

## Calculation of a vacuum system of the installation for cleaning the surface of metal rolling by a cathode spot of a vacuum arc

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**Abstract.** In this work are presented the installations for cleaning the surface of rolled products (wire and ribbon) from scale and technological lubricant with gateway systems of open type. The calculation of gateway devices and the optimal selection of pumping systems are shown.

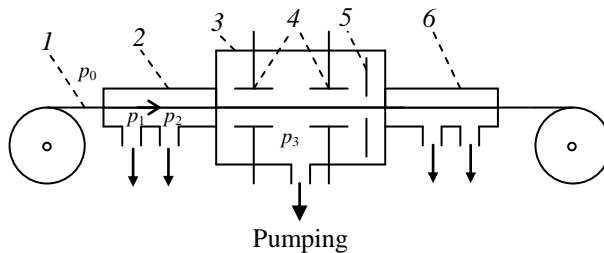
In recent years in Russia is actively developing a scientific and applied direction of research associated with the modification of the material surfaces using the cathode spots of a vacuum arc discharge. In many works was shown the ability to carry out hardening of the surface layers of materials [1], to restore the shape of plastically deformed surfaces [2], to form on the surface of a regular microrelief [3], to carry out the surface passivation [4], to prepare the surface for flaw detection [5], etc. However, the most significant scientific and applied results were obtained using the cathode spots of a vacuum arc discharge for the tasks of surface cleaning [6] from such contaminants as mill scale, rust, oil film, etc. Figure 1(a) shows the installation for cleaning the surface of a rod with a diameter of 6.5 mm from the scale and figure 1(b) shows the installation for cleaning the surface of a metal strip with width of 12 cm for the thresholds of cars from a technological lubricant.



**Figure 1.** Vacuum arc installations for cleaning rods from scale (a) and metal strips from technological lubricant (b).

The main directions of improving the reliability, performance and efficiency of the technology and equipment for the vacuum arc cleaning are the improvement of management systems of the cathode spots, optimization of the design and geometry of the cathode-anode nodes and the gateway systems, optimal choice of the vacuum pumps, solution of the problems associated with the disposal of cleaning products from the vacuum system, optimization of the thermal processes on the electrodes, etc.

Figure 2 shows a simplified schematic diagram of the vacuum arc installation for the continuous surface cleaning of a strip metal.



**Figure 2.** Schematic diagram of the vacuum arc installation for the continuous surface cleaning of metal rolling.

Product (tape) 1 from the unwinding drum, situated at the atmospheric air, through the entrance gateway 2 is continuously supplied into the vacuum chamber 3. In a vacuum chamber between the product, which acts as the cathode, and the anodes 4 using the ignition electrode (not shown in the diagram) is ignited a vacuum arc discharge. Using a system of electrodes 5 discharge on the cathode surface opposite each of the anodes is localized in a zone of a certain area. The cleaned product from the vacuum chamber through a gateway is pulled to the atmosphere and is wound on a drum. For maintaining in a vacuum chamber of a required pressure pumping using vacuum pumps is conducted not only from the chamber but also from the gateways. In figure 2 is conventionally depicted a three-stage gateway system.

For an optimal design of a gateway system is usually taken the criterion of a minimum total pumping speed of all the vacuum pumps used in the system. This criterion is proportional in the first approximation to the cost of manufacturing a gateway system.

For any of the intermediate chamber of the  $i$ -th gateway of the installation, it can be written the equation of material balance

$$Q_i = Q_{ip} + Q_{i+1}, \quad (1)$$

where  $Q_i$  – total flow of leakage and gas release in the  $i$ -th chamber;  $Q_{i+1}$  – flow of gas leaving into the next ( $i+1$ ) chamber;  $Q_{ip}$  – gas flow pumped by the pump from the  $i$ -th chamber.

This equation can be rewritten in a different form

$$Q_i = S_i p_i + U_{i+1} (p_i - p_{i+1}), \quad (2)$$

where  $S_i$  – effective pumping speed of the pump in the chamber;  $p_i$  – pressure in the  $i$ -th chamber;  $p_{i+1}$  – pressure in the ( $i+1$ )-th chamber;  $U_{i+1}$  – conductivity of the pipe connecting  $i$ -th and ( $i+1$ )-th chambers.

