Demixing in the plasma created in capillary discharges with polymeric wall

A S Pashchina
Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia
fgrach@mail.ru

Abstract. The results of spectral diagnostics of erosion plasma obtained in a pulsed discharge in a capillary with an evaporating wall made of hydrogen-carbon and fluorine-carbon polymers - polymethylmethacrylate and polytetrafluoroethylene - are presented. It was found that in both cases the distribution of chemical elements along the discharge radius is highly inhomogeneous, and their concentration ratio differs significantly from that in the capillary wall. The mass of particles is a common sign characterizing the demixing degree of chemical elements and direction of diffusion flows in fluorine-carbon and hydrogen-carbon plasmas. In both cases, lightweight particles are concentrated in the central high-temperature region, while heavy ones run away onto the low-temperature peripheral region of the discharge. Estimates show that the thermal diffusion mechanism is quite capable for providing the observed demixing degree of chemical elements. Favorable conditions for thermal diffusion processes are formed in the layer adjacent to the capillary wall, where the intense dissociation of radicals occurs, and the temperature gradient reaches up to $\nabla T \sim 10 \text{ eV/mm}$.

1. Introduction
In most scientific and technical applications of a gas discharge, one has to deal with plasma of a complex chemical composition. The composition of such a plasma, as a rule, is inhomogeneous - the ratio of the concentrations of chemical elements does not remain constant and can vary both in space and in time. The reason for this phenomenon, called the "demixing effect", is the diffusion of the plasma components relative to each other, caused by the gradients of concentration, pressure, temperature, as well as external forces (in particular, the electric field), which are somehow present in the gas-discharge plasma [1,2]. The most important processes leading to the diffusion separation of particles are: concentration diffusion, which results in the localization of chemical elements with a high ionization potential in the high-temperature region; thermal diffusion and diffusion caused by frictional forces, which, as a rule, lead to an increase in the concentration of chemical elements with a lower atomic weight in the high-temperature region; as well as diffusion caused by external forces, for example, an electric field, which results in an increase in the concentration of chemical elements with a high ionization potential in the anode region.

Over the past years, significant progress has been made in understanding of physics and numerical simulating of the processes responsible for demixing in multicomponent plasma. The majority of studies on this issue have been carried out for the free burning and stabilized electric arcs in gas mixtures [3–7]. Incommensurably less attention is paid to the study of this phenomenon in ablation-type discharges (such as capillary discharges, laser ablation discharges), whose state of research does not allow making
unambiguous conclusions regarding the role of certain processes causing the separation of chemical elements. The recent publication by Becerra et al. [8] perhaps is currently the only experimental work in which the spatial distributions of the partial pressures of chemical elements were obtained, convincingly evidencing a strong inhomogeneity and the complex spatial distribution of chemical elements in a capillary discharge.

Similar conclusions were obtained in our previous works devoted to the study of a pulsed discharge in a capillary made of a hydrocarbon polymer - polymethylmethacrylate (PMMA) - more than half of which is hydrogen [9,10]. It was found that the proportions of chemical elements in the plasma vary significantly relative the original composition of the ablating substance. In particular, the hydrogen accumulates in the hot axial zone of discharge against the strong decrease in the carbon fraction. It was also found that the separation of chemical elements occurs in a spatial region enclosed within a capillary bore [10]. However, the question about the nature of the processes capable for such a strong demixing of chemical elements remains open. Therefore, an attempt was made to clarify this issue. For this purpose, studies were carried out, the task of which was to determine (using the methods of optical emission spectroscopy) the radial distribution of the chemical elements concentration that make up the plasma-forming substance. Polymers - polytetrafluoroethylene \((C_2F_4)_n\) and polymethylmethacrylate \((C_5H_8O_2)_n\) - were chosen as the source of the plasma-forming substance. These polymers were selected because they contain fluorine and hydrogen, which differ significantly in masses and ionization potentials, but are approximately in the same proportions with respect to carbon. This greatly facilitates the interpretation of experimental results and identification of the processes responsible for the inhomogeneity of the plasma chemical composition.

