Pure & Appl. Chem., Vol. 66, No. 6, pp. 1215–1222, 1994.
Printed in Great Britain.

Review of plasma development in the former Soviet Union

O. Yas'ko

Heat & Mass Transfer Institute, Belorussian Academy of Sciences, 15 P. Browky St. 220 072, Minsk, Belarus

Abstract: Some information, concerning the research on plasma development in the former Soviet Union, is presented. Numerous investigations on different plasma problems are carried out in Russia and the other republics in spite of the very severe crisis. The results of particular interest are pointed out.

INTRODUCTION

The countries of the former Soviet Union are now suffering a very severe crisis. Science finds itself in the most difficult situation. Scientific teams have very limited possibilities for doing research now and scientific information exchange has almost ceased. It is practically impossible to organize scientific conferences because of transport and hotel expenses which have turned to be inaccessible for scientists. Even telephone and mail communications cause essential losses to the budgets of scientific organizations. The living standard of the soviet scientists has fallen below the level of manual workers. This situation forces the talented scientists to leave the country looking for jobs abroad; others try to escape poverty by means of commercial activity and also leave science.

But the situation is not absolutely hopeless. The developed scientific structure is still alive. The majority of scientific teams go on with their research. Any opportunity is taken to continue investigations. It is rather difficult to collect the recent scientific information in such circumstances. Some of the leading scientists have complied with my telephone request, and I am much obliged to them. Other information was taken from recent literary sources, which are not easily available abroad (1-4). A great number of organizations are concerned with plasma research and application in the former Soviet Union. Now the most of investigations are performed in Russia, as the research centres are situated mainly there. But the plasma science is so common now, that such research is done at almost every physical or technical University and higher school throughout the territory of the country.

PLASMA GENERATION

The high-enthalpy plasmatron with interelectrode multi-section inset (5), the arc plasmatron with stepwise electrode diameter (6), and the high-power impulse plasmatron (F.G. Rutberg (7), pp. 768-770) are examples of useful inventions made previously. The gas supply distribution over the axis in plasmatron with multi-section inset enables the extension of the arc length at constant gas flow rate. As a result, the arc voltage, power, efficiency and plasma-jet enthalpy increase. Similar results are given by the gas supply distribution over the length of porous interelectrode insert. The stepwise electrode embodies simple plasmatron design which ensure reliability, increasing current-voltage characteristics and long-time electrode operation. But the double-jet plasmatron, which is made of two connected in series diversipolar torches is considered to be rather attractive now (8). This device enables treating both electrically conductive and nonconductive materials by the open arc, or it can be used as an arc heater in high enthalpy plasma reactors.

Radio-frequency and especially microwave heating received considerable attention in the Soviet Union. Low power devices are widely used in microelectronic and in thermal plasma technology. The power of RF plasmatrons is up to 1 MW. Inductive RF-heating was mostly used before, but now capacitative and torch discharges have also become rather popular. Recent announcement about plasma weapon developed in Russia is a clear evidence of good Russian experience in microwave heating. It is pointed that plasma cloud, generated at the junction of two microwave beams, can destroy any flying object (9). A powerful nonequilibrium atmospheric pressure stationary microwave discharge is described by A.A. Bobrov and G.R. Lysov((2), pp 68-70). The diffusive discharge (f=915 MHz, power to 300 kW) is excited from 4 generators in an air vortex chamber with radius R=0.5m and height h=0.2m. Discharge radius equals 0.5 R, temperature at the periphery T_e = 0.5 to 1.0 eV, T_g =1200 to 1800 K, electron density N_e =(3 to 5)x10^{11}cm^{-3} and E=300 to 500 V/cm. Authors intend to generate a 3 MW discharge from 10 separate generators.

The electron-beam discharge is mainly used in vacuum but it is also applicable at atmospheric pressure. The original method of the electron extraction from vacuum consists of beam focusing on the partition and burning it through by the beam. The atmospheric air inleakage is prevented by outflowing electrons. A multistep graphite barrier with pumped down interpartitions is put into practice. An air stream at mean mass temperature of 12x10^3 K and pressure of 3 MPa is produced by a lMW electron beam; the total efficiency is equal to 0.5. (A.S. Koroteev, I.I. Shishkanov (4). part 1, pp 385-387).

