1979-07

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AIP Publishing

Khait, Yu, and O. Biblarz. "Influence of turbulence on a diffuse electrical gas discharge under moderate pressures." Journal of Applied Physics 50.7 (1979): 4692-4699.
https://hdl.handle.net/10945/61141

Journal of Applied Physics

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Cite as: Journal of Applied Physics **50**, 4692 (1979); https://doi.org/10.1063/1.326579
Published Online: 24 July 2008

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Influence of turbulence on a diffuse electrical gas discharge under moderate pressures

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(Received 19 December 1977; accepted for publication 13 February 1979)

Aspects of a corona discharge under the influence of a turbulent flow are considered. This problem represents an extension of the already complicated situation of discharges in very nonuniform electric fields but in nonmoving gases. Our approach is restricted to providing a qualitative and semiquantitative description of some important phenomena occurring in plasmas formed in a turbulent gas which flows through the strong nonuniform electric field present in the small corona region. These phenomena lead to interesting experimentally observable effects; in particular, they allow a substantial increase of current and power consumption in the diffuse discharge which is associated with a sharp enhancement of transport coefficients in the hydrodynamically turbulent plasma. Estimates of the relative current increase and power consumption (turbulent-to-laminar) can be made with the information presented. These estimates are in agreement with observations.

PACS numbers: 52.80.Hc, 47.25. – c, 52.25.Fi

I. INTRODUCTION

Discharges in flowing gases at moderate pressures are presently of interest due to their application to plasma chemistry[1–7] and to electric-discharge convection lasers.[8,9] In plasma chemistry, a branch of applied chemical physics, partially ionized gases are used for chemical, metallurgical, and other applications under quasiequilibrium and nonequilibrium conditions. In particular, relatively low-pressure discharges (i.e., in the 10-Torr range) have been successfully operated. But presently one of the important problems in plasma-chemical processes is to scale the effective operating pressure up to and beyond 1 atm. The influence of turbulence, which can be more substantial at the higher pressures, is important because turbulence affects the energy consumption and stability of the discharge through the mixing and homogeneity of the reagents. Electroaerodynamic lasers are of interest in the high-energy-laser field owing to their high efficiency relative to the gasdynamic laser (GDL) and to their simplicity of operation relative to chemical lasers. The low-pressure laser discharge[8,9] with convective rates which allow satisfactory cooling and removal of poisonous by-products is now commonly used. However, discharge power is limited by arc breakdown, which becomes the upper limit in the output power of the laser. Hydrodynamic turbulence is known to affect these discharges due to increased convection and mixing.[10–12] Turbulence makes it possible to disperse the discharge, allowing larger currents and higher power consumption to exist in a prearcing mode. The turbulent diffusivities enable molecular gases (such as atmospheric air) to accept additional diffuse discharge power, making them much more attractive for plasma-chemical processes. In particular, we have observed[11] sharp increases in the power input—on the order of 200–500 times the no-flow values. This increase is attributed primarily to turbulence.

The precise mechanisms which allow turbulent discharges to absorb significant additional eneryg are not fully understood; a "thermal" streamer model has been suggested.[13] We believe that the observed increase in energy deposition in turbulent discharges reflects very deep changes caused by the turbulent-flow/gas-discharge interaction. For this reason, in this paper we focus on the effects of turbulence on the properties of gas discharges. We also suggest mechanisms related to the turbulence/gas-discharge interaction.

II. CONDITIONS OF THE PROBLEM

We consider gas discharges of relatively low power under the following experimentally observed conditions.

(1) The degree of ionization is low, and hence the electron-electron, ion-ion, and electron-ion interactions are negligible compared with electron-neutral and ion-neutral interactions.

(2) Mean translational energies of the heavy particles ($\bar{\epsilon}_a$ for atoms, $\bar{\epsilon}_m$ for molecules, and $\bar{\epsilon}_i$ for ions) remain close to their values at the gas temperature, but the electron mean translational energy $\bar{\epsilon}_e$ may be higher.

(3) Joule heating of the gas is not considered to be substantial.

(4) The flows are subsonic and the gas is essentially incompressible.

