val; L, number of intervals; m, small rectangle of spectrum; M, number of rectangles with $K_{\ell m} > 0$; and ~, approximate value.

LITERATURE CITED

1. S. P. Detkov and O. A. Bryukhovskikh, Inzh.-fiz. Zh., 60, No. 6, 1022-1028 (1991).
2. S. P. Detkov and O. A. Khalevich, Inzh.-fiz. Zh., 35, No. 3, 486-491 (1978).
3. S. P. Detkov and O. A. Bryukhovskikh, Teplomassoobmen MMF. Sektsii 1, 2. Ch. 2, 177-188 Minsk (1989).
4. S. P. Detkov and O. A. Bryukhovskikh, Inzh.-fiz. Zh. 51, No. 6, 1027-1030 (1986).
5. S. P. Detkov and A. V. Vinogradov, Izv. Vyssh. Uchebn. Zaved., Chern. Metall., No. 2, 142-146 (1974).
6. W. L. Grosshandler, Int. J. Heat Mass Transfer, 23, No. 6, 1447-1459 (1980).
7. S. P. Detkov and O. A. Bryukhovskikh, Int. J. Heat Mass Transfer, 32, No. 4,729-733(1989).
8. S. P. Detkov and V. V. Perunkov, Inzh.-fiz. Zh., 60, No. 2, 303-310 (1991).
9. J. M. Hartmann, R. L. Di Leon, and J. Taine, J. Quant. Spectr. Rad. Transfer, 32, No. 2, 119-127 (1984).
10. S. P. Detkov and O. A. Khalevich, Inzh.-fiz. Zh., 36, No. 2, 270-278 (1979).
11. V. G. Lisienko, V. V. Volkov, and A. L. Goncharov, Mathematical Simulation in Furnaces and Aggregates [in Russian], Kiev (1984).

EFFECT OF THE PHYSICAL PROPERTIES OF A MATERIAL ON THE ELECTRODE EROSION IN A HIGH-CURRENT PULSED DISCHARGE

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UDC 537.523

Correlation analysis of the experimental data on the erosion of different metals for pulsed currents ranging from 2 A to 800 kA has determined that the erosion depends on the physical properties of the electrode material. The nature of the given relation is found to be determined by the amplitude of the discharge current and the electrode separation. Conclusions are made about the mechanism of electric erosion of electrodes.

Introduction. The electric erosion of electrodes in a pulsed discharge is seriously hindered by the unsteady nature of the erosion processes, the fact that the current density has not been established, etc. (see [1-4]). Experimental determination and subsequent theoretical analysis of the dependence of erosion on the physical properties of the electrode material are one way of obviating these difficulties to a considerable degree. In this domain it is necessary to point out studies for a vacuum arc with a current of 80-800 A [3] as well as for a pulsed gas discharge with a current of 250 A [5] and 150-800 kA [6]. At the same time virtually no use is made of the results of experiments [7-24], in which the erosion of different metals was compared over a wide range of energy conditions, but as a rule the data were not processed mathematically and were not compared with each other.

In the present study, by means of mathematical processing and systematization of the results of [5-24] we find the dependence of erosion on the physical properties of a metal for pulsed currents of 2 to 800 kA.

Dependence of Erosion on the Physical Properties of the Electrode Material. The mathematical processing of the experimental data consisted of using correlation analysis, i.e., in each series of erosion resistance for each physical parameter the well known procedure [25] is used to calculate, "clean up," and evaluate the statistical significance of the correlation coefficients characterizing the coupling constant between the erosion and the

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TABLE 1. Electrical Conditions of Electrode Tests and Correlation Coefficients in Region IV (in accordance with Fig. 1)