PLASMA CHEMISTRY

Extensive plasmachemical etching experiments are carried out now (2). Some new results have been obtained on the role of minor admixtures in plasma, combined action of charged and neutral particles, passivation of the treated surface by electrode and construction materials, e.t.c. (D.I. Slovetsky (2) pp. 385-387). A new method of dynamic surface treatment by thermal plasma at atmospheric pressure is a matter of particular interest. The essence of the method is surface processing by two double-jet plasmatrons (Kulik et al (4) part II, pp. 321-322). The method incorporates fast diagnostic and control technique because of high heat flux density and short-duration of the processes (A.A. Antropov et al (4) part II pp. 223-224). The method of dynamic thermal plasma treatment enables performing different operations in microelectronic technology including etching, coating, removal and deposition.

Investigations of film deposition phenomena have been extended to plasma polymerization processes during the recent years (2). Different substances were studied: dichlorethane, toluol, dimethyl benzene, phenol (A.G. Bubnov et al (2) pp. 89-91), styrene, tetrafluorethylene, hexafluoropropylene (G.K. Vinogradov et al (2) pp. 115-123), heteroorganic compounds (CH_3"R, where " = C, Si, Ge, Sn; R = $-CH=CH_2$, $-C\equiv CH$; B. Tkachuk (2) p. 420), various organic compounds: saturated, unsaturated, aromatic, hydrocarbons, organometallics (S.A. Krapivina et al (2) pp.243-245).The performed studies showed that polymer thin films have rather good electrical, optical, acoustic and waveguide properties ($\in$ = 2.5 to 5, tgδ = $5\cdot10^{-3}$ to 10^{-4}, rv=10^{16} to 10^{18} Ohm-cm; E_{br} = 10^6 to 10^7 V/cm; B.Tkachuk (2) p. 420). The experiments have suggested that side by side with gas phase kinetics of chemical transformation the next critical factors governing plasma polymerization are: 1) the neutral-charged particles flux ratios 2) the concentration proportion of free radicals and stable products in the gas phase 3) The electronic properties of the solid surface. Therefore the reactor gas dynamics and charged particle flux must be controlled for replication of the polymerization process.

Modification of polymer materials by etching in cold oxygen plasma was investigated to change the wetting angle of the surface. Experiments showed that such etching decreases the wetting angle from 91° to 10°, that leads to hydrophilization of the material. But the wetting angle increases on average by 10° at polymerization in neutral argon plasma that causes increase in hydrophobity (S.A.Krapivina et al (2) pp. 243-245). The alteration in the surface properties during the etching depend on plasma composition and pressure, energy and dose of the bombarding particles as well as on the surface morphology and temperature (A.I. Maximov, V.A. Titov (2) pp. 282-284).

The useful work along the line of textile materials treatment has proved the possibility of plasma technology utilization in wool, cotton, silk and other branches of textile industry. Pure ecological technology and equipment has been developed to replace the chlorination process during preparation of woollen fabrics before printing (B.L. Gorberg et al (2) pp. 139-141).

The silica fibres formation with PCVD method has also received considerable attention. RF and microwave discharges were used in recent experiments on light-guide structures production in tetrachlorsilane plasma in vacuum and at atmospheric pressure (V.G. Artyushenko, L.M. Blinov et al (2) pp. 36-38, 64-67, 349-352).

Interaction of different elements and compounds with plasma flows, kinetics of chemical reactions, heat-and mass transfer processes, evaporation and condensation phenomena and physical-chemical properties of materials depending on experimental conditions are studied to elucidate the problem of dispersed material treatment. Some processes of manufacturing of refractory materials and abrasive powders (nitrides, oxides, carbides, borides and their composites) are developed. Some evidence is obtained as to the pronounced effect of raw material concentration, mixing and thermal treatment conditions on the specific surface of the plasma treated powder. Ultrafine powders of the incipient nucleus sizes with highly defected crystallite structure can be manufactured by plasmachemical methods. High activity, small particle sizes and homogeneous composition of such powders suggest their use in the technology of catalysts, ceramics, refractories and fillers (A.S. Eliseeva et al (2) pp. 165-167). Other plasma conditions enable production of clad powders.

