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TWO-BAFFLE TRAP FOR MACROPARTICLES

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In this work, properties of two-baffle macroparticle traps were investigated. These properties are needed for designing and optimization of vacuum arc plasma filters. The dependencies between trap geometry parameters and its ability to absorb macroparticles were found. Calculations made allow one to predict the behaviour of filtering abilities of separators containing such traps in their design. Recommendations regarding the use of two-baffle traps in filters of different builds are given.

INTRODUCTION

One of the most prevalent methods of film deposition is vacuum arc technique. Coatings obtained by this method possess high service characteristics. Application range of such films is rather wide: from diffusion barriers in microelectronics and tool wear protection to decorative coatings on dishes and door handles. But vacuum arc technique has intrinsic drawback – there are some relatively big fragments among cathode erosion products, a so-called macroparticles. Their ingress on the workpiece commonly results in degradation of film quality.

Macroparticle filters, or separators, are employed in order to filter off macroparticles from plasma [1, 2]. Their operation principle implies spatial separation of movement trajectories of macroparticles and useful plasma components, i.e. ions and electrons. Some kind of obstacle is placed between cathode and the workpiece, which purpose is to eliminate the direct line-of-sight between these areas. Plasma is being transported bypassing this obstruct by curved magnetic field. Due to the fact that mass to charge ratio of macroparticle is high, they are nearly not affected by the transporting field. Moving along straight trajectory, macroparticles are unable to get to the substrate without colliding with the obstacle. However macroparticles can reach the substrate by rebounding from plasma duct walls. Due to the collisions, macroparticles are loosing some part of their velocity and at some point become incapable to move further any longer. To increase the number of collisions, additional obstacles are being placed on the route of macroparticles. These obstacles represent a set of ribs (also known as baffles), mounted on the walls of plasma-guiding channel.

Effectiveness of separators can be evaluated by counting a number of macroparticles or defects they left in a coating [3]. The method suggests presence of manufactured filter, therefore making construction changes in such case is difficult. That is why it is reasonable to perform evaluation of filtering abilities of separator before its manufacture, i.e. at the stage of separator development. Computer simulation of macroparticle movement trajectories can drastically assist in problem of filters engineering and estimation of their efficiency. Specialized software MPT (Macroparticle Tracer) was developed for these purposes earlier [4]. Several highly effective baffle constructions for T-shaped magnetic filter [5] were designed with its aid.

It was established during engineering, that two types of baffle constructions (traps) are involved in the process of macroparticle absorption (filtering off). In the first case, construction contains a bunch of baffle and plasma duct wall. Here, the baffle is tilted towards macroparticles emission source – the cathode. Another baffle system represents a set of two parallel baffles which are tilted away from the cathode. According to the constructive differences these two baffle species possess, they can be respectively separated into two types: an "angular" trap and a "two-baffle" trap. It was found that the effectiveness of the traps emphatically relies on the angle which is formed between the trap baffle and plasma duct. There was also observed a strong dependency of filtering abilities these traps have on their location relative to macroparticle emissions centres. The concepts being responsible for such behaviour are currently unknown. Their understanding may significantly simplify the problem of vacuum arc plasma filters engineering. The influence of angular type traps geometry and location inside separator on their effectiveness was studied earlier [6]. Therefore the scope of current work is the investigation of two-baffle traps properties. All calculations this work contains were made in two-dimensional approximation.

COMMON PROPERTIES

Two-baffle trap is schematically shown in Fig. 1. It consists of two parallel baffles with equal length which are attached to plasma duct wall at some distance *s* from each other. Free ends of baffles are directed away from macroparticle emission source. Angle β between baffle and plasma duct wall can take values in range $0 < \beta \le 90°$. Macroparticle is assumed intercepted by the trap if it gets into space between baffles. At this rate, macroparticle will either collide with trap baffles not less than two times or once with the stopper (described below). This requires satisfaction of next conditions:

$$d_{min} < d \le \min\{d_{max}, c\}, \quad (1)$$

$$0 < \alpha < 90°, \quad (2)$$

where d – distance between the baffle attachment and macroparticle collision points; c – baffle length; α – angle between the baffle and macroparticle trajectory (hereinafter "glancing" or "grazing" angle);