Source of data	Electrical conditions		Correlation coefficients				Significance level for 80%
	I, kA	τ, μsec	$R(m, T_m)$	$R(m, T_b)$	$R(m, c)$	$R(m, \lambda)$	
[7], A (R=6,8 Ω)	0,03*)	4—6†)	0,78	0,82	0,93	—	0,72
[8], A	0,05	0,4	0,86	0,88	0,97	—	0,72
[9], A	0,2—0,5*)	0,1—0,3*)	0,79	0,71	0,72	—	0,38
[9], K	0,2—0,5*)	0,1—0,3*)	0,84	0,74	0,70	0,65	0,38
[10], A	0,3—0,9*)	0,1—0,4*)	0,87	0,74	0,85	—	0,42
[11], A	0,4—1,2*)	0,1—0,4*)	0,64	0,31	0,82	—	0,42
[12], A	2,0	0,13	0,91	0,87	0,96	—	0,32
[13], A	2,5	0,15	0,91	0,22	0,87	—	0,57
[13], K	2,5	0,15	0,97	0,16	0,33	0,42	0,57
[14], A, V	8,0	0,18	0,96	0,88	0,42	—	0,48
[15], K+A	25	4	0,59	0,46	0,86	—	0,45
[16], (K+A)/2, V	150	0,004	0,37	0,18	0,89	—	0,63
[6], NP , V	800	0,4	0,97	0,97	0,99	—	—†)

Note: A is the anode erosion, K is the cathode erosion, K + A is the total erosion of the cathode and anode, (K + A)/2 is the measured arithmetic mean of the cathode + anode erosion, NP denotes no polarity given for the experiment electrodes, and V denotes oscillatory capacitor discharge.

*The electrical conditions were calculated from the standard formulas on the basis of the discharge circuit used.
†The significance level was not calculated because a small number (3) of metals was studied.

physical parameter of the metal. The natural logarithm of the erosion was used in the calculation to eliminate nonlinear effects. The erosion was converted to weight units (g/C). An exception is the study by Raikhbaum and Krest'yaninov [21], which does not give the numerical values of the erosion. In processing the results, therefore, they used the relative erosion, i.e., the number of the metal in the erosion resistance series was taken to be the value of the erosion. The electrical conditions of the discharge [5-24] are given in Tables 1 and 2. The electrode separation and the medium in which the discharge occurred in the experiments [5-24] are shown in Fig. 1.

The results of processing, i.e., the absolute value of all correlation coefficients that are stastically significant for a probability of 80% or higher are given in Fig. 2 and Tables 1 and 2. Table 1 also gives the correlation coefficients for a discharge with large erosion (10^{3}-10^{-2} g/C for refractory metals). The correlation coefficients for conditions with less erosion (10^{-4}-10^{-6} g/C), are given in Fig. 2 and Table 2.

As we see from Fig. 2 and Tables 1 and 2, the melting point, boiling point, heat capacity, thermal conductivity, and the first ionization potential have a statistically significant effect on the magnitude of the erosion. Moreover, the erosion of the metal affects its electrical conductivity. The electrical conductivity of the metal, however, is functionally related to its thermal conductivity, the correlation coefficients for them are almost the same and, therefore, it was not possible to separate the effect of the given parameters on the erosion. The heat capacity, specific heat of melting, and specific heat of vaporization are also functionally related and have almost identical correlation coefficients. Moreover, the melting and boiling points of the metal are functionally related.

As we see from Tables 1 and 2, however, the correlation of the erosion with the melting point is much less distinct than that with the boiling point when the erosion is considerable (10^{-3}-10^{-2} g/C) as well as when the erosion is smaller but in a vacuum discharge (experiments [19, 20]).

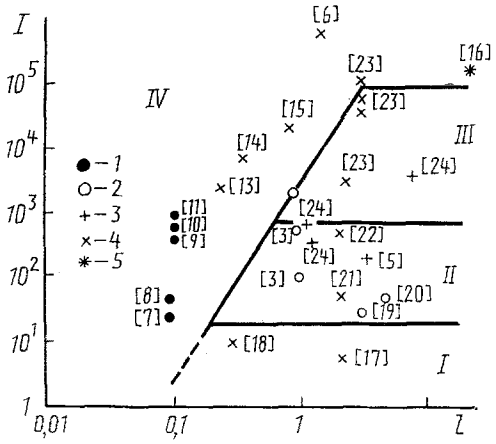

Fig. 1. Conditions of the experiments in [3, 5-24]: 1) discharge in kerosene; 2) vacuum discharge; 3) discharge in inert gases; 4) discharge in air; 5) discharge in an electrical gas. I, A; ℓ, mm.

