Linear model of the electrogasdynamic characteristics of the dry electrostatic cooling nozzle

N V Khripunov
Togliatti State University, Russia, 445020, Togliatti, Belorusskaya St., 14

E-mail: hrnv2@ya.ru

Abstract. A brief review of the essence and physical mechanisms of dry electrostatic cooling technology is presented, the areas of application of this technology are described and the main aspects which hamper its wide use are formulated, in particular the insufficient theoretical study of the issue of determining the main electrogasdynamic parameters of the nozzle of the dry electrostatic cooling unit while designing technological operations. The maximum electric voltage, ensuring stable corona discharge in the nozzle of the unit without transition to spark discharge - pre-spark voltage - was accepted as the main indicator of effective functioning of the unit of dry electrostatic cooling. Experiments were performed to study the impact of nozzle diameter and air pressure on the pre-spark voltage. In the course of the experiments a linear dependence of the pre-spark voltage on the nozzle diameter was found. It was also found that there is a constant for all diameters of stabilization air pressure, above which the pre-spark voltage does not change significantly. Experiments were carried out to study the impact of nozzle needle offset on the pre-spark voltage at an air pressure equal to the stabilization pressure. As a result of the experiments, the limit offset of the needle ensuring stable functioning of the dry electrostatic cooling unit was found. The parameter of nozzle geometry - modified diameter - is proposed. This parameter integrates the nozzle diameter and the needle offset. Using the modified diameter, an easy-to-use linear dependence between the studied parameters is obtained.

1. Introduction
The nozzle of the dry electrostatic cooling unit is a system of two electrodes ensuring the existence of a corona discharge in the turbulent air flow.

Dry electrostatic cooling systems are used in metal cutting as an alternative to liquid cooling. The elimination or minimization of the use of coolant in metal machining is an important task. Among the reasons for worldwide interest in the problem of "dry" machining, first of all, environmental considerations and, in particular, the tightening of legislation, in connection with which the costs of coolant utilization have increased significantly, should be emphasized. On the other hand, evolution of metal cutting processes is associated with an increase in cutting speed, and as is known, with an increase in cutting speed, the temperature in the machining zone and the contact density of the tool with the workpiece increases. For this reason, the efficiency of the use of liquid coolant with the increase of the cutting speed decreases. In solving the problem of reducing the use of coolant when cutting metals, the methods of machining without the use of cooling, with minimal use of liquid and the use of non-liquid coolant are actively researched [1].

The essence of the method of dry electrostatic cooling (DEC) [2] consists in supplying the cutting zone with air treated by corona discharge. A grounded nozzle with a centrally located needle, to which...
a constant voltage $U$ is supplied, is used to produce a corona discharge. Inside the nozzle, an overpressure of air $P$ is created, resulting in an air flow with velocity $V$ (figure 1).

![Figure 1. Scheme of the nozzle of a dry electrostatic cooling unit.](image)

The efficiency of the DEC technology has been confirmed by both research and industrial tests in the machining of various metallic materials at various technological operations [3, 4, 5, 6]. However, the widespread use of this technology is largely constrained by the lack of practical universal theory-based recommendations for the choice of mode of operating the dry electrostatic cooling unit.

When using DEC the tool life increase is caused by the following processes: intensive cooling due to the presence of charged particles; formation of a boundary film, adsorptionally and chemically connected with the rubbing tool surface; passivation of juvenile surface, occurring as a result of reaction of active components of physical and chemical plasma, arising in the cutting zone during pyrolytic transformations and in conditions of high shear stresses and exoelectronic emission; increase in the rate of diffusion of electrically charged particles into the plastic deformation zone due to a significant potential difference arising in the air flow. The listed physical aspects mainly depend on the flux density of charged particles entering the cutting zone with the air flow [7, 8]. This value directly depends on the power spent on the ionization of the air flow, which is determined based on the voltage $U$ applied to the needle and the corona discharge current $I$. It is obvious that the conditions of corona discharge combustion are directly determined by the velocity $V$ of the air flow, which, in turn, is directly related to the air pressure $P$ supplied to the nozzle. Also, the electric power transmitted to the air flow by the corona discharge depends on the nozzle geometry - the outlet diameter $d$ and the value of offset $a$ of the corona discharge electrode relative to the nozzle plane. The upper limit of variation of the described parameters is the transition of corona discharge into spark discharge. Moreover, in the case when the offset of the needle $a$ exceeds the permissible one, the spark discharge occurs along the shortest path and not from the tip of the needle electrode (figure 2). This is also a limiting factor.

![Figure 2. Type of spark discharge depending on needle offset ($d = 3$ mm).](image)
The aim of the research is to experimentally establish the dependences of the operation mode of the DEC unit at which the maximum degree of airflow modification by corona discharge takes place.

In the course of the work the following tasks are solved:

1. The dependence of the pre-spark voltage on the nozzle diameter and air pressure was studied.
2. The impact of needle offset on the value of the pre-spark voltage was researched.
3. Based on the results of the experiments, a linear model linking the investigated parameters is proposed.

2. Materials, tools and methods

For the experiments, an upgraded unit DEC "Varkash" equipped with interchangeable nozzles with a diameter $d$ from 2 to 6 mm and a voltage regulation unit up to 14 kV with a step of 0.25 kV was used. Pressure $P$ of the air supplied to the nozzle was regulated by the built-in manometer of Festo air preparation unit connected to the industrial compressed air network with a nominal pressure of 0.6 MPa. The voltage of the DEC unit was maintained corresponding to the pre-spark stable corona discharge mode - the maximum at further increase of which the corona discharge transforms into a spark discharge. The voltage regulator of the SEA setup increased the voltage until the spark discharge occurred, after which the voltage was decreased by one step of the regulator.

