plasma-fuel spraying and conventional one, respectively), it is desirable to take into account other factors that are important for efficiency of these systems. Thus, a significant parameter when comparing thermal spaying in different mixtures, according to [11, 13], is the ability of heating factor (*AHF*), applicable for a number of gases, which are suitable for plasma jet heating and melting of ceramic powders in the technologies with these materials:

$$AHF = \frac{L(T_\mathrm{g} - T_\mathrm{p})^2(<\lambda_\mathrm{g}>)^2}{<\eta_\mathrm{g}>\nu_\mathrm{g}} = \frac{\tau(T_\mathrm{g} - T_\mathrm{p})^2(<\lambda_\mathrm{g}>)^2}{<\eta_\mathrm{g}>} = \frac{H_\mathrm{m}^2 d_\mathrm{p}^2 <\rho_\mathrm{p}>}{16} = DMF. \tag{1}$$

Here: d – diameter of heated powder particulates; DMF – the difficulty of melting factor; H_m – total enthalpy of the melting; L – length of hot zone of plasma jet (where the heating and melting proceed); $\tau = L/\nu_\mathrm{g}$ – average passing time of plasma gas via this zone; T – temperature; initial powder temperature $T_\mathrm{p} \approx 300$ K; ν – linear velocity; $<\eta>$, $<\lambda>$ – average dynamic viscosity and thermal conductivity of the gas; ρ – density; indexes are: g – gas; p – particulates. The modified variant of this factor:

$$AHF' = (<\lambda_\mathrm{g}>)^2 / <\eta_\mathrm{g}>. \tag{2}$$

It was deduced based on the kinetic model [11, 13] for intensive heating of oxide powders in the conditions of arc plasma jet processing, for which the energy balance equation for two-phase flow is:

$$\pi d_\mathrm{p}^2 h(T_\mathrm{g} - T_\mathrm{p}) + h_\mathrm{r}(T_\mathrm{g}) = \frac{1}{6}\pi\rho_\mathrm{p} c_\mathrm{p} d_\mathrm{p}^3 \frac{dT_\mathrm{p}}{dt} + \pi d_\mathrm{p}^2 \varepsilon_\mathrm{p}\sigma T_\mathrm{p}^4. \tag{3}$$

The parameters here are: h, h_r – gas to powder heat transfer coefficients on convection and radiation mechanisms, respectively; c_p and ε_p – specific heat capacity and emissivity of the powder; σ – Stefan–Boltzmann constant.

The left side of the equation (3) describes the energy transferred from the plasma by convection and conduction (first term) and by radiation (second term). The right side of (3) presents the energy absorbed by the powder which results in an increase of the particulates' enthalpy (first term) and radiation losses from them (second term). The integration of simplified form of this equation (for the case without taking into account radiation energy transfer in the torch and at the assumption, that the Nusselt number for heat transfer Nu = 2) followed by its association with the solution of movement equation for the heated particulates leads to the expression (1) for *AHF*.

Using the thermophysical properties of various gases and their mixtures in the range of 300–3800 K (calculated for the thermodynamically equilibrium case at ambient pressure, with the use of thermodynamic code TERRA of Bauman MGTU [14, 15]), corresponding to the main plasma gases applicable for thermal spraying [1–7, 16–18], we found the dependences for the modified *AHF′* of these gases (Figure 1). They show that the variant of the (air + alkane)-mixtures (including the (air + NG)-mixture with stoichiometry corresponding to fuel complete oxidation to CO_2, H_2O) is suitable to provide one of the highest levels of *AHF′* at the fixed total heating time of powder in the gas (τ = const), thereby it is an efficient heat transport gas, which allows to obtain high heating rate of ceramic powder in it, that makes it possible to decrease by several fold the heating time of the particulates to their melting point, and also provide (in the case of polydisperse powders) fast heating even for the coarse fraction particles. It is also significant, that the calculation shows that this (air + alkane)-mixture is a few times more efficient in terms of *AHF′* level than as N_2 and Ar, typical for gas media of industrial spraying units [1, 16–17, 19]. Moreover, to heat a gas, e.g., for the range of 300–3200 K in the case of (air + NG)-mixture (and for the (air + LPG)-mixture of close composition), according to the calculated data, an enthalpy difference no higher than $\Delta H = 7.0$ MJ/kg is required, which is technically achievable for the use of our combined (plasma-fuel)-system as well as when operating with the torch with arc stabilization by these mixtures [18, 20].