Studies of single-stage plasmachemical conversion of organic waste in cocurrent air and steam plasmas have shown that the latter is more effective (A.G. Beskov and A.L. Suris (2), pp. 55-57). The degree of the initial material conversion to CO and H_2 increases with enthalpy (conversions are 90% and 97% to CO and H_2 respectively at $H = 9$ MJ/m^3). The process is practically insensitive to the raw material composition, whereas the product composition depends on O/C ratio of the source. Application of plasma composition depends on O/C ratio of the source. Application of plasma technology to burning wastes, contaminated with radio-active impurities, and subsequent residue vitrification enables furnishing a suitable burning atmosphere, temperature rise and reduction of the exhaust gas amount. However, the radio-nuclides volatilization, especially cesium-137, is higher then with conventional processes. Some improvements in technology have offered volatilization reduction to 4 to 5% at 5 to 7 kWh/kg of glass, and this work continuing (S.V. Stefanovsky et al (2) pp. 395-397).

The studies of waste-water decontamination by anode microdischarges have revealed that at initial carbamide resin concentration of (0.8 to 1.0 g/l) the separation degree accounts for 90 to 95%; for chlorophos (0.1 g/l) that figure amounts to 95 to 100%, and for saturate, nonsaturate and aromatic compounds as well as for oils (0.1 to 40 g/l) the value makes up 80 to 95%. Water, containing Co and Cr ions can be completely decontaminated (A.M. Sisikov et al (2), pp. 382-384). Ultraviolet radiation from corona and spark discharges was employed for air purification from phenol-formaldehyde resin. Polymerization occurs under the affect of radiation, and conversion degree rises with energy input. Purification amounts to 95% at 4 Wh/m^3 with initial concentration of 16 mg/m^3 (S.A. Zhdanok et al (l) part III, pp. 210).

METALLURGY ENERGETICS

Attention is paid to the low-power combined plasma-induction melting and to the plasma treatment of metal immediately in ladles (N.A. Swidunovich et al (l) p 171). Plasma-jet blowing through the metal at proper gas and additives consumption and temperature enables refining, modifying and alloying. In addition, studies of refractory ceramics melting are being carried out (V.G. Lukyashchenko (4), part II, pp. 253-254).

Investigations on plasma application to ferrous extractive metallurgy are directed to the developing of monostage processes using reducing syngas instead of coke. Coal and shales from different fields are gasified in steam, air and steam-air plasmas to obtain syngas ((10); D.M. Bochkis et al (l),part III,pp.112-113). The gasification degree makes up 98%, desulphurisation degree amounts to 90% and specific power consumption accounts for 1.8 to 7 kWh/kg fuel. The total concentration of $CO + H_2$ in syngas equals 35-80%, and its specific-volume yield amounts to 0.5 to 1.9 m_3/kg fuel. The plasma-gasification process can be controlled to optimize for $(CO+H_2)/N_2$ ratio. Research is also done on complex coal processing during the plasma gasification. The use is made of slag to extract some rare elements (Mo,V,U) and with its subsequent utilization as structural material. Rhenium is recovered from the gas phase in oxide form Re_2O (P.M.Bochkis et al (2) pp.74-76).

The general layout of environmental clean energo-technological plant is considered by V.A. Frolov et al ((l),part III,pp.172-173;(11)). Syngas obtained in the reactor is used in metallurgy and in energetics. The syngas usage in blast furnace promotes coke saving of 25-30% and production capacity increasing by 20-25% as compared with the conventional method. Syngas, obtained by plasma gasification of coal, can be competitively used in direct reduction. The coke consumption reduction and the recycle use of blast furnace top gas after membrane purification from oxidants enable considerable decrease of environment pollution.

The work is also undertaken along the line of combined aggregate developing. The plasma-arc furnace with melted metal layer, flowing down by the discharge chamber wall, is an example of such a design. Disperse material processing in that reactor is made in two stages: heating and solid-phase reduction by electric arc followed by melting and liquid phase reduction in the following down layer. The further long-time processes can be obviously performed in the accumulative puddle (M.V. Fisenkov and A.V. Nikolaev (4), part II, pp. 410-411).