(5) Self-magnetic fields are negligible.

(6) The pressures are above several hundred Torr and up to a few atmospheres.

(7) The geometry of the problem is typified by Fig. 1 (Ref. 11) and detailed in Sec. III.

(8) Molecular gases with electron-attaching properties (such as air) are described.

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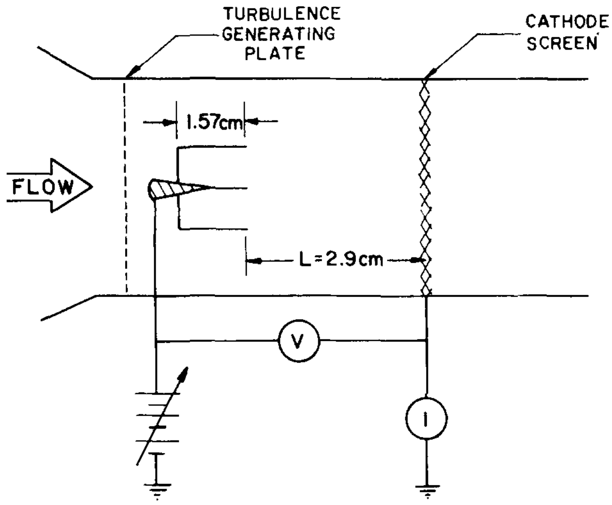


FIG. 1. Schematic of experimental setup.

(9) Ions (and electrons) are assumed to attain the laminar or turbulent motion of the neutral background gas everywhere except at the sheaths, and the diffusion of charged particles (i.e., ambipolar diffusion) as well as the diffusion of heat and momentum can be expressed through transport coefficients of the neutral gas. But such parameters as electrical conductivity should be calculated separately. These assumptions have been discussed in Refs. 12 and 14.

Under the conditions enumerated above, charged particles collide mainly with neutrals. The frequency ν_M of these collisions is much higher than any frequencies ω_t of the turbulent fluctuations. Thus, at least for the ions and possible cluster particles, we can assume that they are directly involved with the turbulent fluctuations of the neutral gas. Electrons become involved through Coulomb coupling. The actual processes in a discharge under turbulent conditions have a three-dimensional character with simultaneous mass, momentum, energy, and charge transfer; as a result, this situation presents a very difficult problem for exact analysis. At present, the formulation of turbulence for un-ionized flows and the theories of electrical gas discharges are incomplete. This is why one can hardly expect to solve with any degree of exactness the problem of turbulent-flow/gas-discharge interactions. We shall resort, therefore, to the use of approximation analysis and similitude theory to obtain qualitative and semiquantitative results for the main features of the problem. On this basis, we combine theories of turbulence and turbulent-transport coefficients with a model of the discharge to obtain expressions for the power consumption and other observables.

III. GEOMETRY

Figures 1 and 2 depict the geometry under consideration. Prior to the test section (see A-A′ in Fig. 2), the gas passes through a plenum chamber of large cross section with a relatively low Reynolds number $\mathrm{Re} < \mathrm{Re}^*$, where Re^* is the critical Reynolds number for these particular conditions. The flow entering is purely laminar because any residual upstream turbulence can be purposely removed. Before entering the test section, the velocity of the gas increases markedly and Re may become greater than Re^*, which leads to the formation of turbulent boundary layers at the test section walls; these comprise the regions A′B′C′ and ACB′ in Fig. 2. In the center of the channel a laminar core exists (the region A′B′A shown in Fig. 2). All experimental equipment is located within this laminar core. This equipment includes the metallic pins serving as anodes, with a density b_p pins per unit cross-sectional area. The cathode may consist of several airfoils or of coarse wire mesh. The interelectrode distance is L.

Controlled turbulence is generated in the laminar core by grids and screens[15] located at a distance r_g upstream of the discharge region. The gas with speed v is introduced in the discharge region after passing one or more screen/mesh combinations. In this fashion, various turbulent-flow configurations can be generated.