2. The object of research and the methods of plasma diagnostics

A capillary spark gap is used for plasma obtaining (figure 1). The main elements of the capillary spark gap are: the capillary bore, the internal electrode (anode), tightly mounted to the capillary inlet, and the external electrode (cathode). A copper rod with a diameter of 2.4 mm is used as an external electrode. In order to obtain the most symmetric picture of the plasma parameters distribution in the transverse direction, as well as to minimize the influence of the external electrode on the flow pattern, the latter was placed strictly along the axis of the capillary at a distance of \(l=10-15\) mm from its edge. Capillaries made of polymethylmethacrylate and polytetrafluoroethylene were used in experiments. The initial diameter of the capillary bore is \(d=1\) mm, and the depth is \(h=5\) mm. The inner electrode is made of nickel. This choice was made because the absence of strong lines of Ni I and Ni II in the investigated spectral range, which makes it possible to minimize the undesirable effects of superposition of spectral lines, which significantly complicate the spectra processing.

Figure 1. Principal design of the capillary spark gap (not in scale).
The capillary spark gap is driven by a pulse-forming network (PFN), which consists of capacitor banks charging to desired voltage, inductor and auxiliary network used for discharge ignition [9]. The capacitor banks with total capacitance of \( C = 470 \, \mu \text{F} \) are charged by rectifier circuit up to the voltages of \( U = 500-800 \, \text{V} \), so the energy input into the capillary spark gap is \( Q = 60-150 \, \text{J} \). The selected nominals of capacitors and the inductor (\( L = 210 \, \mu \text{H} \)) provide the discharge current pulse corresponding to a sine half-wave with the discharge pulse duration of \( \tau = 1 \, \text{ms} \). The peak discharge current reaches \( I_{\text{m}} = 350-450 \, \text{A} \), and the voltage drop along the discharge is \( U = 150-250 \, \text{V} \). Typical waveforms of the discharge voltage and current are presented in figure 2.

![Figure 2. Typical waveforms of the discharge voltage (black squares) and discharge current (red squares). The blue filled rectangle marks the camera exposition time and the moment corresponding to spectra recording.](image)

The discharge ignition starts in the ambient air atmosphere (\( P = 10^5 \, \text{Pa}, \; T = 298 \, \text{K} \)). After the discharge ignition, the capillary wall starts to vaporize due to the heat flux from the discharge. Then the evaporated substance enters the capillary bore, where it is heated, dissociated and ionized. In a short period of time (less than 100 \( \mu \text{s} \)), the evaporated substance completely displaces the air that previously filled the capillary [11]. The resulting plasma flow rapidly expands from an open end of the capillary bore into the ambient air atmosphere. Due to the Joule heating from the electrical discharge and the mass addition from the capillary wall, the plasma flow velocity reaches sonic speed and the flow becomes choked at the capillary bore exit. That’s why the flow pattern of the freely expanding plasma discharge of high pressure from the capillary bore is a supersonic underexpanded jet. The plasma jet is the only section of the discharge available for diagnostics using optical emission spectroscopy. Inside the capillary bore, this is prevented by absorption and/or scattering of plasma radiation in the thickness of the capillary bore material. Since we are interested in the processes inside the capillary, we focused on the spatial region adjacent to the capillary edge. The cross section of the plasma jet, spaced from the capillary edge at a distance of \( \delta = 0.3 \, \text{mm} \), was chosen for spectral diagnostics (see figure 1). In this cross section, the flow expansion does not influence significantly on the flow structure and the plasma state, that permit us to get an idea about the character of the chemical elements spatial distribution, which should not differ greatly from that inside the capillary bore. Estimates show that the plasma in this cross section is optically thin and, with the exception of the peripheral region, it is in the state close to local thermodynamic equilibrium (LTE), which makes it possible to use standard methods of spectral diagnosties to estimate the plasma parameters.