The studies are undertaken in order to stabilize fuel combustion in power plant boilers. Poor quality fuels such as brown coals, shales and peat are mainly investigated. The plasma torch promotes volatilization and partial coke gasification for a part of the whole coal-dusted-air flow. The stable burning of that part of the flow ensures good combustion of the whole fuel due to irradiation from the plasma-stabilized torch. Plasma stabilized combustion eliminates the fuel-oil consumption, decreases incomplete combustion two to three times and reduces the nitride-oxide exhaust by 25-30%. The power consumption for combustion stabilization amounts to 2-3% of the furnace thermal power (Z.S. Sakipov et al (4), part II, pp. 245-246). A simple reliable device for the stabilization of coal-dust fuel combustion is proposed by G.A. Desyatkov et al ((12), pp. 499-516). A three-phase high-voltage A.C. arc burns between the rod electrode tops being blown out by the gas flow and selfmagnetic field; that forms plasma torch 70 cm long at $U = 10$ kV, $I = 10$ to 15 A. Ignition of the phase-arcs every half a period is ensured by the neighbouring arcs. Application of plasma to the stabilization of high-quality fuel combustion has also given a positive effect. It enabled increasing the combustion completion in the furnace of a marine boiler by 1 to 4% and to decrease the carbon oxide exhaust 1.2 to 1.6 times.(G.F. Romanovsky et al (2), pp. 358-360).

PLASMA SPRAYING

There are some recent publications in English which provide sufficient information regarding the studies of plasma spraying made in the former Soviet Union (12, 13). Theoretical and experimental investigations are performed to elucidate the disperse materials heating processes in plasma jets and to reveal the mechanism of melted accelerated particles interaction with the surface. It is revealed that powder polydispersion and plasma jet temperature-velocity inhomogeneity prevent the homogeneous heating and acceleration of all the particles.

Evidence is obtained as to the chemical interaction of the powder with oxygen from the air. It substantially depends on the powder-gas ratio. The oxidation is low at $C < 20\%$, but at high proportion it experiences a rise caused by the powder temperature increase because of radiation screening due to higher powder density (M.V. Zakc et al (4), part II, pp. 282-283). The disperse material heating in vacuum is investigated by B.M. Grigorovich et al ((4), part II, pp. 363-364). The characteristic feature of this work was powder heating inside the arc column. The heat exchange between arc plasma and powder is approximated by a generalized expression. The under-water plasma spraying was also investigated and some advantages of the process were revealed: the increase of powder heating, owing to the higher pressure, fast cooling of the coating, the unused powder doesn't pollute air because of absorption by water (A.A. Verstak, V.A. Okovity (2), part III, p. 120) . Some characteristic features of thermo-reactive polymer-materials plasma spraying are reported by Ju.M. Novak et al ((2), pp. 303-305).

ELECTRODE-REGION PHENOMENA

The considerable magnification of the thermo-electron-emission current density at low temperatures, as compared to the Richardson-Dushman equation, has received a keen interest and stimulated some investigations. The effect was attributed to electronic-work function reduction with temperature decrease (Zayatuev (4), part II, pp. 92-93). The different cathode spots form on clean and dirty surfaces can also be attributed
to the electronic work functions differences. The low work-function of impurities results in erosion decrease in comparison with clean surfaces. Therefore, the reasonable way to cathode erosion domination is electrode material alloying with low work-function mixtures (V.I. Krizhanovsky et al (4), part II, pp. 6-7; V.P. Zinovieva et al (1), part I, pp.126-127). However, if the alloy is unstable (crystal lattice changes the form with temperature variation) the mechanical destruction can occur. The electrode material also should not react with the heated gas, unless special "thermo-chemical" cathodes are used. The method of electrodes sintering of metal powder seems valuable for cathode alloying. The sintering can be performed directly in the plasmatron under affect of electric arc (V.I. Lakomsky and A. Ya. Taran (4), part II, pp. 10-11).

The recycling of metal vapour at the cathode surface is one of the reasons for the small hot cathode erosion. Some attempts are undertaken to enhance this mechanism and to reduce the erosion by this manner. For this purpose thermocathodes are put into cavities that prevent metal vapour removal by the gas flow (A.S. Anshakov et al (4), part II, pp. 48-49). A similar method is connected with the continuous regeneration of a consumable hot electrode by the heated material. This method can be useful for graphite electrodes at carbon-containing heating gas. The theory and experiment indicate that partial pressure of the deposited component must be higher then the saturated vapour pressure of the electrode material at the surface temperature (M.G. Fridland (4), part II, pp. 86-87).

Electrode operation period can be also increased by arc-root scanning along the electrode surface. The conventional method is used in hollow cylindrical electrodes for arc-root rotation by aerodynamic or magnetic field forces. Attention has been recently paid to the simultaneous axial arc-root scanning in order to enlarge the consumable electrode surface. A promising method of axial scanning has been brought into use by A.M. Zimin et al ((3), part I, pp. 124-125). A new technique has been recently applied to control of rear electrode gas dynamic in order to ensure the quasi-solid manner of gas flow rotation around the whole electrode inner space. Arc spot movement along the electrode surface became more even under such conditions, and erosion decreases (L.I. Sharakhovsky et al (4), part II,pp. 26-27).