Figure 2 represents a comparison of the levels of influence of thermodynamic factors and kinetic parameters (such as *AHF*) for different variants of reaction systems of the analyzed type for the

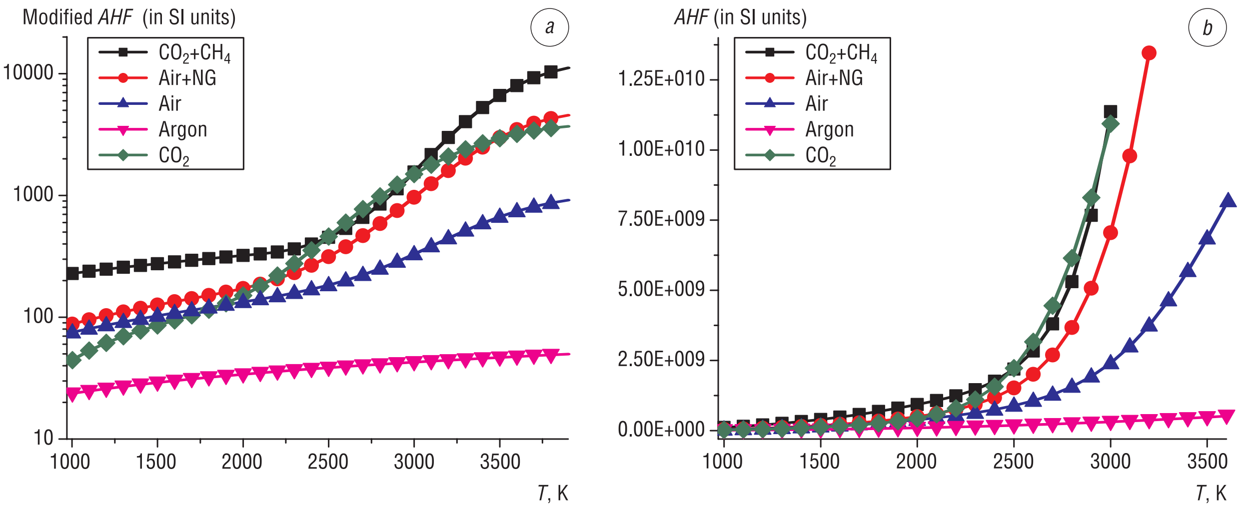

Figure 1. Temperature dependences (in SI units) for the modified "ability of heating factor" *AHF'* [11, 13] (*a*) and for complete variant *AHF* of the factor (*b*) for a number of individual and mixed plasma gases (at pressure p = 0.101 MPa), which are applicable for arc jet heating and melting of ceramic powder materials. Symbols: Air + NG = the mixture of air and natural gas with the stoichiometric ratio, corresponding to the value of equivalence ratio ER = 1.0 (i.e. equivalently to the conditions of ideal CA-APS-process). For the case of N_2-plasma, absent on the figure, the level of *AHF'* at $T \leqslant 3500$ K is near the values, which were found for the air case