Plasma parameters were determined on the basis of 2D emission spectra recorded on the CCD array (255x1024 pixels) of the Andor iStar high-speed camera installed in the output focal plane of the MS-257 spectrograph. For this purpose, an enlarged sharp image of the selected cross-section of the discharge was projected onto the spectrograph entrance slit. The spatial resolution of the recorded
spectra is 10 μm per pixel. The temporal resolution is limited by the camera exposition, whose value did not exceed $\tau_{\text{exp}} < 20 \mu s$, that is significantly less than the discharge pulse duration ($\tau = 1$ ms). The spectra were recorded at the moment when the discharge current reached its maximum (see figure 2).

The emission spectrum intervals containing a sufficient number of spectral lines necessary for the synchronous (during one discharge pulse) determination of the electron temperature, electron number density, and molar fractions of chemical elements composed the plasma forming substance were selected. The spectral interval 650-690 nm turned out to be the most suitable for both types of plasma forming substances (figure 3). This interval include the contours of the hydrogen H$_\alpha$, 656.28 nm and fluorine FI 685.6 nm lines, used to determine the electron number density based on the linear and quadratic Stark effect, as well as the lines of singly ionized carbon atom (doublet C II 657.8 nm, 658.2 nm and multiplet C II 678.36 nm), used to determine the electron temperature by the method of the relative intensities of these lines. The selected methods are insensitive to changes in the relative concentrations of chemical elements and, therefore, can be used for independent estimating the electron number density and temperature, which, along with the measured intensities of the named emitters, are used as the input parameters for estimating the molar fractions of chemical elements.

![Emission spectra of the discharges in (a) hydrogen-carbon and (b) fluorine-carbon mixtures, used for estimating the plasma parameters.](image)

**Figure 3.** Emission spectra of the discharges in (a) hydrogen-carbon and (b) fluorine-carbon mixtures, used for estimating the plasma parameters.

3. Calculation of the plasma component composition

To estimate the component composition of the plasma, a system of equations was solved, including the Saha equation for each chemical element, as well as the equations of state, conservation of charge, and conservation of matter [12]. As the initial data, we used the radial profiles of the electron number density and temperature calculated on the basis of the recorded side-on 2D spectra after the inverse Abel transformation. The calculation was carried out in the approximation of LTE plasma, which includes neutral and singly ionized atoms of each chemical element. As a result of the calculation, the molar fractions of chemical elements, the degree of ionization of each chemical element, and the effective degree of plasma ionization were determined.

4. Measurement and calculation results

The radial profiles of the electron number density and electron temperatures in the cross-section spaced from the capillary edge at a distance of 0.3 mm for discharges in hydrogen-carbon and fluor-carbon mixtures are presented in figure 4. It can be seen that for similar discharge conditions, there is a similar course of the radial distributions of the electron number density and temperature for the two types of mixtures. In both mixtures, a monotonic decrease in the electron temperature from the center to the
discharge periphery and a nonmonotonic variation of the electron number density, which tracks the change in the local values of pressure and temperature, are observed. The numerical values of the electron number density in the central region are also similar for both discharges. However, the electron temperature depends significantly on the mixture chemical composition: it is approximately one and half times (for 0.7-0.8 eV) higher for a discharge in a hydrogen-carbon mixture compared to a discharge in a fluorine-carbon mixture (cf. figure 4a and figure 4b).

Figure 4. The radial profiles of the electron number density (red lines) and electron temperatures (black lines) in the cross-section spaced from the capillary edge at a distance of 0.3 mm for discharges in (a) hydrogen-carbon and (b) fluorine-carbon mixtures, obtained in similar discharge conditions.