The discharge instability increases as the arc spots of the first kind are changing to the second kind during the cathode surface cleaning from impurities by electric arc (V.F. Puchkarev (1), part I, pp. 114-115). However, the discharge instability is affected not only by the surface processes but also by the phenomena occurring in the vicinity of the electrode. The unstable splitting of the arc column on separate canals near the anode surface has been observed by G.A. Dyuzhev et al ((1), part I, pp. 76-77). The separate arc spots don't make any melted traces. The instability is assumed to be caused by the lack of ionization in the vicinity of anode.

Electrode material affects the phenomena in arc spots with the aid of the Thompson effect. Heat removal from the spot to the body is retarded by the positive thermoeffect (L.M. Vasilyak and D.U. Polyakov, (4), part II, pp.30-31). The chemical interaction of electrode material with the heated gas enhances due to intensive diffusion stimulated by arc spot high temperature. For example, the oxygen diffusion along the boundaries of crystalline grains in W-cathode brings about the increase of WO_3 concentration, which generates the mechanical stresses that cause material destruction (R.A. Vasyliev et al,(3),part I,pp.119-120).

MODELLING

Studies of the plasma processes are undertaken applying experimental investigations as well as mathematical and physical modelling. Rather comprehensive mathematical models are used (B.V. Potapkin et al (2), pp. 340-342; Ju.V. Bruevich et al (4), part II, pp. 113-114; E.V. Kulumbaev et al (12), pp. 42-54; O.P. Solonenko and A.P. Zinoviev (12), pp. 105-121; A.F. Stekolnilov et al (1), part I, pp. 27-28, etc) but here only some problems of physical modelling will be considered.

An energy number $K_{en} = H/\Sigma Q_i$, which is ratio of plasma enthalpy to the thermal effect of the chemical reaction of the desired product formation, has been justified as being rather effective (A.L. Suris (2), pp. 404-405). This number specifies both the temperature level of the process and the raw material composition. It has proved to be the major factor when the characteristic times of desired product formation from different components are approximately equal. To specify reactant mixing the number $K = (K_{ai} - K_{mi})/(K_{1i} + K_{2i} - K_{mi})$ is proposed. Here: K_{ai}, K_{1i}, K_{2i} are the mass concentration of component i at the reactor axis, in the plasma jet and in the input product, respectively, K_{mi} is the mean cross section mass concentration of component i.

The impulse proportion of the cross and axial flows, the average residence time of different components, the input orifice diameter as well as ratio of the reactor diameter to the number of the input orifices ought to be equal for model and industrial similar reactors (A.L. Suris (2), pp. 401-403). Some numbers which characterise the relative rate of product quenching by different methods - drops of liquid, solid particles, cold walls are also computed making use of energy parameters relations as in the case of energy number (A.L. Suris (2), pp. 404-405).

There is no single similarity theory for different electric discharges. The whole variants of electric discharge similarity can be referred to two theories - Boltzman's and Poisson's (A.A. Ruhadze et al (1), part I, pp. 223-224). The Boltzman's similarity assumes spatial and time factors for similar discharges to have linear relations $r\sim = \sim k \bullet r$, $t = k \bullet t$. This similarity is determined by integer exponent α; $\xi(r,t)=k^{\alpha}$ $\xi(r,t)$. The velocity and temperature fields, as well as velocity distribution functions are invariant ($\alpha=0$). The electric potential difference between the similar points and ionization degree are also invariant. Poisson's similarity holds at scale invariation of Maxwell equations. The difference between two theories vanishes for quasi-neutral plasma.

The numbers which specify the energy-exchange processes, often being used to describe an approximate similarity of electric arc discharges, belong to Boltzmann's similarity. The numbers, describing the removal from an arc of Joule dissipation energy by convection, conduction and volume radiation, are usually employed. The mechanism of heat transfer by thermal turbulence has been recently begun to be investigated. The turbulent number coincides with convective one at $v = \sqrt{h}$ where v is velocity and h is the enthalpy. That assumes turbulent flows generation at the expense of plasma thermal energy in contrast to the kinetic energy of the flow responsibility for hydrodynamic turbulence. Thermal-turbulent heat-exchange is shown to take place in highly unstable cross-flow arcs. In longitudinally blown arcs it appears at the arc column periphery, but the helium arc seems to experience thermal-turbulent heat transfer in the centre of the column too (T.V. Lactyushina et al (7), pp. 691-700). A very puzzling experiment with hydrogen-ion acceleration can, probably, be also explained by the generation of thermal turbulence (A.A. Kabantsev et al (7). pp. 691-700). A very puzzling experiment with hydrogen-ion acceleration can, probably, be also explained by the generation of thermal turbulence (A.A. Kabantsev et al (1), part I, pp. 194-195).