Written equations (1), (2) are true for all the gateway chambers, except for the middle working chamber. For this chamber the equation (2) takes the following form

$$Q_c = 2Q_c + Q_t = S_c p_c, \quad (3)$$

where  $Q_c$  – leakage from the gateways;  $Q_t$  – technological gas release;  $S_c$  – effective pumping speed of the pump in the working chamber.

Equation (2) for  $k$  gateways can be represented in the form

$$S_c p_c = U_k (p_{k-1} - p_k), \quad (4)$$

where  $S_c$  – pumping speed of the pump in the chamber without regard to the own gas release and the availability of the output gateway. For simplicity let us assume that

$$p_i \gg p_{i+1}; U_i \gg U_{i+1}, \quad (5)$$

i.e. the gateway system is efficient enough, then

$$S_i = \frac{p_{i-1}}{p_i} U_i, \quad i = 1, 2, \dots, k. \quad (6)$$

The sum of all the pumping speeds of the vacuum pumps in the gateway system, as follows from (1)

$$C = \sum_{i=1}^k S_i = \sum_{i=1}^k \frac{p_{i-1}}{p_i} U_i. \quad (7)$$

Differentiating (7) by  $p_i$ , we can get the minimizing function  $C = f(p_i)$

$$\frac{\partial C}{\partial p_i} = \frac{U_{i+1}}{p_{i+1}} - \frac{p_{i-1} U_i}{p_i^2} = 0. \quad (8)$$

Hence the system of equations for selecting an optimum pressure in the gateway chambers is

$$p_i = \sqrt{\frac{U_i}{U_{i+1}} p_{i-1} p_{i+1}}. \quad (9)$$

Defining a constant length of a gateway system

$$L = \sum_{i=1}^k l_i$$

in addition to equation (7), differentiating it under these conditions by  $l_i$ , can be found the minimum conditions of the function  $C = f(l)$  depending on the relative length of the gateway channels. In [7] are recommended the optimum pressures (figure 2) and the relative length of the gateway channels, for example, for three levels of a gateway system

$$p_1 = 0.5\sqrt[3]{p_0^6 p_3}; \quad p_2 = 0.4\sqrt[3]{p_0^4 p_3^3}; \quad l_1 = 4/7; \quad l_2 = 2/7L; \quad l_3 = 1/7L, \quad (10)$$

where  $p_0$  – inlet pressure in a gateway system (atmospheric);  $p_3$  – output pressure from the gateway system (in the chamber);  $p_1$  – pressure in the first stage of the gateway;  $p_2$  – pressure in the second stage of the gateway (figure 2).

The number of the levels of a gateway system should be chosen depending on the pressure in the working chamber. If the product for cleaning is a tape, for calculating the conductivity of the gateway channels we need to use the formula for the conductivity of two parallel narrow rectangular slots in the viscous flow regime of gas flow

$$U_i = \frac{610 p_{av}}{l_i} (a_1^3 b_1 + a_2^3 b_2), \quad (11)$$

where  $a$ ,  $b$  – dimensions of the short and long sides of the rectangle;  $p_{av}$  – average pressure in the gateway channel;  $l_i$  – length of the  $i$ -th channel of the gateway. For example, the average pressure in the first gateway channel  $p_{av1} = (p_0 + p_1)/2$ .

The calculation of conductivity in a molecular-viscous mode can be approximately carried out, summing up the conductivity in the viscous and molecular flow regimes. As the calculation formula for the conductivity of a narrow rectangular slit in the molecular regime can serve the following expression

$$U_i = 27 \lg \left( \frac{l}{a} \right) \frac{a^2 b}{l}. \quad (12)$$

The flow of gas passing through a gateway channel is

$$Q_i = U_i (p_{i-1} - p_i). \quad (13)$$

The effective pumping speed in the gateway channel is determined by formula

$$S_i = Q_i / p_i, \quad (14)$$

the calculation using which allows to select the pump needed to pump a given gateway channel.

Let us consider an example of the design calculations for a gateway system presented above, taking into account the given recommendations. Working pressure in the chamber will be taken equal to  $p_3 = 0.1$  Torr. At first approximation let us consider that the gas flow in all the gateways is viscous. The total length of the gateway chambers will be taken equal to  $L = 21$  cm. Then, in accordance with the relations (10):  $L_1 = 12$  cm,  $L_2 = 6$  cm,  $L_3 = 3$  cm,  $p_1 = 195$  Torr,  $p_2 = 7$  Torr.