The reason for the significant difference in the electron temperature in these discharges will be clear if we consider the distribution of the molar fractions of chemical elements (figure 5). In contrast to a discharge in a hydrogen-carbon mixture, where the hydrogen is localized in the center and carbon is displaced into the low-temperature peripheral zone, the discharge in a fluorine-carbon mixture is characterized by an opposite tendency, namely, an increase in the carbon fraction and depletion in the fluorine fraction in the high-temperature central zone. So the predominance of carbon in the axial discharge zone, whose energy of the first excited state is more than half the energy of the first excited state of the hydrogen atom ($E_2^C=4.18 \text{ eV} < E_2^H=10.2 \text{ eV}$), is precisely the reason for the lower electron temperature in the fluorine-carbon plasma. The demixing degree of chemical elements in a hydrogen-carbon mixture is much higher than in fluorine-carbon plasma. In the latter case, an increase in the molar fraction of carbon and a decrease in the molar fraction of fluorine in the axial discharge zone relative to their initial proportion does not exceed 2 times, while the molar fraction of carbon in the axial discharge zone in the hydrogen-carbon mixture decreases by more than an order of magnitude. The concentration ratio of chemical elements becomes close to their initial proportion only at the discharge periphery. Besides, in the far peripheral zone, the concentration ratio of chemical elements also varies relative its initial proportion in the ablating substance, but already in the opposite direction. That is, the peripheral zone of the discharge in hydrogen-carbon mixture is enriched with carbon, and of the discharge in fluorine-carbon mixture is enriched with fluorine. In a number of cases, such facts were observed.
5. Discussion

The experimental results indicate that the mass of particles is a common sign characterizing their spatial separation and the direction of diffusion flows in a capillary discharge. The separation of particles according to this sign can only be caused by a temperature gradient initiating the processes of thermal diffusion and diffusion due to frictional forces. Obviously, these processes can significantly affect the plasma chemical composition only in those spatial domains where the diffusion times do not exceed the characteristic gas-dynamic time, $\tau = \frac{\lambda}{v_g}$. These conditions are fulfilled inside the capillary bore - in the boundary layer and in the stagnant zone closer to the capillary bottom. Moreover, the role of thermal diffusion can be significant only near the capillary wall, where the temperature gradient is maximum. Barodiffusion can take place only in the nonisobaric flow region of the underexpanded supersonic jet but not inside the capillary, where the pressure gradients are vanishingly small. Judging by the results of experiments, its role is still insignificant immediately after the capillary edge, where the 2D spectra were recorded. Concentration diffusion, which causes an increase in the concentration of atoms with a high ionization potential in the high-temperature zone, if it plays, then an insignificant role in comparison with thermal diffusion. In hydrogen-carbon plasma, its action can lead to an increase, and in fluorine-carbon plasma - to a weakening of the demixing. Ambipolar diffusion leads to the same effect, whose role in both cases is reduced to the outflow of ions of easily ionizing carbon atoms to the negatively charged capillary wall. However, the contribution of ambipolar, as well as concentration diffusion, is difficult to distinguish against the background of the strong demixing effect observed in the experiment, which can be caused only by thermal diffusion and/or diffusion due to frictional forces.

To estimate the scale of quantities characterizing the thermal diffusion process, we consider a narrow layer near the capillary wall, in which the evaporated atoms leaving the wall with a temperature $T_s \approx 600-900$ K are heated to a temperature $T_1$, which is reached at the outer boundary of this layer. Let us limit the temperature of the outer boundary of the layer to $T_1 < 10000$ K, at which the degree of ionization of the considered mixtures does not exceed 0.1. In this case, it is sufficient to restrict ourselves to considering binary mixtures containing only atomic components in the proportions of $[C]:[H]=1:2$ and $[C]:[F]=1:2$. Let us choose the thickness of the near-wall layer, in which a rapid increase in the particle temperature occurs, to be equal to 100 mean free paths [13]. For typical values of the pressure inside the capillary, $P \approx 1$ MPa, and the temperature at the external boundary of the layer, $T_1 \approx 10000$ K, the thickness...
of this layer will be \( \Delta x \approx 100 \, \mu m \), which will give estimation of the temperature gradient of \( \nabla T \approx 10 \, eV \, / \, mm \). Taking into account the accepted restrictions, the diffusion flow of component "1" relative to the average mass velocity will be

\[
J_1 = n_1 m_1 w_1 = \frac{n_1^2}{\rho} m_1 m_2 [D_{12}]_1 d,
\]