DIAGNOSTICS

The majority of nonmilitary scientific organizations of the former Soviet Union could not get or develop modern diagnostic instrumentation during the last period of its existence because they were as poor as church mice; and these circumstances cause severe effects on the whole level of the science. The situation is becoming for worse now. Nevertheless, theoretical investigations and development of new diagnostic equipment continue. Some works can be mentioned on spectral measurements of electric fields in plasma (V.P. Gavrilenko (7), pp. 753-757), probe measurements at high pressure (N.B. Kolokolov et al (7), pp. 765-767), tomography (V.A.Zhovtyansky (7), pp. 758-764, (14)), innerresonator spectroscopy (V.S. Burakov et al (1), part II, pp. 204-205), polychromohologram interferometry (A.G. Zhyglinsky et al (4), part II, pp. 171-172), etc. A simple method of heterogeneous flow-velocity measurement including droplets is also of interest (V.L. Levitin and M.A. Samsonov (1), part II, pp. 204-205).

ACKNOWLEDGEMENTS

Author acknowledges the financial support of ISPC-11 Organizing Committee and the valuable information from some Russian scientists.

REFERENCES

1. Physics of low-temperature plasma (editor O.G. Martynenko). Proc. VIII All-Soviet Union Conference on Plasma Physics of lowtemperature plasma,3 parts,Minsk,Spt.17-21,1991.(Russian).
2. Proc. of International Symposium on Theoretical and Applied Aspects of Plasma Chemistry,Riga,Sept.24-27,1991.(Russian and English).
3. Low-temperature plasma generators (editor M.F.Zhukov), Proc. X All-Soviet Union Conference on generators of low-temperature plasma,2 parts,Kaunas,Sept.16-18,1986.(Russian).
4. Low-temperature plasma generators (editor M.F.Zhukov), Proc. XI All-Soviet Union conference on generators of low-temperature plasma,2 parts,Novosibirsk,June.20-23,1989.(Russian).
5. M.F.Zhukov,A.S.Anshakov,I.MZasypkin,Ju.V.Kurochkin,V.P.Lukashov, A.V.Pustogarov, Electric-arc generators with interelectrode inserts,Novosibirsk,"Nauka",1981.(Russian).
6. A.I.Zhydovich,S.K.Fravchenko,O.I.Yas'ko. Two-jet-outflow plasmatron with stepwise electrodes diameter,JEP,Vol.15,No 2,pp. 203206,1969.(Russian).
7. Invited Papers of VIII All-Soviet Union Conference on physics of low-temperature plasma,JEP,Vol.62,No 5,1992.(Russian).
8. J.Zheenbaev,V.S.Engelsht, Double-jet plasmatron,Frunze,Ilim, 1983. (Russian).
9. Russia suggest the cooperative with USA experiment on plasma weapon before Vancouver,Izvestia,(April 2,1993,No 61(23916), p.1).
10. M.F.Zhukov,R.A.Kalynenko,A.A.Levitsky,L.S.Polak. Plasmachemical processing of coal.Moskow,"Nauka",1990.(Russian).
11. V.Frolow et al. Syngas production by plasma coal gasification process,Journal of High Temperature Chemical Processes,Vol.1,No 3, pp. 51-55.
12. Plasma jet in the development of new materials technology (Editors O.P.Solonenko and A.I.Fedorenko), Proc. of Int. Workshop,Sept. 3-9,1990,Frunze,USSR;Utrecht,The Netherlands;Tokyo,Japan.
13. High-temperature dust-loaden jets in plasma technology,Proc.Int. Workshop, Sept 6-8 1988, Novosibirsk, USSR
14. Theory of Thermal Electric Arc Plasma (Editors M.F. Zhukov and A.S. Koroteev), Novosibirsk, "Nauka", 1987, Vol. 2, 212-269. (Russain).