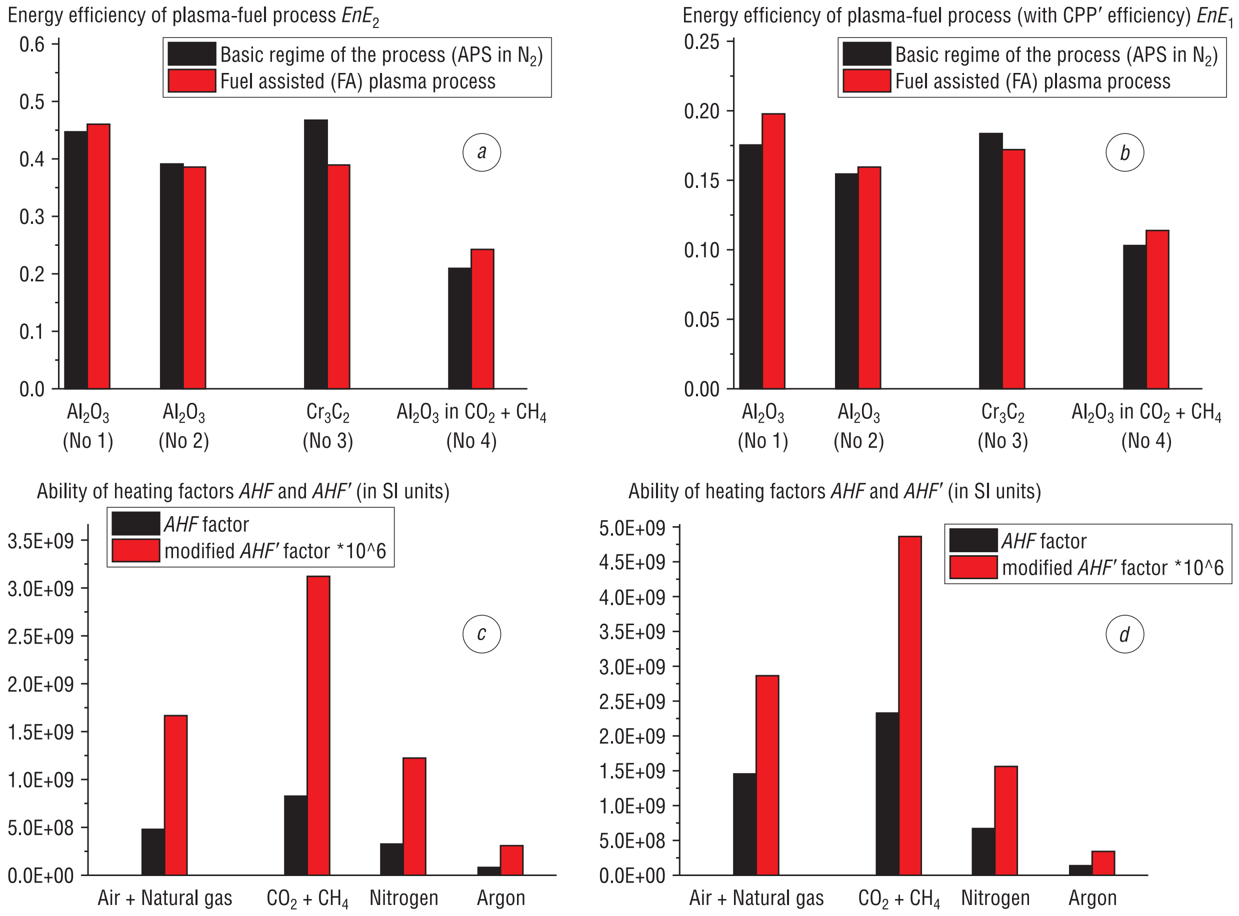

Figure 2. Comparison of thermodynamically found energy efficiencies EnE_1 and EnE_2 (*a*, *b*) for the cases of C–H–O–N–Ar–Me- (Me = Al, Cr) and C–H–O–Al-systems (p = 0.101 MPa) as the simulants for the regimes of plasma spraying (APS) with the fuel assistance, and the values of averaged modified ability of heating factor *AHF'* and for complete variant *AHF* of the factor (*c*, *d*) for individual (N_2, Ar) and mixed (alkane-based) gases. *a* – Comparison for EnE_2 [12]; *b* – comparison for EnE_1; the values of *AHF'* and *AHF* factors for the temperatures range up to 2500 K (*c*) and the values of the factors for the range up to 3000 K (*d*)

application in plasma-fuel spray units. It shows that the kinetic component, i.e. the potential intensity of the ceramic materials heating in various gas mixtures, for which the Figure shows the values of the *AHF* and *AHF′* factors depended on the composition of plasma gas, that were averaged for two conditionally specified temperature ranges from ambient temperatures up to 2500 K and up to 3000 K), can provide a stronger effect than the thermodynamic component (expressed in terms of the energy efficiencies) – at least by 1.5–2 fold for the case of alkane-containing gas mixtures (e.g. (air + natural gas)-ones) in a comparison with simple plasma gases, such as air, nitrogen or argon (for the specified ranges on *T*, which are typical for operating conditions of the analyzed group of APS-processes with ceramic powders).