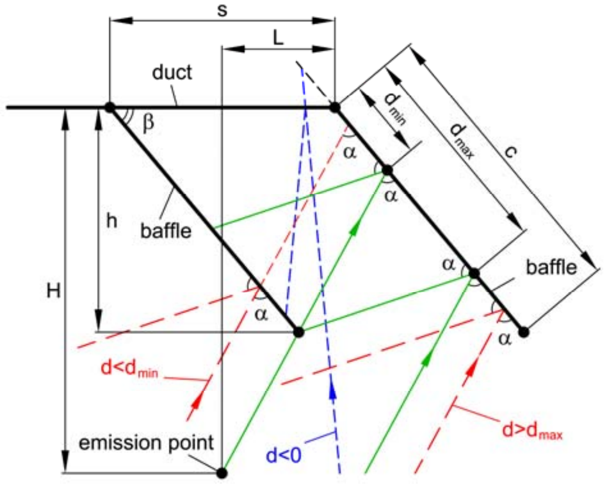


Fig. 1. Schematic representation of two-baffle trap

d_{min} and d_{max} − minimum and maximum possible values of distance d which are defined as:

$$d_{min} = \frac{h}{\sin(\beta)} - s\frac{\sin(\alpha+\beta)}{\sin(\alpha)}, \tag{3}$$

$$d_{max} = \frac{h}{\sin(\beta)} - s\frac{\sin(\alpha-\beta)}{\sin(\alpha)}, \tag{4}$$

where h − height of the trap (baffle) against plasma duct wall. If $d < d_{min}$ is true, then macroparticle will hit outer side of the baffle and will not get inside the trap. If $d > d_{max}$, two variants are possible: in case $d_{max} > c$ ($\alpha < \beta$) macroparticle will fly past the trap, otherwise (i.e. $d_{max} \le c$), after collision with the first baffle, macroparticle will fly past the second one (see Fig. 1).

It should be noted, that value d can take negative values. If so, it means that macroparticle collided plasma duct wall, not trap baffles. Thus macroparticle, in fact, gets into the angular trap [6] consisting from one baffle of two-baffle trap and duct wall. Such situation corresponds to the worst-case scenario: as it has been established during simulation [5] and will be shown below, effectiveness of two-baffle traps is extremely low for low values of macroparticle grazing angles. Positive effect of angular trap presence will be observed only when macroparticle incidence angle is small relative to the angular trap [6], which is possible only in a narrow range of β angle values. Therefore it is advisable to use two-baffle traps having some kind of "stopper" (diaphragm) (Fig. 2) at their base. However such approach imposes an additional limitation on the trap geometry:

$$s < \frac{2h}{\sin(2\beta)}. \tag{5}$$

Fulfilment of this condition ensures that effective baffle length Δ (Fig. 3) will always greater than zero. All subsequent calculations are made for traps with stoppers. Negative values of d for such traps correspond to macroparticle collision with the stopper.

As in case of angular trap, there is some threshold value d_t of distance d for two-baffle trap. Depending on which one is greater, the number of macroparticle collisions N with the trap may vary (± 1 in general case). But since only minimum value of N represents practical value, only it will be considered further.

Being intercepted by the trap, macroparticle will alternately hit baffles and travel some distance δ inward the trap between these collisions (see Fig. 3). Once macroparticle has travelled distance equal Δ, it will collide with the stopper and change its initial direction to backward one (i.e. outward the trap) and after it travels distance $\Delta - 2\varepsilon + \delta$, it will leave the trap space. So, full distance the macroparticle covers is equal $2\Delta - 2\varepsilon + \delta$. Knowing geometrical parameters of the trap one can obtain a relation for minimum number of macroparticle collisions inside the trap:

$$\begin{cases} N = 2\left\lfloor \tan(\alpha)\dfrac{h-0.5s\sin(2\beta)}{s\sin^2(\beta)} \right\rfloor + 2 \text{ for } \alpha > \alpha_t \\ N = 1 \text{ for } \alpha \le \alpha_t \end{cases}, \tag{6}$$

$$\alpha_t = \arctan\left(s\sin^2(\beta)\left(2h-0.5s\sin(2\beta)\right)^{-1}\right),$$

where α_t − threshold angle at α values below which, macroparticle is able leave the trap right after colliding the stopper (i.e. no collisions with baffles occur). Here $\lfloor X \rfloor$ means rounding of value X to the nearest integer towards zero (floor function).