TABLE 2. Electrical Conditions of Electrode Tests and Correlation Coefficients in Regions I-III (in accordance with Fig. 1)

Source of data	Electrical conditions		Correlation coefficients		Significance level for 80%
	I, kA	τ, μsec	$R(m, T_m)$	$R(m, T_b)$	
[17], K	0,002—0,01	1000	0,15	0,11	0,42
[17], A	0,002—0,01	1000	0,06	0,10	0,42
[18], K	0,01	2,4	0,61	0,45	0,35
[18], A	0,01	2,4	0,74	0,72	0,35
[19], K	0,02—0,1	4000	0,90	0,78	0,45
[20], K	0,07	—†	0,87	0,36	0,63
[21], (K+A)/2, V	0,05—0,09*	0,0005—0,01*	0,72	0,73	0,33
[5], K	0,25	0,01	0,81	0,72	0,40
[23], K	0,45	0,01	0,92	0,83	0,32
[22], (K+A)/2, V	0,6—1,8*	0,001—0,01*	0,68	0,83	0,28
[23], K	0,8	0,3	0,84	0,76	0,32
[24], K, V	3,5	0,09	0,93	0,89	0,34
[23], K, V	4,5	0,2	0,97	0,85	0,32
[24], K, V	31	0,22	0,92	0,69	0,34
[24], K, V	54	0,35	0,81	0,65	0,34
[24], K, V	90	0,64	0,68	0,42	0,34

*The electrical conditions were calculated from the standard formulas on the basis of the discharge circuit used.
†Data not given.

Under all conditions the effect of the work function on the erosion was statistically insignificant even for an 80% confidence coefficient, although the work function of the metals ranged from 2.7 to 5.3 eV.

The effect of the mechanical properties on the erosion was not considered in this study since such an effect has been previously observed when integrated heating of the entire electrodes is considerable [24] and can also be observed in a discharge with a small (about 0.3 mm) electrode separation [14].

On the whole, as shown in Fig. 1 and Table 3, the entire range of pulsed currents from 2 A to 800 kA is divided into four regions, each of which has corresponding dependence of the erosion on the physical properties of the electrode material. In Table 3 the dependence is in the form of empirical formulas constructed mainly from the results of correlation analysis. The boundaries between the regions, as is seen from Fig. 1, are determined primarily by the amplitude of the discharge current and the electrode separation. The effect of the discharge time, the gas pressure, etc., vary much less at the boundaries between the regions. The magnitude of the erosion, its polarity (ratio of cathode erosion to anode

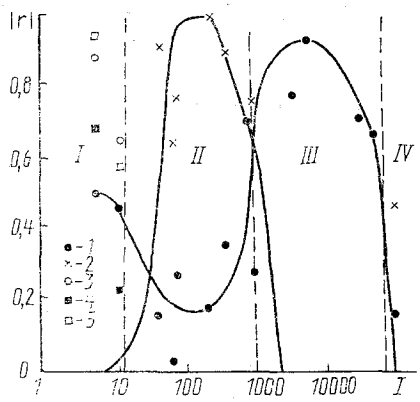

Fig. 2. Correlation coefficients in regions I-IV (in accordance with Fig. 1): 1) between the erosion of the metal and its thermal conductivity (cathode); 2) between the erosion of the metal and its heat capacity (cathode); 3) between the erosion of the metal and its thermal conductivity (anode); 4) between the erosion of the metal and its ionization potential (cathode); 5) between the erosion of the metal and its ionization potential (anode).

TABLE 3. Experimental Dependences of the Erosion of a Metal on Its Physical Properties

Region	Dependence of erosion on physical members	Polarity of erosion	Magnitude of erosion (refractory metals),
I	$m_k^* \sim T_m^{-1}\lambda^{-1}\exp^{-u}$ $m_a^* \sim T_m^{-0,5}T_b^{-0,5}\lambda^{-1}\exp^{+u}$	$m_k \approx m_a$	10^{-6}—10^{-5}
II (gas discharge)	$m_k^* \sim T_m^{-1}T_b^{-0,2}c^{-1}\lambda^{-0,1}$	$m_k \gg m_a$	10^{-6}—10^{-5}
II (vacuum discharge)	$m_k \sim (cT_m)^{-1}$	$m_k \gg m_a$	10^{-5}—10^{-4}
III	$m_k \sim T_m^{-1}T_b^{-0,5}\lambda^{-x}$ $(x = 0,5 - 1,5)$	$m_k \gg m_a$	10^{-5}—10^{-4}
IV	m_k† $\sim T_m^{-1}\,c^{-0,5}\lambda^{-0,5}$ $m_a \sim (cT_m + Q_m)^{-1}$	$m_k \approx m_a$	10^{-3}—10^{-2}

*The electrical conductivity instead of the thermal conductivity may have an effect.
†For the range of currents from 380 to 2500 A.

erosion), the nature of the erosion traces, and of course the mechanism of electrode erosion also vary at the boundaries between the regions.