Thus, for the regimes considered that simulate spraying of oxides (e.g. Al_2O_3), in terms of the thermodynamic parameters of efficiency, they are not only slightly superior to the conventional variant of the powders heating during spray (in N_2-plasma), but in addition, the regimes of the plasma-fuel process potentially have an advantage over N_2-plasma regimes in terms of such kinetic parameter as the *AHF′*.

Gas dynamic calculation of possible regime of gas-vortex intensifier for fuel injection into the plasma spraying device (power up to 40 kW). The calculation of the flow dynamics in the zone of mixing of the plasma jet from the arc torch (described in [12]) with the gas mixture, blowing through the vortex chamber (i.e. to the fuel intensifier, joined coaxially with the anode of the torch (at the outlet from which it is provided for powder injection from the feeder)), showed that the axial velocity of the resulted gas mixture flow in the plane of its exit from the chamber to side of the flow moving to the metal substrate to be coated at the optimal (on the levels of power and electric current ($\geqslant 350$ A)) regimes of its operation is fairly high for the stabilization of the near-axial core of the mixed flow and was found to be 50–70 m/s even with the minimal flow rate of the (N_2 + air + LPG)-mixture – $G = (2–3) \cdot 10^{-3}$ kg/s and without taking into account the input momentum of N_2 jet after the anode. In the case when the effect of the estimated level of N_2 jet velocity after the anode nozzle was taken into account (the mass averaged velocity was found to be 800–1150 m/s, at the jet Reynolds number (Re) of 1700–2100), – the axial velocity of the resulted gas mixture flow is $\geqslant$ 850–1200 m/s, that corresponds to the typical level for thermal spraying systems of APS-type [1, 16]. The basic configuration of the vortex chamber is shown in Figure 3; the anode diameter for the torch joined to the chamber – 0.006 m; material of the ring in the chamber is 20X23H13 alloy steel. It was also evaluated that the tangential component of the gas velocity at the exit of the ring (from its tangential holes) of the vortex chamber (with an inner radius of 0.025 m) is 95–120 m/s in the basic regimes on the flow rate of air-fuel mixture. To calculate the axial velocity in the chamber' outlet to the attached channel with diameter of