It can be seen from (6) that the number of intercepted macroparticle collisions with the trap depends on all geometry parameters of the trap. The number N grows along with an increase of the trap height h and a decrease of its step s or angle β. It is connected to the fact that an increase of h when β = const, as well as a decrease of β when h = const, leads to growth of effective baffle length Δ. Reduction of N during step s growth is the result of accompanying increase of distance δ, which macroparticle travels between collisions. Thereby the determining factor is

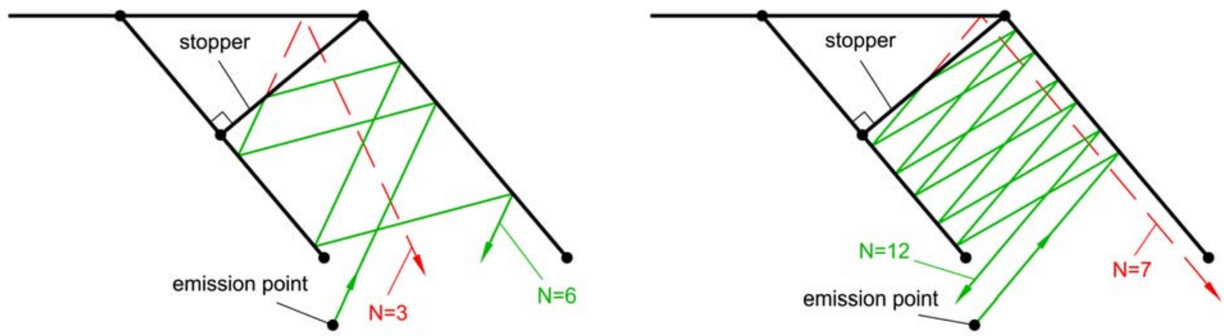
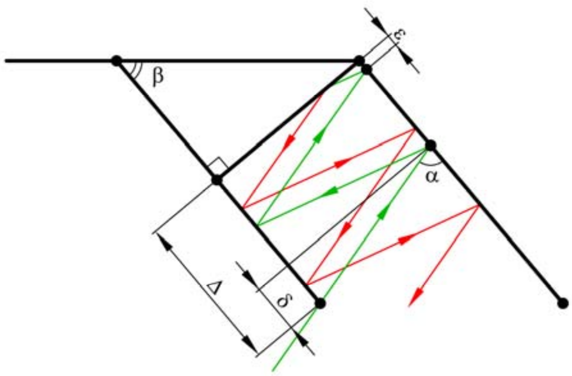


Fig. 2. Trajectory of macroparticle which was intercepted by two-baffle trap with (solid line) and without (dashed line) the stopper



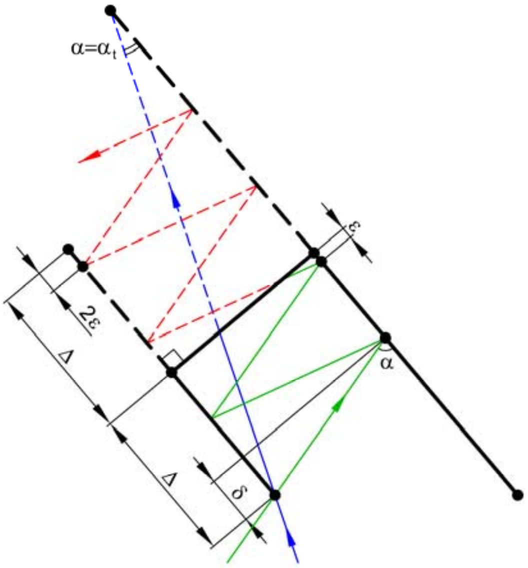


Fig. 3. Real trap and its equivalent construction used for the calculation of macroparticle collisions number, which consists of the trap and its reflection with respect to the stopper

not specific value of the trap step or height, but their "correct" relation: if $h/s = \text{const}$, then $N = \text{const}$ too if other conditions are equal. The h/s relation should be chosen depending on the trap angle, macroparticle grazing angles range and needed value of N. According to this, dependency $N = f(\alpha,\beta)$ is of interest, it is shown in Fig. 4.