As we see from Table 3, in all four regions the erosion depends on the melting and boiling points of the metal. An exception, as is seen from Tables 1 and 2, were the erosion series of [16, 17], apparently because the phase transition temperatures of the metals are so close to each other.

In region I (I = 2-10 A) the erosion also depends on the thermal conductivity and the ionization potential of the metal atoms. A higher ionization potential increases the cathode erosion and decreases the anode erosion [17]. For this reason, Pravovernov and Struchkov [18] did not detect the effect of the ionization potential since they had considered the total erosion of both electrodes. Observable erosion traces [18], the current, and the

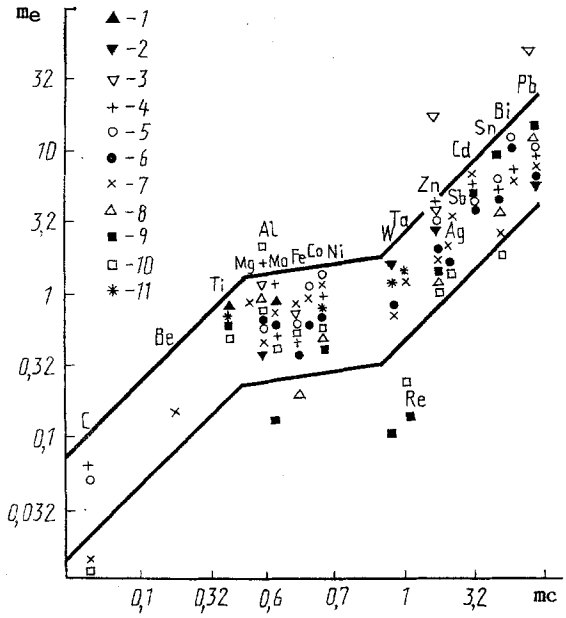

Fig. 3. Comparison of experimental erosion with that calculated from the empirical formula of an anode of region IV: 1) [6]; 2) [7]; 3 [8]; 4) [9]; 5) [10]; 6) [11]; 7) [12]; 8) [13]; 9) [14]; 10) [15]; 11) [16]. The metals studied (in order of increasing m_c): C, Be, Ti, Mg, Al, Mo, Fe, Co, Ni, W, Ta, Re, Zn, Ag, Sb, Cd, Sn, Bi, and Pb. m_e, m_c, rel. units.

magnitude of the erosion enable us to conclude that the first region corresponds to a transitional regime from cathode spots of the first kind to cathode spots of the second kind (according to the classification of Rakhovskii [1]). With the experimental data available the first region can be extended only to discharge in air as yet.

In region II (I = 20-800 A, vacuum and gas discharge) the cathode erodes by an order of magnitude more than the anode does. The erosion of the cathode is proportional to its heat capacity, the effect of the thermal conductivity on erosion is very weak. The nature of the erosion traces and the magnitude of the erosion in region II correspond to single and group cathode spots of the second kind.

Conversely, in region III (I = 3-50 kA, gas discharge) the erosion depends on the thermal conductivity and is completely independent of the heat capacity of the metal. A gradual transition from cathode spots of the second kind to formation of a macrobath of molten metal.

Region IV correpsonds to a strong erosion of the electrodes, about 10^{-3}-10^{-2} g/C. As we see from Fig. 1, region IV extends to a discharge with a current above 10^4-10^5 A, when a macrobath of molten metal forms on the electrodes as well as in a discharge with a lower current but with a smaller electrode separation of the order of 0.1-0.3 mm. The discharge can occur in any medium, i.e., liquid, gas, or vacuum. The anode erosion in region IV is determined by the heat capacity and the melting point of the metal. The erosion of the cathode is also affected by its thermal conductivity. Separate data on cathode erosion in region IV are available only for currents 380-2500 A. With increasing current thermal conductivity evidently ceases to have an effect since at 25-800 K, when the total cathode and anode erosion, the correlation between the erosion and the thermal conductivity is statistically insignificant even for 30% probability.