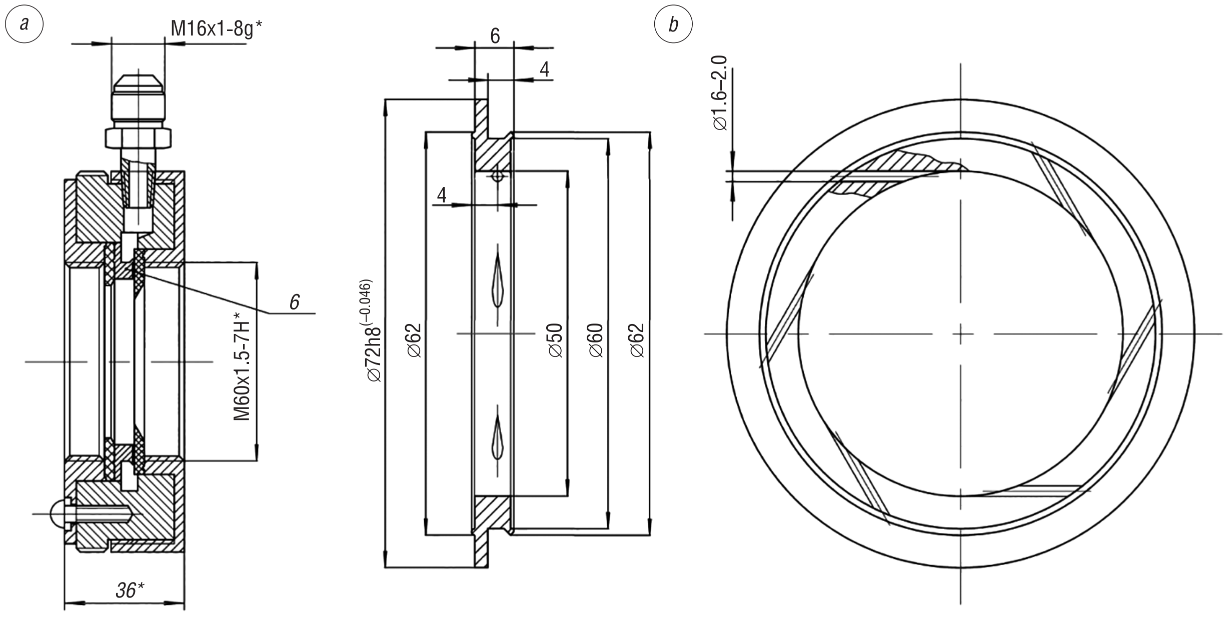

Figure 3. Outline for the fuel vortex chamber (*a*) in experimental plasma-fuel intensifier and for ring of the chamber' (*b*). The dimensions for all parts are in mm

0.058 m (serving a function of protective shroud (similar to the used in the oxy-fuel spray system [21]) for the zone between the exit from the intensifier and the region near the substrate) we used the method based on semi-empirical dependences [22, 23], which were tested in a number of the experiments with DC arc torches of 50–300 kW power with air and other plasma gases:

$$V_{\text{ch}} = V_{\text{p}}(R_{\text{p}} / R_{\text{ch}})^n = (C_1G + C_2G^{1.2})(C_3 + C_4G^{0.2}/R_{\text{el}})^n, \qquad (4)$$

where: $C_1 = 4.42\varepsilon/(\rho F)$; $C_2 = 2.79\varepsilon^{0.2}/(R^{1.8}\rho F^{0.2}\mu^{0.2})$; $C_3 = 1.33R$; $C_4 = 0.69F^{0.8}/(R\varepsilon^{0.8}\mu^{0.2})$; ρ and μ – gas density and dynamic viscosity at the exit from the ring of the chamber; R_{ch} and R – are the inner radii of the attached (to the chamber) channel and of the ring, respectively; F – the area of the inlet holes in the ring; ε – factor of gas velocity saving in the chamber; n – empirical coefficient dependent on the gas dynamic regime in the chamber.

In the equation (4) the gas velocity at a border of quasi-potential flow zone (with radius R_P) at the exit from the vortex chamber/injector is:

$$V_P = C_1G + C_2G^{1.2.} \qquad (5)$$

Experimental testing of upgrading system based on the plasma torch with emission cathode at UPU-3D unit operating with N_2-plasma and air-fuel (quasi-binary) mixture injection into the intensifier; the contribution of thermal efficiency of the unit parts in the process efficiency. Simplified testing of the upgrading system based on the UPU-3D unit for spraying [16, 17] was carried out at the operation with DC electric arc torch (with button-type cathode of Th-doped tungsten rod) with our special fuel intensifier and attached cylindrical protective channel (shroud) of steel. For this the regimes were used with the fixed power on the arc of the torch ($P = 30 \pm 2$ kW), which differed in the composition of the obtained gas mixture jets, when such combination of gases as N_2 with mixture of LPG and air (from the low pressure compressor) was injected. Cooling water flow rate per 1 m^2 of the internal surface of the torch electrodes was not less than 5 ± 1 kg/s. During our experiments (propane + butane)-based LPG (commercial SPBT grade on the GOST 20448-90 [20]) was used, injected into the unit from gas cylinders of 1.6 MPa pressure. The system showed quite stable operation in the chosen parameter ranges (in terms of gas flow rates and the torch power). Figures 4, 5 show the results of photoregistration of high-enthalpy gaseous and two-phase gas-powder jets (with powder injection as the simulant of refractory material for the spraying) with variable composition in different test regimes of the investigated system with the plasma torch. According to our calorimetric data, it provides 30–35 % more energy emission from the intensifier generated jet (in atmospheric air conditions), in a comparison with the torch operating regime with N_2-plasma with the same power on the torch arc.