IV. APPROXIMATE APPLICATION OF THE KOLOMOGOROV THEORY OF LOCALLY DEVELOPED TURBULENCE

We shall consider the case where the plate in Fig. 3 creates turbulence in the discharge space with $\mathrm{Re} \gg \mathrm{Re}^*$ ev-

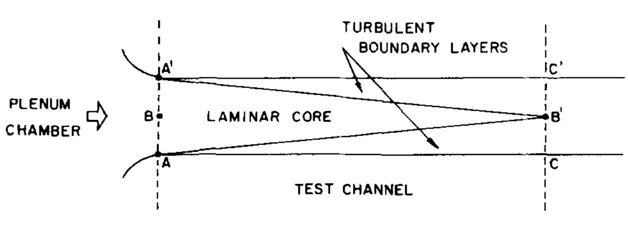
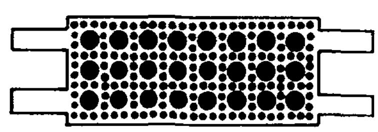


FIG. 2. Developing flow in a channel.



MATERIAL : PHENOLIC

LENGTH (cm)	13.4
WIDTH (cm)	5.6
THICKNESS (cm)	0.46
DIAMETER (cm)	
LARGE HOLES:	0.95
SMALL HOLES:	0.32

FIG. 3. Turbulence-generating plate.

erywhere, with the possible exception of small regions near solid surfaces. For such a case, we can apply the theory of locally developed turbulence for a qualitative consideration and perhaps a rough semiquantitative estimate of the turbulent-flow/gas-discharge problem. We shall use Landau's interpretation of the turbulent theory.[16]

The smallest linear scale λ_0 of turbulence and its corresponding frequency ω_0 are

$$\lambda_0 \cong \left(\frac{\mathrm{Re}^*}{\mathrm{Re}}\right)^{3/4} l \tag{1}$$

and

$$\omega_0 \cong \frac{\Delta v}{l}\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{3/4}, \tag{2}$$

where Re* is the local critical Reynolds number, Re $= l\Delta v/\nu_M$ (ν_M being the molecular kinematic viscosity), l is the largest scale of the turbulence, and Δv is the corresponding velocity of the turbulent pulsations. Consider simple estimates of λ_0 and ω_0 under experimental conditions and compare these estimates with an effective size $d_s \simeq S^{1/2}$ of the test tunnel's cross section of area S (which is nearly square) and with the mean distance $r_p \simeq b_p^{-1/2}$ between pins in the discharge zone. If $\Delta v \lesssim v = 10^4$ cm/sec, $l \simeq d_s \simeq 4$ cm, $\nu_M \simeq 0.2$ cm²/sec, and $\mathrm{Re}^* \simeq 50$, one can obtain

$\mathrm{Re} \simeq 2\times 10^5$,

$\lambda_0 \simeq 10^{-2}$cm,

$\omega_0 \simeq 10^6$ sec^{-1}.

These values show that λ_0 satisfies the following conditions:

$$\lambda_0 \ll d_s \quad \text{and} \quad \lambda_0 \ll r_p, \tag{3}$$

where $d_s \cong 4$ cm $> r_p \cong 1$ cm. In this case, it is possible to choose many regions in the discharge space (not too close to the surface) with a linear scale δL which satisfies the conditions

$$\lambda_0 \ll \delta L \ll d_s \quad \text{and} \quad \lambda_0 \ll \delta L \ll L, \tag{4}$$

where L is the effective length of the discharge space without the sheaths. Then the discharge volume $d_s^2 L$ contains many volumes $(\delta L)^3$, each of which has many turbulent degrees of freedom $(\delta L/\lambda_0)^3$, and each of which can be approximately described by the isotropic-turbulence model.