The empirical formulas in Table 3 are given without numerical coefficients so as to exclude the effect of the discharge time, the gaseous medium, and other external factors, which have virtually no influence on the correlation between the erosion and the physical properties of the metal but can change the magnitude of the erosion severalfold. The most exact formulas, those for regions II and IV, not only describe the relative position of the metals in the erosion series but are also in quantitative agreement with the experimentally observed erosion. In Fig. 3 the erosion calculated from the empirical formula of Table 3 for an anode in region IV is compared with the experimental value. The deviations in Fig. 3 all occur mainly for [14], and clearly, are associated with the observed [14] effect of the mechanical properties of the material on the erosion. The erosion of the metals in Fig. 3 is given in units relative to erosion of copper.

Comparison of the empirical formulas of Table 3 with the theoretical equations [1-4] of the energy balance at the cathode (1) and the anode (2) also make it possible to make conclusions about the physical mechanism of the erosion:

$$W_+ + W_n + W_v + W_N = W_\Phi + W_\lambda + W_e, \quad (1)$$

$$W_- + W_n + W_v = W_\Phi + W_\lambda. \quad (2)$$

The fact that the erosion is completely independent of the work function of electrons from the surface of pure metals enables us to conclude that for a given group of materials emission cooling of the surface and the variation of the electrode temperature as a result of the Nottingham effect, i.e., field emission of electrons below or above the Fermi level, play no appreciable role in the erosion processes.

The fact that in regions II and IV the erosion does not depend on the electrical conductivity shows that the effect of Joule–Lenz heat is negligible in those regions and the surface energy source, i.e., bombardment of the surface of the electrodes with positive ions in region II and neutral particles in region IV, is dominant.

The fact that the thermal conductivity has no effect, or very little effect, on the erosion validates (for a cathode in region II and an anode in region IV) the theoretical models of [3, 5, 6], according to which the melting front of the metal propagates considerably more rapidly than heat is transferred into the electrode, whereby the main part of the incoming energy is expended on heating and melting the metal. The models of [3, 5, 6] are obviously not applicable in regions I and III, where thermal conductivity has a strong effect.

The dependence of erosion on the melting point in region II (in a vacuum discharge) as well as all of region IV is further proof that in these cases metal is ejected mainly in the liquid phase and the drops of molten metal observed among the erosion products are formed right on the surface of the metal and do not condense from the vapor phase.

CONCLUSION

1. The nature of the thermal destruction of electrodes is determined primarily by the amplitude of the discharge current and the electrode separation; the range of pulsed currents from 2 A to 800 kA as a function of those parameters is divided into four regions, each of which has it own corresponding erosion characteristic, including it own erosion mechanism.

2. For each of the four regions we have obtained a dependence of the erosion on the physical properties of the metal, which can serve as a criterion of the reliability of the theoretical models of the erosion process and are also used for choosing the most erosion-resistant materials.

NOTATION

m, erosion, g/C; m_k, cathode erosion, g/C; m_a, anode erosion, g/C; m_c, erosion calculation from empirical formula, rel. units; m_e, experimentally observed erosion, rel. units; I, amplitude of discharge current, kA; τ, length of discharge pulse, msec; ℓ, electrode separation, mm; R, correlation coefficient; T_m, melting point, K; T_b, boiling point, K; c, heat capacity, J/(kg·deg); Q_m, specific heat of melting, J/kg; U, first ionization potential, V; W_v, Joule-Lenz heat; W_+, W_-, and W_n, energy released at the electrodes under bombardment with positive, negative, and neutral particles, respectively; W_N, the energy released as a result of the Nottingham effect; W_Φ, energy expenditure on heating and vaporization; W_e, energy expenditure on emission cooling; W_λ, energy transferred into the electrode; and λ, thermal conductivity, W/(m·deg).