where

\[
d = \nabla X_1 + k_T \nabla \ln T
\]

describes the diffusion forces caused by the concentration “1” relative to the mass averaged velocity, \( \rho \) and \( n \) are the number and mass density of the gas mixture, \( m_1 \) and \( m_2 \) are the atomic masses of the respective components, \( n_1 \) is the number density of component “1”, \( [D_{12}]_1 \) is the binary diffusion coefficient in the first approximation Champan-Cowling [14], \( k_T = \alpha_T X_1 X_2 \) is the thermal diffusion ratio. The Soret coefficient, or thermal diffusion constant \( \alpha_T \), is defined as [15]

\[
\alpha_T = \frac{\mu_{12}}{k} \xi_{12} \frac{1}{n[D_{12}]} \left( \frac{\kappa_2}{m_2 X_2} - \frac{\kappa_1}{m_1 X_1} \right)
\]

where \( \kappa_1, \kappa_2 \) are partial thermal conductivity coefficients, \( \mu_{12} = \frac{m_1 m_2}{m_1 + m_2} \) is the reduced mass of colliding particles, \( k \) is the Boltzmann constant, \( \xi_{12} = \frac{1}{5} \nu_{12}^{-4} \) is a coefficient depending on the type of the interaction potential of colliding particles, \( \nu_{12} \) is the repulsive index in the interaction potential. For the model of atoms - solid elastic spheres, we have: \( \nu_{12} \rightarrow \infty, \xi_{12} = 0.2 \).

In the absence of a concentration gradient (\( \nabla X_1 = 0 \)), the diffusion rate of component “1” due to the temperature gradient can be estimated from the relation

\[
w_1 = \frac{n^2 m_2}{\rho n_1} [D_{12}]_1 k_T \nabla \ln T,
\]

and equating to zero the diffusion flux, one can estimate the demixing degree of component “1” caused by thermal diffusion

\[
\delta_1 = \frac{X_1}{X_1^0} = \frac{1}{X_1^0} \frac{\tau \alpha_T}{1 + \tau \alpha_T},
\]

where \( X_1^0 \) – molar fraction of component “1”, corresponded to the initial composition of mixture, and \( \tau = T_1 / T_s \).

We estimate the mass averaged velocity of the ablating substance using the continuity equation

\[
\rho s v_s F_s = \rho a v_a F_a
\]

where \( \rho, v, F \) – are the density, velocity and surface area, respectively, and the subscripts ’s’ and ’a’ refer to the wall and cross-section at the capillary outlet, respectively. Taking into account that the flow rate at the capillary edge is equal to the speed of sound, the mass averaged velocity of the ablating substance on the capillary wall is

\[
v_s = \sqrt{\frac{\gamma k}{M m_p T_s}} \frac{d}{4 h}
\]

where \( \gamma \) is the plasma effective adiabatic index, \( M \) is the effective molar mass (\( M_{CF2} = 16.7 \) for fluorine-carbon and \( M_{CH2} = 4.7 \) for hydrogen-carbon mixture), \( m_p \) is the proton mass, \( d \) and \( h \) are the diameter and depth of the capillary bore, respectively.

The estimates of the parameters characterizing the thermal diffusion process in the fluorine-carbon and hydrogen-carbon mixtures are presented in Table 1. The values of the binary diffusion coefficient, thermal diffusion constant, and diffusion rates depend mainly on the ratio of the atomic masses of
chemical elements included in the mixture: the greater the difference between the atomic masses of chemical elements, the higher the values of these parameters. Due to the large difference in masses, $m_C/m_H=12$, the diffusion rate of hydrogen and carbon corresponding to a given temperature gradient exceeds the mass averaged velocity of the ablating substance, while the diffusion rate of fluorine and carbon, whose masses differ only by $m_F/m_C=1.58$ times, is about an order of magnitude lower than the mass averaged velocity. At the same time, the estimates and experimental values of the demixing degree of chemical elements are in good quantitative agreement for both hydrogen-carbon and fluorine-carbon mixtures. So the thermal diffusion mechanism is quite capable of providing the observed demixing degree of chemical elements.