From the diagram in Fig. 4 one can assess macroparticle absorption effectiveness of two-baffle traps having their height to step ratio equal to 1. It is clear that if values of step and height are changed, the diagram will have somewhat different look: as long as h/s increases, the interfaces of the regions will be lower and lower. But the nature of relationships will remain unchanged. It is also can be seen from the diagram, that traps with $\beta \geq 45°$ have nearly same efficiency: there is no essential variation of the range of absorbed macroparticles. At this rate, if specified value of N is achieved, the use of the traps with angles other than 90º is not economically feasible, because classical "straight" trap ($\beta = 90°$) is the most simple one with respect to its cost and material input. As for the traps with angles lower than 45º, their efficiency rapidly increases with angle β fall off. This is related to the constancy of h

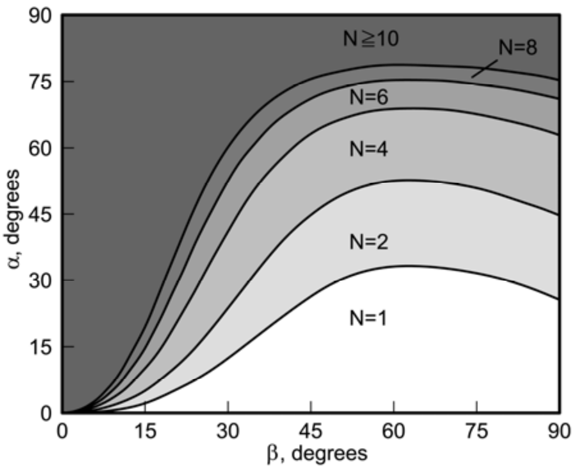


Fig. 4. Minimum macroparticle-trap collisions number against macroparticle glancing angle (α) and the trap angle (β) for h/s = 1

value, because a decrease of β leads to higher values of effective baffle length Δ (see Fig. 3). Moreover, the distance between baffles (not step) decreases, which means value of δ become lower. Such change in Δ and δ causes significant gain of collisions number N. Because N raises for all macroparticles (for all glancing angles) the range of macroparticles which are being absorbed widens. However one should keep in mind that along with trap angle decrease, the number of macroparticles which are capable to get into such trap from a particular point also decreases. Besides, β lowering brings about higher values of "unused" baffle length. Collision of macroparticle with baffle in this area corresponds to $d > d_{max}$, i.e. the macroparticle will not get into space between trap baffles and therefore can not be absorbed. As a result, despite the high values of N, performance of such baffles design as a trap for macroparticles is extremely low. Baffles of this kind are playing the role of macroparticle "reflectors" [5] which is equally important in designing of effective filters.

Previously [6], in the work devoted to study of angular trap, it was established that for every trap with angle β and given efficiency factor N, there is some critical value of macroparticle glancing angle α_{cr}. If an angle at which macroparticles are get into angular trap exceeds value of this critical angle, then the number of macroparticle-trap collisions N will have lower value than desired. Calculation of critical grazing angle value is needed for estimation of filtering abilities of traps with known location of emission centres relative to the traps. Obviously, critical angle also exists for two-baffle traps. The dependence of its magnitude on values of β is corresponding to interfaces of regions for different N values in Fig. 4. From relation (6) it is easy to obtain value of critical angle for $N = \left\{2k;\, k \in \mathbb{N}^*\right\}$:

$$\alpha_{cr} = \arctan\left(\frac{sN\sin^2(\beta)}{2h - s\sin(2\beta)}\right). \qquad (7)$$