LITERATURE CITED

1. G. A. Lyubimov and V. I. Rakhovskii, Usp. Fiz. Nauk, 125, No. 4, 665-706 (1978).
2. G. V. Butkevich (ed.), Electric Erosion of High-Current Contacts and Electrodes [in Russian], Moscow (1978).
3. E. Hantzsche, Beiträge aus der Plasmaphysic, 20, No. 1, 62-76 (1978).
4. J. Lafferty (ed.), Vacuum Arcs [Russian translation], Moscow (1982).
5. I. Sh. Libin, Radiotekh. Élektron., No. 6, 1026-1032 (1959).
6. G. S. Belkin and V. Ya. Kiselev, Zh. Tekh. Fiz., 37, No. 5, 977-979 (1967).
7. K. Al'binskii, Stanki Instrument, 3, No. 7, 7-11 (1964).
8. V. Germokh, Chekhoslovats. Fiz. Zh., 3, 232-240 (1953).
9. B. R. Lazarenko and N. I. Lazarenko, Electric-Arc Machining of Conducting Materials [in Russian], Moscow (1958).

10. B. R. Lazarenko and N. I. Lazarenko, Physics of Electric-Arc Machining of Materials [in Russian], Moscow (1946).
11. B. N. Zolotykh, Physical Foundations of Electric-Arc Machining of Metals [in Russian], Moscow (1958).
12. V. Germokh, Chekhoslovats. Fiz. Zh., 9, 221-230 (1959).
13. B. Zhitka, Chekhoslovats. Fiz. Zh., 3, 241-245 (1953).
14. A. Z. Aksel'rod, S. I. Kotenev, E. A. Nosova, and E. A. Popov, Izv. Severo-Kavkaz. Nauchno. Tsentr. Vyssyh. Shkoly. Ser. Tekh. Nauk, No. 4, 61-64 (1983).
15. W. R. Wilson, Trans. AIEE, 74, Part 3, No. 3, 657-664 (1955).
16. V. V. Zorin, E. Yu. Golovina, I. N. Mazurina, et al., Zh. Tekh. Fiz., 56, No. 5, 926-929 (1986).
17. A. D. Gut'ko, Electrical Contacts [in Russian], Moscow–Leningrad (1964), pp. 53-73.
18. N. L. Pravovernov and A. I. Struchkov, Élektrotekhnika, No. 1, 46-47 (1976).
19. M. P. Reece, Proc. IEE, 110, No. 4, 793-811 (1963).
20. G. N. Klyarfel'd, N. A. Neretina, and N. N. Druzhinina, Zh. Tekh. Fiz., 39, No. 6, 1061-1065 (1969).
21. Ya. D. Raikhbaum and A. G. Krest'yaninov, Izv. Akad. Nauk SSSR, Ser. Fiz., 18, No. 2, 258 (1954).
22. I. A. Grikit, V. V. Polonik, and V. P. Garashchenko, Zh. Prikl. Spektrosk., 17, No. 4, 585-591 (1972).
23. A. Z. Aksel'rod and E. A. Popov, Élektron. Tekh. Ser. 4, No. 5, 15-20 (1985).
24. A. Z. Aksel'rod, A. V. Kartushin, E. A. Popov, and Z. M. Tidzhieva, Élektron. Tekh., Ser. 4, No. 4, 8-10 (1986).
25. I. P. Sharapov, Application of Mathematical Statistics to Geology [in Russian], Moscow (1971).

DIFFUSION OF GASEOUS EMISSIONS IN THE TURBULENT WAKE OF A PIPE

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UDC 532.517.4

The concentration of gas effluxing through a circular pipe into an external flow is determined as a function of the distance on the basis of theoretical and experimental data for nitrogen, hydrogen, and helium for small ratios of the efflux and flow velocities, when the jet regime of diffusion degenerates into diffusion in the region of a turbulent wake of the source.

The distribution of the concentration of a gaseous jet diffusion into a cross flow for values of the hydrodynamic parameter $1 \leq q \leq \infty$ is described in [1]. However, the values of $0 \leq q \leq 1$, when the gas or a mixture of gases effluxes into an external flow whose velocity is relatively low, are also of interest. In this case the discharged gas diffuses in the region of the turbulent wake of the source (Fig. 1). The solution of the equation of turbulent diffusion for a stationary point source with constant turbulent diffusion coefficient and constant velocity of the cross flow has the following form [2]:

$$m(x, y, z) = \frac{M}{4\pi K x} \exp\left[-\frac{u_a(y^2 + z^2)}{4Kx}\right]. \quad (1)$$

This formula gives the following expression for the on-axis concentration, which is maximum in the section x = const:

$$m_{\max}(x, 0, 0) = \frac{M}{4\pi K x}. \quad (2)$$

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