V. TRANSPORT COEFFICIENTS IN DISCHARGES WITH TURBULENT FLOWS

The molecular transport coefficients, i.e., the mass diffusivity D_M, the momentum diffusivity ν_M, and the thermal diffusivity χ_M are connected with their turbulent counterparts D_t, ν_t, and χ_t by the following relationships[16]:

$$\left.\begin{matrix} D_t \\ \nu_t \\ \chi_t \end{matrix}\right\} \cong \frac{\mathrm{Re}}{\mathrm{Re}^*}\left\{\begin{matrix} D_M \\ \nu_M \\ \chi_M \end{matrix}\right. , \tag{5}$$

and since $D_M \approx \nu_M \approx \chi_M$, then

$$D_t \approx \nu_t \approx \chi_t. \tag{6}$$

The effective diffusivities of the neutral gas thus become

$$\left.\begin{matrix} D \\ \nu \\ \chi \end{matrix}\right\} \cong \left(1+\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)\left\{\begin{matrix} D_M \\ \nu_M \\ \chi_M \end{matrix}\right. . \tag{7}$$

This approach has been used[2,17] for the consideration of some transport phenomena in plasma jets. An analogous expression may accordingly be written for the ion diffusivity:

$$D_i \cong \left(1+\frac{\mathrm{Re}}{\mathrm{Re}^*}\right) D_{iM}, \tag{8}$$

where it is possible that $D_{iM} \neq D_M$.

When Re≫Re*, one may neglect the 1 in Eqs. (5)–(8) and get

$$\left.\begin{matrix} D \\ \nu \\ \chi \end{matrix}\right\} \simeq \left\{\begin{matrix} D_t \\ \nu_t \\ \chi_t \end{matrix}\right\} \simeq \frac{\mathrm{Re}}{\mathrm{Re}^*}\left\{\begin{matrix} D_M \\ \nu_M \\ \chi_M \end{matrix}\right. . \tag{9}$$

These expressions allow us to obtain the effective turbulent ambipolar diffusion coefficient D_{A_T} from the well-known expression

$$D_{AM} = \frac{D_{iM}\mu_{eM} + D_{eM}\mu_{iM}}{\mu_{iM}+\mu_{eM}}, \tag{10}$$

where μ_{iM} and μ_{eM} are the ion and electron mobilities, respectively. It is easy to show that if Re≫Re*, then for turbulent flow

$$D_A \cong \left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right) D_{AM}. \tag{11}$$

For nonequilibrium plasmas, where the mean translational energy of the electrons $\bar{\epsilon}_e$ is much higher than either $\bar{\epsilon}_M$ or $\bar{\epsilon}_i$, we have

$$D_{AM} \simeq D_{iM}\frac{\bar{\epsilon}_e}{\bar{\epsilon}_i} \tag{12}$$

and

$$D_A \simeq \left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right) D_{iM}\frac{\bar{\epsilon}_e}{\bar{\epsilon}_i}. \tag{13}$$

One can see from Eq. (13) that a very large increase of D_A is possible if the Reynolds number is high enough and if $\bar{\epsilon}_e$ is much more than $\bar{\epsilon}_i$. Large values of Re/Re* are unlikely for a "fine" wire mesh where the wire diameter is small and where the space between wires is large. It is possible, however, to produce large Re/Re* with suitable grids and screens (see Fig. 3, for example). A large ratio $\bar{\epsilon}_e/\bar{\epsilon}_i$ can be expected in discharge regions where the electrical field strength E is large enough.[18-21] In particular, in the corona region under turbulent conditions[11] E is estimated to be several tens of kV/cm, and thus $\bar{\epsilon}_e/\bar{\epsilon}_i \gg 1$ with Re/Re*≫1. In this case, D_A can be very large. In locations of low enough electric field,

$$D'_A \simeq 2D_{it} \simeq 2\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right) D_{iM} < D_A. \tag{14}$$

The low-electric field conditions can be encountered in a region external to the corona discharge (L_b in Fig. 4).

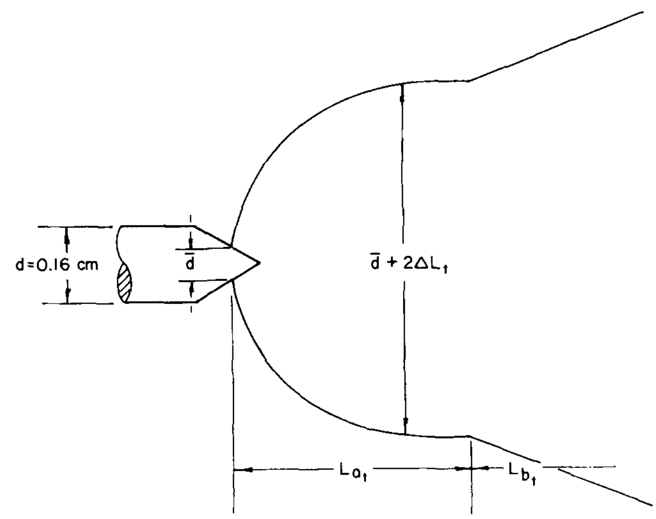


FIG. 4. Detail of pin region.