In contrast to angular trap, where condition $\alpha < \alpha_{cr}$ was needed to be true, two-baffle trap requires satisfaction of condition $\alpha > \alpha_{cr}$. In other words, efficiency of angular traps rises with macroparticle

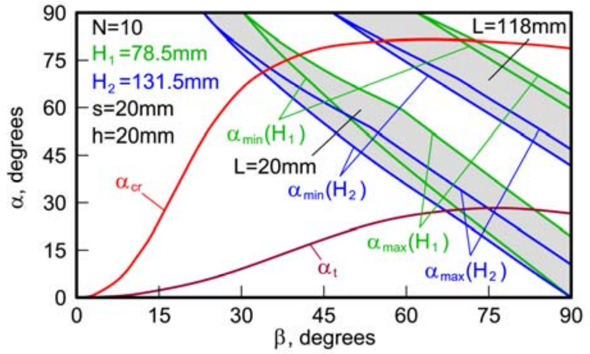


Fig. 5. The dependences of critical angle value and macroparticle glancing angles range (greyed) on the value of two-baffle trap angle, which is placed inside the anode of T-shaped separator at different distance away from the cathode. Calculation was made for the nearest and the farthest (relative to anode) points on the cathode working surface

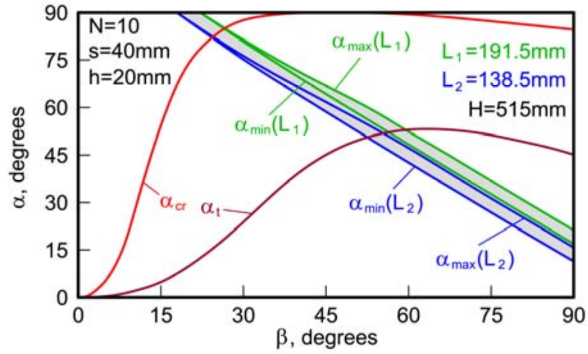


Fig. 6. The dependences of critical angle value and macroparticle glancing angles range (greyed) on the value of two-baffle trap angle, which is placed inside the output section of T-shaped separator. Calculation was made for the nearest and the farthest (relative to anode) points on the cathode working surface

grazing angle decrease, while effectiveness of two-baffle traps – with its increase.

As it was mentioned above, α angle at which a macroparticle is able to get inside two-baffle trap depends on both the trap geometry and relative location of the trap and emission centres – cathode working surface. Value of the angle is always within $0 < \alpha \le 90^\circ$ range. Knowing the coordinates of the trap one can narrow glancing angles range to:

$$\begin{cases} \alpha_1 < \alpha \le \alpha_2 \text{ for } \beta \le \beta_t \\ \alpha_1 < \alpha \le \alpha_4 \text{ for } \beta > \beta_t \end{cases}, \quad (8)$$

where

$$\alpha_1 = \arctan\left(\frac{H\cot(\beta) + L - s}{H - (L-s)\cot(\beta) - h\sin^{-2}(\beta)}\right),$$

$$\alpha_2 = \arctan\left(\frac{H\cot(\beta) + L + s}{H - (L-s)\cot(\beta) - h\sin^{-2}(\beta)}\right),$$

$$\alpha_4 = \arctan\left(\frac{H\cot(\beta) + L}{H - L\cot(\beta) - h\sin^{-2}(\beta)}\right),$$

$$\beta_t = \arctan\left(\frac{L + \sqrt{L^2 + H^2 - h^2}}{H - h}\right),$$

where L, H − values defining the distance from emission point and the trap (see. Fig. 1); β_t − the trap angle higher than which $d_{max} > c$ becomes possible, i.e. macroparticle will pass by the baffle. As it can be seen from (8), the difference of ranges for $\beta \le \beta_t$ and for $\beta > \beta_t$ is only in their upper limit. So, if all angles within the range (8) have higher values than α_{cr}, then all macroparticles being emitted from the point moved away from the trap on distance defined by H and L will be absorbed by this trap.