The limitation of a binary mixture model does not allow us to take into account the diffusion caused by frictional forces (so-called temperature diffusion), which can lead to even stronger effects than thermal diffusion [2,16]. Temperature diffusion is a consequence of the temperature dependence of the plasma component composition. Its role can be especially great in those temperature ranges and spatial domains where the concentrations of plasma components change most rapidly due to dissociation and ionization [16]. Favorable conditions for temperature diffusion exist in the low-temperature near-wall region, where there is an intense dissociation of $C_n$, $C_nH_m$, $C_nF_m$ radicals, which are present there in significant amounts. Accurate consideration of the contribution of temperature diffusion is possible in the framework of the combined diffusion coefficient model proposed by Murphy [2], which is beyond the scope of this work and requires separate studies.

### Table 1. Estimates of the main parameters characterizing thermal diffusion.

| Parameter                                 | Substance | CF$_2$ | CH$_2$ |
|-------------------------------------------|-----------|--------|--------|
| Initial mole fraction of element “1”, $X_1$ |           | 2/3    | 2/3    |
| Initial mole fraction of element “2”, $X_2$ |           | 1/3    | 1/3    |
| Mass-averaged velocity of the ablating substance, $v_s$, m/s |           | 75     | 140    |
| Diffusion velocity of element “1”, $w_1$, m/s |           | -4     | 1050   |
| Diffusion velocity of element “2”, $w_2$, m/s |           | 12     | -170   |
| Thermal diffusion constant for carbon, $\alpha_T$ |           | -0.15  | 2.5    |
| Binary diffusion coefficient, $[D_{12}]$, m$^2$/s |           | 0.005  | 0.022  |
| Demixing degree for carbon, $\delta_C$ (estimates) |           | 1.75   | <1/100 |
| Demixing degree for carbon, $\delta_C$ (experiment) |           | 1.8    | 1/16   |

Index ‘1’ is correspond to F and H, index ‘2’ is correspond to C

Data are calculated for $T_1=10^4$ K, $P=10^6$ Pa

### 6. Conclusions

Spectral diagnostics of the erosive plasma obtained in pulsed capillary discharge with an evaporating wall fabricated of polymers with different chemical composition has been carried out. The profiles of the electron number density and temperature, as well as of the radiation intensity of the main spectral components, were obtained, with the help of which the spatial pattern of the distribution of the main chemical elements that make up the erosion plasma was reconstructed. Polymers - polytetrafluoroethylene and polymethylmethacrylate - were used as a source of a plasma-forming substance, which contain fluorine and hydrogen, whose masses and ionization potentials differ
significantly, but their mole fractions are approximately the same with respect to carbon. It was found that in both cases the distribution of chemical elements along the discharge radius is highly inhomogeneous, and their concentration ratio differs significantly from that in the capillary wall. It was found that the mass of particles is a common sign characterizing the demixing degree of chemical elements and direction of diffusion flows in fluorine-carbon and hydrogen-carbon plasmas. In both cases, lightweight particles are concentrated in the central high-temperature region, while heavy ones run away onto the low-temperature peripheral region of the discharge. The demixing degree of chemical elements depends on the ratio of their masses: the greater this ratio, the greater the demixing degree. It is the latter circumstance that is responsible for the significant (up to one and a half times) difference in the electron temperature in the hydrogen-carbon and fluorine-carbon plasma, since in the first case there is a strong depletion, and in the second enrichment of the paraxial discharge zone by easily ionizing carbon.

Analysis shows that, in the absence of pressure gradients, the separation of particles by mass can only be caused by a temperature gradient initiating the processes of thermal diffusion and diffusion due to frictional forces. Favorable conditions for these processes are formed in the layer adjacent to the capillary wall, where the intense dissociation of radicals occurs, and the temperature gradient reaches up to $\nabla T \approx 10 \text{ eV/mm}$. The performed estimates show that the thermal diffusion mechanism is quite capable for providing the observed demixing degree of chemical elements. However, it is impossible to completely exclude from consideration other demixing mechanisms - the concentration and ambipolar diffusion - in which a hydrogen-carbon mixture can lead to an increase, and in a fluorine-carbon mixture - to a weakening of the demixing effect. However, their contribution is difficult to distinguish against the background of a strong demixing effect provided only by thermal diffusion.