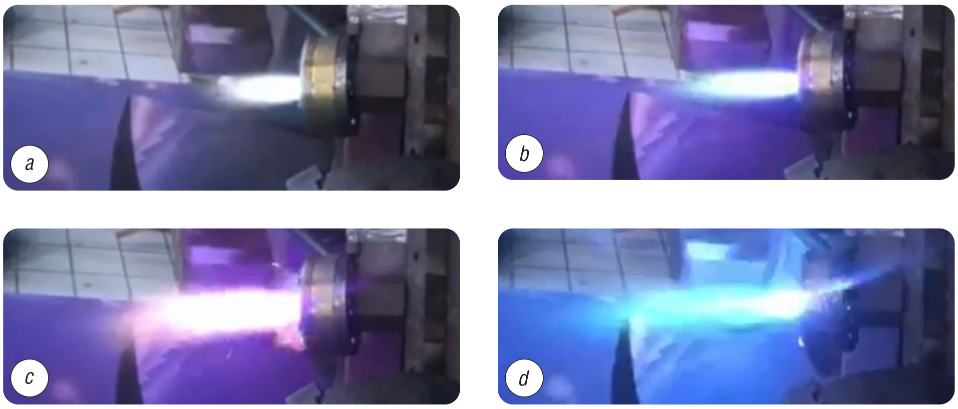

Figure 4. Photos of high-enthalpy gas jets in the test regimes of the spraying experimental system on the base of DC plasma torch with fuel intensifier. The operating regimes were used with fixed torch' power (30 ± 2 kW), differing in the jet composition: N_2 (*a*), air (*b*), (N_2 + air + LPG)-mixture at gas flow rate ratio, which provides on the thermodynamic estimation the conditions for spraying of carbide powders (for example, Cr_3C_2) in reducing medium (*c*); similar gas mixture, but with the flow ratio that provides the conditions for the spraying of oxide ceramic powders in oxidative medium (*d*)

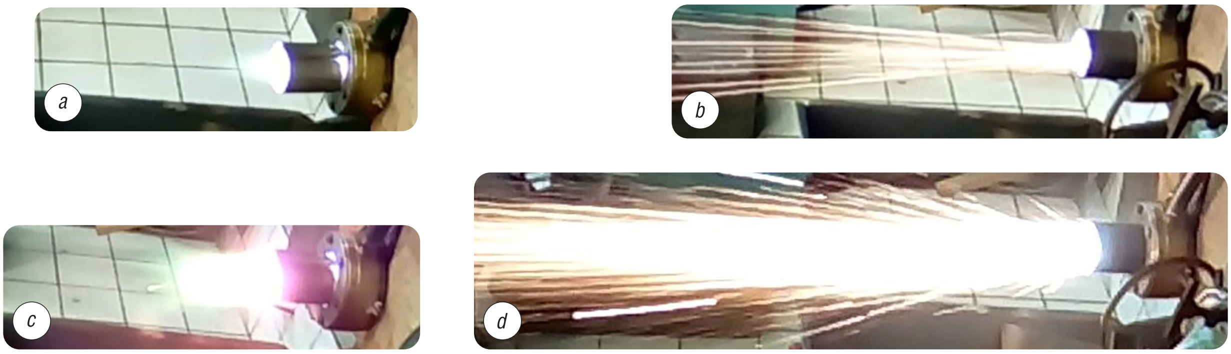

Figure 5. Photos of gas jets (*a*, *c*) and gas-powder jets (*b*, *d*) under the different test regimes of the upgrading system of UPU-3D type for plasma-fuel spraying (CA-APS) on the base of the torch with fuel intensifier and attached cylindrical shroud. The regimes with the fixed torch' power (30 ± 2 kW) were used, differing in the jet composition: N_2 (*a*), N_2 + metal powder ($\leqslant$ 50 mm particle sizes) (*b*), (N_2 + air + LPG)-mixture (*c*), (N_2 + air + LPG) + metal powder (*d*)