Each experiment was repeated three times at constant modes of operation of the DEC unit. The average of three repeats was used as the result.

In the first series of experiments, the nozzle diameter $d$ and air pressure $P$ were varied with control of voltage $U$.

The second series of experiments was aimed at studying the effect of needle offset $a$ on the efficiency of the DEC unit.

The pressure $P$ varied from 0 to 0.4 MPa, the nozzle diameter $d$ - from 2 to 6 mm, and the needle offset $a$ - from 0 to 2.5 mm. Step of varying pressure $P$ is 0.05 MPa, nozzle diameter $d$ is 1 mm, needle offset $a$ is 0.25 mm.

3. Results and discussion

The results of the first series of experiments (table 1) show that the pre-spark voltage $U$ for nozzle diameters from 2 to 6 mm varies linearly with a proportionality factor of 1.5 kV/mm. With increasing air pressure $P$, at first there is an increase in $U$, then $U$ stabilizes and changes insignificantly with increasing $P$. For all studied diameters, the stabilization pressure is 0.2 MPa.

Table 1. Dependence of voltage (kV) on nozzle diameter and air pressure.

| Air pressure (MPa) | Nozzle diameter (mm) | Proportionality factor |
|-------------------|----------------------|------------------------|
|                   | 2    | 3    | 4    | 5    | 6    |                  |
| 0                 | 2.00 | 3.00 | 5.00 | 6.50 | 7.50 | 1.45             |
| 0.05              | 3.25 | 4.75 | 6.50 | 8.00 | 9.25 | 1.53             |
| 0.10              | 3.75 | 5.00 | 6.75 | 8.00 | 9.25 | 1.40             |
| 0.15              | 4.00 | 5.50 | 7.50 | 8.75 | 10.25| 1.58             |
| 0.20              | 4.75 | 6.50 | 8.00 | 9.50 | 10.75| 1.50             |
| 0.25              | 4.75 | 6.50 | 7.75 | 9.25 | 10.25| 1.38             |
| 0.30              | 4.25 | 6.25 | 7.50 | 9.25 | 10.50| 1.55             |
| 0.35              | 4.50 | 6.25 | 7.75 | 9.00 | 10.75| 1.53             |
| 0.40              | 4.50 | 6.50 | 7.75 | 9.50 | 10.50| 1.50             |

Average 1.49

Obviously, as the diameter of the nozzle increases, the operation occurs with more corona discharge energy and the charge carried by the air flow into the cutting zone increases. The placement of the
corona needle outside the nozzle has a similar effect. The limiting value of the offset is the one at achievement of which the spark discharge with increasing voltage occurs not from the tip of the needle cone, but from the formative - along the shortest path. According to the results of the experiments (table 2), it was shown that the maximum offset of the needle $a$ ensuring operation without spark discharge along the shortest path is 0.4 of the nozzle diameter. In the second series of experiments, for each nozzle diameter, the upper limit of the needle offset variation was determined by the occurrence of a spark discharge along the shortest path.

**Table 2.** Dependence of voltage (kV) on nozzle diameter and needle displacement at $P = 0.2$ MPa.

| Needle offset (mm) | 2   | 3   | 4   | 5   | 6   |
|-------------------|-----|-----|-----|-----|-----|
| 0                 | 4.75| 6.50| 8.00| 9.50| 10.75|
| 0.25              | 5.00| 6.50| 8.25| 9.75| 10.75|
| 0.50              | 5.25| 7.00| 8.25| 10.00| 11.00|
| 0.75              | 5.50| 7.25| 8.75| 10.00| 11.25|
| 1.00              | 0$^a$| 7.75| 9.25| 10.50| 11.25|
| 1.25              | 0$^a$| 8.00| 9.75| 11.00| 11.75|
| 1.50              | 0$^a$| 0$^a$| 10.00| 11.25| 12.25|
| 1.75              | 0$^a$| 0$^a$| 0$^a$| 11.50| 12.50|
| 2.00              | 0$^a$| 0$^a$| 0$^a$| 11.75| 12.75|
| 2.25              | 0$^a$| 0$^a$| 0$^a$| 12.00| 13.00|
| 2.50              | 0$^a$| 0$^a$| 0$^a$| 0$^a$| 13.50|

$^a$ Spark discharge along the shortest path

Assuming that the mechanisms for increasing the charge transported by increasing the diameter $d$ of the nozzle and by offsetting $a$ of the needle are similar, let us introduce a nozzle characteristic that combines the diameter and offset of the needle: the modified diameter $d_m$.

$$d_m = 2 \sqrt{\frac{d^2}{2} + a^2},$$

(1)

The data of tables 1 and 2 for pressure $P = 0.2$ MPa expressed in $d_m$ are shown in figure 3.
The graph shows good linearization and can be approximated by the expression:

\[ U = 1.5d_m + 2.15 \]  \hspace{1cm} (2)

The formulas establish the dependence between the geometric parameters of the nozzle, the applied air pressure and the maximum voltage at which the stable corona discharge takes place.

4. Conclusions

As a result of the work the linear dependence between the pre-spark voltage of DEC unit and the nozzle diameter and the limiting value of the needle offset, providing the DEC unit operation without discharge along the shortest path, were obtained.

Based on the analysis of the results, a complex parameter - the modified diameter of the nozzle and a linear model describing the studied parameters - are proposed.

The use of the given dependences makes it possible to make preliminary calculations related to the electrogasdynamic characteristics of the DEC process and to select the power of DEC units when developing technological operations, taking into account the restrictions on the overall dimensions of nozzles and on the air pressure.

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