But in any case, the key factor providing the observed demixing degree of chemical elements in a capillary discharge is a giant temperature gradient near the capillary wall, unattainable in other types of discharge. This property of a capillary discharge can be used in various scientific and practical applications associated with the separation of chemical elements, obtaining high-speed plasma flows with the required properties, industrial plasma technologies, etc. The influence of spatial inhomogeneity on thermophysical, transport, electrophysical and optical properties, obviously, must be taken into account when creating numerical models of a capillary discharge, performing spectral diagnostics, etc.

Acknowledgements
The author expresses deep gratitude to Prof. Chinnov V.F. for useful advice and remarks, and to Dr. Efimov A.V. for software development and assistance in its mastering. This work was supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. 075-00460-21-00).

References
[1] Zhdanov V M 2002 Transport processes in multicomponent plasma (New York-London: Tailor & Francis)
[2] Murphy A B 1993 Diffusion in equilibrium mixtures of ionized gases Phys. Rev. E 48 3594–603
[3] Murphy A B 1997 Demixing in free-burning arcs Phys. Rev. E 55 7473–94
[4] Wang H X, He Q S, Murphy A B, Zhu T and Wei F Z 2017 Numerical Simulation of Nonequilibrium Species Diffusion in a Low-Power Nitrogen–Hydrogen Arcjet Thruster Plasma Chem. Plasma Process. 37 877–95
[5] Murphy A B, Tanaka M, Yamamoto K, Tashiro S, Sato T and Lowke J J 2009 Modelling of thermal plasmas for arc welding: The role of the shielding gas properties and of metal vapour J. Phys. D. Appl. Phys. 42
[6] Rat V, Murphy A B, Aubreton J, Elchinger M F and Fauchais P 2008 Treatment of nonequilibrium phenomena in thermal plasma flows J. Phys. D. Appl. Phys. 41
[7] Jeničt J, Takana H, NishiYama H, Bartlová M, Aubrecht V and Murphy A B 2020 Modelling of inhomogeneous mixing of plasma species in argon–steam arc discharge for broad range of
operating conditions *Eur. Phys. J. D* 74 22

[8] Becerra M, Pettersson J, Franke S and Gortschakow S 2019 Temperature and pressure profiles of an ablation-controlled arc plasma in air *J. Phys. D. Appl. Phys.* 52 434003

[9] Pashchina A S, Efimov A V and Chinnov V F 2016 Optical Investigations of the Multicomponent Plasma of the Capillary Discharge: Subsonic Outflow Regime *High Temp.* 54 488–502

[10] Pashchina A S 2020 On the reasons of spatial heterogeneity of the plasma chemical composition in ablation controlled discharges *J. Phys. Conf. Ser.* 1698 012008

[11] Pashchina A S, Efimov A V and Chinnov V F 2017 Optical investigations of multicomponent plasma of capillary discharge. Supersonic outflow regime *High Temp.* 55 650–64

[12] Lochte-Holtgreven W 1968 *Plasma diagnostics* (Amsterdam: North-Holland Pub. Co.)

[13] Keidar M and Beilis I I 2006 Nonequilibrium thermal boundary layer in a capillary discharge with an ablative wall *Phys. Plasmas* 13 11–4

[14] Chapman S and Cowling T G 1970 *The Mathematical Theory of Non-uniform Gases* (Cambridge: Cambridge University Press)

[15] Hirschfelder G O, Curtiss C F and Bird R B 1954 *Molecular theory of gases and liquids* (New York: Wiley)

[16] Murphy A B 1994 Demixing due to frictional forces in an electric arc *Phys. Rev. Lett.* 73 1797–800