When determining such parameter that we specified early in the modeling of the system [12], as the thermal efficiency of the attached to plasma-fuel intensifier (i.e. plasma torch with coaxially joined vortex chamber/injector for input of air-fuel mixture) additional cylindrical channel (protective shroud) $\eta_{cs} \approx 0.75$, the already known criterion dependences for similar high-temperature devices can be used. For example, the case of the experimental variant of PDS-3D plasma torch (based on button-type Hf cathode, tubular copper anode and coaxial cylindrical electrically neutral channel) can be considered as a relatively close analog in terms of the temperature regime and gas flow composition in flue channel. The equation for its generalized thermal efficiency (which is equal to ((1–η)/η), where η is experimentally measured thermal efficiency of the torch) when operating on the mixtures of air and LPG [20] has the following form:

$$\tilde{\eta} = 3.02\cdot 10^{6}\left(\frac{I^{2}}{Gd}\right)^{-0.80}\left(\frac{G}{d}\right)^{-0.71}\left(1-\gamma_{\mathrm{p}}\right)^{0.39} \text{ (correlation coefficient of this dependence } R = 0.97\text{)}. \quad (6)$$

In this equation (6) such parameters were used as: *I* is the electric current, *G* is the total gas flow rate via this plasma heater, *d* is the anode diameter of the torch, g_p is the fraction of LPG in the input mixture.

It was found, based on (6), that the value of total thermal efficiency of the torch with the additional shroud $\eta_{pl} \cdot \eta_{cs}$ will be 0.55–0.60 for plasma-fuel system simulated in our investigation. We also found the values close to this level (± 10 %) when using two related criterion equations for heat transfer in parallel-flow reactors with ambient pressure N_2-plasma jets and injection of additional hydrogen-containing (HC) gasified feedstock:

$$\text{i) } \mathrm{St}_z = 105 \cdot \mathrm{Re}^{-0.85}(L_z/D)^{0.63} \quad (7)$$

(it is data from [24], where St_z and Re are zonal Stanton number for gas-wall heat transfer and Reynolds number for the two-component flow, *D* – channel diameter; L_z – the length of the chosen zonal part of the channel; allowable ranges for these parameters in (7): Re = 700–2300, $L_z/D \leqslant 14.5$);

$$\text{ii) } E_p = 0.68\ \mu_p^{-0.125} \quad (8)$$

(this is on the data [25] for cylindrical plasma reactor with channel length of 6.8 calibers at the operating range of $0.19 \leqslant \mu_p \leqslant 0.42$; here the unit symbols are: $E_p = (q_{wp}/q_w)$ – a correction factor for the heat flux for the two-component heterogeneous mixture in the channel; q_{wp} and q_w – heat fluxes for the heterogeneous mixture and for gas flow, respectively; $\mu_p = (G_p/G_g)$ – the heterogeneity degree of the mixture; G_p and G_g are the flow rates of the HC-feedstock and the main heat transport gas (i.e. N_2)).