TWO-BAFFLE TRAP IN T-SHAPED PLASMA DUCT

Depending on relative location of macroparticle emission centre and the trap, performance of the last one may vary in a wide range, what determines appropriateness of the trap placement in the particular position of plasma guiding channel. In order to determine the effectiveness of two-baffle trap it is necessary to define criterion N, determine grazing angles range macroparticles are getting into the trap and which part of this range the trap is able to absorb.

In case of two-baffle trap placement near the anode exit or inside the output section of T-shaped plasma duct [5], macroparticle can hit the substrate without any additional collision after it has left the space between the trap baffles. At the same time, it is sufficient for macroparticle to bounce off filter walls 10 times [7] to loose its initial velocity. Thereby, macroparticle will be absorbed by separator if $N \ge 10$ condition is true. Further calculations utilize efficiency criterion of said value.

Fig. 5 shows the dependencies of critical (α_{cr}) and threshold (α_t) angles as well as macroparticle glancing angles range for different values of the trap angle β. Two-baffle trap has its height h and step s equal to 20 mm. Calculation was made for two utmost points of the cathode working surface ($H_1 = 78.5$ mm and $H_2 = 131.5$ mm) because grazing angles of macroparticles for other emission centres ($H_1 < H < H_2$) are within this range. So as to determine influence degree of the trap location on its effectiveness, calculations were made for the traps placed at two positions: at the middle of anode ($L = 118$ mm) and at the distance closest to the cathode ($L = 20$ mm). It follows from the figure, that for satisfaction of $N \ge 10$ condition by the trap placed at distance $L = 20$ mm it is necessary for it to have angle in range $23^\circ \le \beta \le 34^\circ$. If the trap is moved on distance $L = 118$ mm away from the cathode, it must have angle $46.4^\circ \le \beta \le 54.2^\circ$. It also can be seen from the figure that in case of interchanging of the baffles designed for $L = 20$ mm and $L = 118$ mm (leaving their angle unchanged) two variants are possible: either the performance of the trap will be greatly reduced or macroparticles will not be intercepted by the trap at all.

It is interesting that the most frequently used "straight" trap ($\beta = 90^\circ$) possesses minimum efficiency. In order to meet appointed above effectiveness factor (with considered values of H, h and s) it needs to be placed at distance $L \ge 550$ mm, what is not always possible. However application of such traps in some cases is the only acceptable option [5]. In the considered T-shaped separator, these traps were used inside the input sections of the plasma duct. They were installed at distance L within the range $269\ \text{mm} \leq L \leq 541\ \text{mm}$ ($H = 98.5$ mm, $h/s = 1$). Effectiveness of the traps is respectively in range from $N \geq 4$ to $N \geq 8$.

As for the efficiency of two-baffle traps in the output section of T-shaped separator, supplementary calculations were performed. The results are given in Fig. 6. The figure shows that for $N \geq 10$ angle of the trap must be in $18^\circ \leq \beta \leq 24.3^\circ$ range. During separator optimization process [5] the one with $\beta = 24^\circ$ was used, that explains high level of observed performance, when macroparticle trajectories were modelled in MPT program. According to Fig. 6, application of "classical" baffles with angle $\beta = 90^\circ$ inside the output section of the duct is inappropriate, at least in its initial part. Effectiveness of these baffles will be minimal ($N = 1$) since macroparticle glancing angle in all possible range has the value lower than α_t. It should be noted, that the trap angle β in this case must not be equal to 45º due to contradiction to statement (5). That is the effective baffle length Δ of considered trap will be equal to zero if $\beta = 45^\circ$ (see Fig. 3).

Based on the calculation results performed in this study several recommendations as for application of two-baffle traps can be given. Traps of this type can be utilized at almost any part of a plasma duct if their angle and step are adjusted correctly. As the distance along duct axis between the trap and the cathode becomes longer, angle and step may be significantly increased what will definitely reduce baffle system cost. Application of 90-degree traps, in common case, is not recommended due to their low efficiency for acceptable values of height to step ratio and typical separator dimensions. The "unused" surfaces of the traps possess the feature to redirect unfiltered macroparticles athwart plasma duct axis. In this regard, installation of two-baffle traps is preferable inside output sections of curvilinear plasma ducts (for example L- and T-shaped) and inside a so-called straight (or rectilinear) separators, where longitudinal movement of macroparticles is unacceptable. It is due to the fact that this kind of macroparticles can not be intercepted by the baffles if their trajectories are close to the axis of the plasma guide.

