A SIMILARITY CRITERION FOR ELECTRICAL DISCHARGE IN GASES

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The familiar Paschen law on electrical breakdown, which is a result of the application of the methods of similarity and dimensionality theory to electrical discharges in a stationary gas, has been of major importance in generalizing the experimental data on electrical breakdown [1]. Recently, these methods have been applied to generalizing the results obtained from experimental studies on electric arcs [2–5]. In this article, a very simple similarity criterion is proposed; this criterion can be applied to various forms of electrical discharges in a channel with a gas stream.

NOMENCLATURE

G—is the gas mass flow rate in the channel per second;
I—is the discharge current;
e—is the absolute value of the charge on an electron;
n—is the particle density;
m—is the particle mass;
ez—is the charge on an ion;
p—is the pressure;
v—is the particle directed velocity;
U—is the arc voltage;
V—is the gas mass velocity;
d and s—are the diameter and area of the channel cross section;
U_s—is the breakdown potential between the arc column and the electrode-channel

The subscripts e, i, and *a* apply, respectively, to electrons, ions, and molecules in the initial gas; n applies to the projection of the velocity on the normal to an element of area ds.

1. Consider a channel with a gas stream; an electrical-discharge current of any form flows along the axis of this channel. As an example, an electric arc is one such type of discharge. Assume that the flow rate of the gas through the channel is such that we cannot ignore its effect on discharge. This effect can be described by using several similarity criteria. One of them is the criterion we have proposed:

$$\Pi = m_a I / eG . \tag{1.1}$$

Let us explain the physical meaning of this criterion. For simplicity, assume that the radial-current component is zero. Then the electric current is defined as the flow of charge through the channel cross section:

$$I = e \int_s \left\{ \sum_z [z n_i(z)\, v_{in}(z)] - n_e v_{en} \right\} ds . \tag{1.2}$$

From (1.2) we obtain

$$\frac{I}{e} = \int_s \left\{ \sum_z [z n_i(z)\, v_{in}(z)] - n_e v_{en} \right\} ds . \tag{1.3}$$

It is clear from (1.3) that I/e constitutes the flow of charge through an area s. If the plasma is neutral and the directed velocity is the same for all ions and close to the plasma mass velocity, i.e.,

$$\sum_z z n_i(z) = n_e, \quad v_{in} = V_n ,$$

the expression for I/e becomes much simpler and is written as

$$\frac{I}{e} = \int_s n_e (V_n - v_{en})\, ds \;.$$

It is now clear that in the last case I/e is the electron flow through an area equal to s and moving together with the gas of heavy plasma components (since m_e is small in comparison with the mass of other particles, the electron contribution to the plasma mass velocity can be ignored).

The flow of molecules of the inital gas until interaction with discharge is given by

$$\frac{G}{m_a} = \int_s n_a v_{an}\, ds \;.$$

Thus, (1.1) is the ratio of the flow of charges of magnitude e and initial-gas molecules through the channel cross section. We should note that Π represents very important physical processes in electrical discharges. In particular, for an electric arc, n_e, n_a, and v_e are fundamental parameters which determine the current density, electric-field strength, and, consequently, the density of the generated Joule heat. In addition, the flow of neutral particles not only characterizes mass transport, but also convective heat transfer at a given temperature. Thus, the energy balance of the arc column in the gas stream depends on Π. Moreover, the quantities making up Π also have a considerable effect on thermodyanmic and transport properties of the arc plasma, excitation processes, ionization, radiation, etc.

The physical constants in the criterion such as m_a, m_e, etc. can be discarded when comparing discharge in gases with the same initial composition. The dimensional complexes obtained in this manner make up the variable parts of the corresponding similarity criteria and are more convenient to use from the viewpoint of minimizing calculations of processing the experimental data and using the obtained generalized characteristics. In this case, I/G, which coincides with the variable part of one of the criteria in [4], is such a dimensional complex.

The effect of electrical discharge on the motion and properties of the gas is often an important parameter. This situation occurs in plasmotrons, arc-extinguishing devices, etc. Clearly, we can also use the proposed criterion in considering the gas dynamic (and other) properties of a gas stream when it interacts with an electric discharge.

2. Since any power combination of criteria is also a similarity criterion, it is possible to give these criteria different forms. Therefore, the experimental data can be processed in various criteria systems or dimensional complexes. Thus, the processing of the volt-ampere characteristics of a steady-state arc, using various systems, leads to the approximate formulas

$$\frac{Ud}{I} = 1170\left(\frac{I^2}{Gd}\right)^{-1.05}\left(\frac{I}{G}\right)^{0.68}(pd)^{0.1}, \tag{2.1}$$

$$\frac{Ud}{I} = 1170\left(\frac{I}{G}\right)^{-1.42}\left(\frac{G}{d}\right)^{-1.05}(pd)^{0.1}, \quad \frac{Ud}{I} = 1170\left(\frac{I^2}{Gd}\right)^{-0.71}\left(\frac{G}{d}\right)^{-0.34}(pd)^{0.1}\;.$$

Here $30 < I < 170$ A; $2 < G < 25$ g/sec; $1 < d < 3.5$ cm; $G/d < 10$ g/sec cm; $10 < p < 30$ N/cm² U is in volts; the working medium is air; the channel wall serves as the anode; the inner face of the electrode is the cathode.

Using (2.1), we can draw some conclusions. As is clear, only by concerning ourselves with some particular system of criteria is it possible to speak of the magnitude of the effect for the criterion (or its variable part) on any discharge property (in this case, on the arc voltage). Thus, for example, the dependence of the arc voltage on the complex G/d when various systems are employed varies. Therefore, the importance of the criterion will remain constant only when a complete set of criteria describing the discharge is specified.

The second conclusion concerns the breakdown potential between the arc column and the electrode channel. As is known [3], the voltage of a steady-state arc is determined by breakdown, i.e., by the quantity U_s. Therefore, allowing for the dependence of U on I/G, G/d, and pd, we can state that U_s also depends on these complexes:

$$\frac{U_s d}{I} = f\left(\frac{I}{G}, \frac{G}{d}, pd\right) \tag{2.2}$$

Thus, in contrast to the Paschen law on breakdown, in the presence of an arc and a gas flow, U_s depends not only on pd but also on I/G and G/d as well.

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