The checking calculation was also performed for thermal efficiency of the shroud after the plasma-fuel intensifier to validate the coefficients (including the thermal efficiency of the (intensifier + shroud)-combination)) for our used thermodynamic model of the spray system [12], taking into account the convection heat transfer of high-temperature flow in it and the energy dissipation transfer by radiation from the heated (up to 800–1100 K according to our experimental measurement) steel wall of the shroud. For this calculation the Nusselt number for gas flows in a cylindrical channel ($\mathrm{Nu} = \alpha d/\lambda_g$) was used in a conventional form of Mikheev's criterion dependence [26] for heat transfer of turbulent flow with a cylindrical channel with diameter *d*: $\mathrm{Nu_d} = 0.021 \cdot \mathrm{Re_d}^{0.80} \cdot \mathrm{Pr}^{0.43} \cdot (\mathrm{Pr/Pr_w})^{0.25} \cdot \varepsilon_l$, where the $\mathrm{Nu_d}$ and $\mathrm{Re_d}$ numbers were evaluated on the internal diameter of the shroud; two variants of the Prandtl number Pr and $\mathrm{Pr_w}$ were used for the gas at the mass averaged temperature in the cross-section of the shroud and for the gas at the shroud' wall temperature, respectively; $\varepsilon_l \approx 1.65$ (at the level $\mathrm{Re_d} \geqslant 10^4$) is the correction factor for non-steady character of the gas flow for the channel length $l/d < 50$. Herewith, it was found that zonal heat transfer coefficient through the wall of the protective steel shroud used in the experiments is at a level of $\alpha \leqslant 70$–90 $\mathrm{W/m^2 \cdot K}$, which results in a level of the thermal efficiency of the (intensifier+shroud)-combination not lower than 0.60–0.65 (even at the value of 0.70–0.75 for thermal efficiency of the plasma torch), and as a result, this confirms the permissibility of earlier used approach for the thermodynamic modeling [12] of the analyzed plasma-fuel system in terms of the level of used values of empirical coefficients, including the thermal efficiency of the system parts.

Totally it is possible to accept, that investigated experimental system, in accordance with the set of preliminary data obtained (including our thermochemical modeling results [12], and current estimation and testing data), makes it possible to provide the opportunity for spraying of easily oxidizable carbide powders [1, 27, 28] (under the conditions of a flow of alkanes partial oxidation products at the equivalence ratio $ER \leqslant 0.5$) as well as for the spraying of oxides (e.g. Al_2O_3 powder) in a flow based on the fuel complete oxidation (air combustion) products, formed in fuel-lean mixtures, characterized by the level of $ER = 1.0$–1.1. This, taking into account the calculated data given in Section 3, creates an opportunity to achieve the improved intensity of coating producing from the carbide and oxide powders in a comparison with standard operating regimes of the commercial spray units of UPU-3D-type with N_2 or Ar plasma, which are still typical for the machine industry in CIS countries [16, 17].

Conclusions. 1. Based on our preliminary thermodynamic modeling results for the cases of C–H–O–N–Ar–Me-systems (Me = Al, Cr) and C–H–O–Al-system [12] (as the simulants of the combined plasma-fuel system with arc plasma torch), the additional thermal engineering analysis of parameters of the system was carried out and herewith some kinetic, heat transfer and gas dynamic theoretical estimations at the fuel intensifier operation with "LPG + air"-mixture had carried out.

2. The optimized regimes investigated by us have an advantage over the N_2-plasma regimes from the point of view of such kinetic parameter of powder heating as the ability of heating factor *AHF′* of the gas medium in spraying system. The calculation performed shows that (air+alkane)-mixtures can be a few times more efficient in terms of *AHF′* level than as N_2 or Ar, typical for industrial spraying units gases. Besides, to heat a gas, e.g., for the range of 300–3200 K in the case of (air+natural gas)-mixture (and for close (air + LPG)-mixture), according to the calculated data, an enthalpy difference no higher than 7.0 MJ/kg is required, which is technically achievable for the use of the (plasma-fuel)-system as well as when operating with the torch with arc stabilization by these mixtures.

3. Experimental system based on standard UPU-3D plasma spraying unit with electric arc torch (30–40 kW) and with fuel intensifier of selected design has been developed and its operation was tested when the combination of N_2 and (LPG + air)-mixture is injected. It was found that stable operation in the range of parameters (in terms of gas flow rates, torch power) is attainable and, according to calorimetrical data, the effect of 30–35 % higher energy emission from plasma torch jet (with attached fuel vortex chamber) relative to the torch regime with N_2-plasma with the same initial power was indicated. The use of the system gives the possibilities for spraying both carbide powders (in reducing medium of the products of fuel' partial oxidation) and oxide materials with increased productivity for obtaining coatings, in a comparison with conventional unit' spraying regimes.

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