Designed earlier [5] baffle system for T-shaped magnetic filter meets the above recommendations and the guidelines as for application of angular traps [6] what explains high filtering properties the system has. The correctness of relationships obtained in this work is confirmed by the results of simulations in MPT.

CONCLUSIONS

During current study, the dependences characterizing effectiveness of macroparticle absorption by two-baffle traps were established. Absorption capacity of the traps grows with a decrease of their angle and with an increase of their height to step ratio. The traps are most effective in absorption of macroparticle flows, which are directed to their baffles at angles close to right one. The efficiency of two-baffle traps that placed in different locations of the anode and inside the output section of the plasma duct was calculated on an example of T-shaped separator. Calculation results are in agreement with MPT simulation results. Acquired relations allow one to predict efficiency of angular traps application on a stage of design of baffle systems used in magnetic separators. The list of recommendations regarding the engineering of baffle systems that are based on such traps was composed.

REFERENCES

1. I.I. Aksenov, A.A. Andreev, V.A. Belous, V.E. Strel'nitskij, V.M. Khoroshikh. *Vacuum arc. Plasma sources, coatings deposition, surface modification.* Kyiv: "Naukova dumka", 2012, 728 p. (in Russian).
2. A. Anders. *Cathodic Arcs: From Fractal Spots to Energetic Condensation*. New York, Springer, 2008, 542 p.
3. R.L. Boxman. Recent developments in vacuum arc deposition // *IEEE Trans. Plasma Sci.* 2001, v. 29, p. 762-767.
4. D.S. Aksyonov. Calculation of Macroparticle Flow in Filtered Vacuum Arc Plasma Systems // *PAST. Series "Physics of Radiation Effect and Radiation Materials Science".* 2012, №2, p.108-113.
5. D.S. Aksyonov. Optimization of T-Shaped Magnetic Separator Filtering Abilities // *PAST. Series "Physics of Radiation Effect and Radiation Materials Science".* 2012, №2, p.102-107.
6. D.S. Aksyonov. Angular Trap for Macroparticles // *PAST Series "Physics of Radiation Effect and Radiation Materials Science".* 2013, №2, p. 123-127.
7. I.I. Aksenov, V.E. Strel'nitskij, V.V. Vasilyev, D.Yu. Zaleskij. Efficiency of magnetic plasma filters // *Surf. Coat. Technol.* 2003, v.163-164, p.118-127.

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ДВУХРЁБЕРНАЯ ЛОВУШКА ДЛЯ МАКРОЧАСТИЦ

Д.С. Аксёнов

Исследованы свойства двухрёберной ловушки макрочастиц, знание которых необходимо при проектировании фильтров (сепараторов) вакуумно-дуговой эрозионной плазмы. Установлены зависимости между геометрическими параметрами ловушки и эффективностью поглощения макрочастиц. Выполнены расчёты, результаты которых позволяют прогнозировать поведение фильтрующих качеств сепараторов, содержащих в своей конструкции такие ловушки. Даны рекомендации относительно применения двухрёберных ловушек в фильтрах различных конструкций.

ДВОРЕБЕРНА ПАСТКА ДЛЯ МАКРОЧАСТИНОК

Д.С. Аксьонов

Досліджено властивості двореберних пасток макрочастинок, знання яких є необхідним при проектуванні реберних систем фільтрів вакуумно-дугової ерозійної плазми. Встановлено залежності між геометричними параметрами пастки та ефективністю поглинання макрочастинок. Виконано розрахунки, результати яких дозволяють прогнозувати поведінку фільтруючих якостей сепараторів, які мають у своєму складі такі пастки. Надано рекомендації стосовно використання двореберних пасток у фільтрах різних конструкцій.