For cleaning of the tape cross section of the gateway channel is a rectangle. The cross section of the tape itself is also a rectangle with sides of 0.7 mm and 120 mm. Combination of the fields of tolerances of mating parts leads to the formation of two rectangular slits with dimensions  $a = 0.2$  mm and  $b = 120$  mm (considering the gap between the tape and the gateway on each side equal to 0.2 mm).

To calculate the conductivity of the first gateway channel let us use the formula for the conductivity of a narrow rectangular slit in the viscous flow regime of a gas flow. The average pressure in the first gateway:

$$p_{av1} = \frac{p_1 + p_2}{2} = 478 \text{ Torr.}$$

The conductivity of two parallel identical slits is equal to

$$U_1 = 2 \frac{610 p_{av}}{L_1} a^3 b = 4.66 \text{ l/s.}$$

The gas flow passing through the first gateway is equal to

$$Q_1 = U_1 (p_0 - p_1) = 2633 \text{ l·Torr/s.}$$

The effective pumping speed of the mechanical pump in the first gateway at  $p_1 = 195$  Torr is

$$S_1 = Q_1 / p_1 = 13.5 \text{ l/s.}$$

Similarly let us perform the calculation of the conductivity of the second and third gateway channels:

$$p_{av2} = 101 \text{ Torr, } U_2 = 2 \text{ l/s, } Q_2 = 376 \text{ l·Torr/s, } S_2 = 54 \text{ l/s,} \\ p_{av3} = 3.5 \text{ Torr, } U_3 = 0.14 \text{ l/s, } Q_3 = 0.97 \text{ l·Torr/s, } S_3 = 10 \text{ l/s.}$$

If there are two identical gateways (input and output)  $S_3$  must be doubled. In this example, for pumping the first and second gateways, and also the vacuum chamber, it is possible to use mechanical pumps. At least in the first channel of the gateway can be used the pump of type NVR-16D, and in the second channel – AVR-50. However, given the additional (not included in the calculations) leakages and releases of gas from the chamber walls, walls of the gateways, fittings, metal surface (especially in the cleaning process), etc. it is needed to increase the performance of the vacuum pumps. This primarily relates to the pump in the vacuum chamber itself. Based on the characteristics of the vacuum chamber evacuation of the specific unit VU-2MBS as a pump for pumping the chamber, it is advisable to use a pump of type AVR-150.

Studies have shown that the process of controlling the cathode spots for the uniform cleaning of the entire surface during the tape-cathode movement is subject to the same laws as in the vacuum arc evaporators [8, 9] with end type cathodes or long cathodes.

Calculation of the shape and geometry of the electrodes (especially the anode) was performed taking into account the balance of power, released at the electrodes. The desire to increase the cleaning rate by increasing the arc discharge current may lead to the occurrence of an anode spot, and as a result, to the installation failure. Therefore, the shape and dimensions of the anode are determined by the technological parameters of the installation.

For the cathode while ensuring uniform cleaning and a predetermined pulling speed, the most important is the temperature of the surface and change of its surface geometry.

## References

- [1] Kuznetsov V G 2009 *Vacuum technique and technology* **2** 81–4

- [2] Kuznetsov V G, Kurbanov T A, Krymov D V and Ponimatkin V P 2014 *Vacuum technique and technology* **1** 78–81
- [3] Kuznetsov V G, Kurbanov T A, Ponimatkin V P and Rizakhanov R N 2013 *Proceedings of the 11-th International Conference “Films and coatings-2013” (Saint-Petersburg)* pp 15–20
- [4] Kuznetsov V G, Kurbanov T A, Krymov D V and Ponimatkin V P 2014 *Vacuum technique and technology* **1** 70–2
- [5] Kuznetsov V G, Kurbanov T A and Ponimatkin V P 2015 *Patent № 2560112 RU. Method of defectoscopy of metal products during their surface treatment*
- [6] Steshenkova N A, Shumilov V P, Kuznetsov V G, Shalimov A G and Sokolov O G 2005 *Herald of shipbuilding technology* **13** 43–50
- [7] Alekseev G A, Nesvizhskiy M B and Shelyubskiy M L 1970 *Reviews on electronic engineering. Microelectronics series* **6** 94