However, even here $D_A \gg D_{iM}$ because of the turbulence. We shall establish that the great enhancement of the transport coefficients, achieved partly by turbulence and partly by the strong electric field, is the key to the explanation of the conspicuous effect of turbulence on the properties of the discharge considered.

Note that we have implicitly assumed [see Eq. (6)] that the dimensionless numbers $P_r \simeq S_c \simeq 1$. However, it is just as easy to introduce values other than 1 into the above expressions. This way we can treat laser-mixture gases.

VI. CORONA DISCHARGE IN A TURBULENT GAS FLOW—STATEMENT OF THE PROBLEM

Many differences exist between corona discharges under no-flow and under hydrodynamically turbulent conditions. These differences lead to directly observable consequences, some of which are considered below.

Under no-flow conditions, corona discharges are very nonuniform in space and time. Typically, the discharge is only active on a few electrode pins. Upon close examination, each discharge looks like a single short-term pulse of current and light. These pulses are connected with avalanches, which concentrate along narrow channels with the high local concentration of charged particles. The channel radius and cross section of the avalanches are[22,23]

$$r_0 \approx \left(6\int \frac{D_e}{v_e}\,dr\right)^{1/2} \quad \text{and} \quad S_M \approx \pi r_0^2, \tag{15}$$

where v_e is the electron drift velocity, D_e is the electron diffusivity {equal to D_{eM} when $r_0 < l_d$ and equal to D_{AM} [see Eq. (10)] when $r_0 < l_d$}, l_d is the Debye length, and D_{eM} is the electron "molecular" diffusivity. In the case under consideration, the number of active pins n_{PM} without a turbulent flow is less than the total n_p (this matter will be treated more fully below). Under the influence of turbulence, the nonuniformities in current and light in space and time decrease, current and energy consumption sharply increase, the breakdown voltage is changed, etc.

Theoretically, the interaction of a turbulent gas with the strong nonuniform-corona electric field leads to new classes of physical problems which are different from conventional gasdynamics and from the theory of nonflow gas discharges. These are the problems of turbulent-flow plasmas – while the turbulent-gas portions pass the corona space, a turbulent plasma is formed. Certainly, the development of turbulent-flow plasma theory will help to better guide experimental work. In this paper we will limit ourselves to a consideration of some physical mechanisms and to some estimates of effects connected with the conditions mentioned above. We shall take into consideration the following facts. As the strong electric field $E_a(\bar{r})$ is confined only within the corona region, gas portions passing through this space are affected by the electric field only for the relatively short time (if v is large) $\tau_a \simeq L_a/v$. Thus every turbulent-gas portion is transformed into a nonuniform turbulent plasma under a short-term "impulse" action of this electric field for the time τ_a, during which plasma decay processes can also develop. Decay processes are characterized by relaxation times t_r and are connected, in particular, with a nonequilibrium energy distribution of electrons. It is known that the problems of energy distributions and rate coefficients in a strong and nonuniform electric field under nonflow conditions,[18,21] and of plasma formation in the impulse nonuniform field without any hydrodynamic turbulence,[24,26] are complicated and far from being understood.

VII. QUALITATIVE PICTURE OF THE CORONA DISCHARGE UNDER TURBULENT CONDITIONS

Under nonflow conditions the nonuniformity of the corona field is characterized by values

$$\left|\frac{\partial E_a}{\partial r}\right| \simeq \frac{E_a - E_b}{L_{aM}} \simeq \frac{E_a}{L_{aM}}, \qquad L_{bM} = L - L_{aM} \gg L_{aM}. \tag{16}$$

In Fig. 4, L_a and L_b (turbulent) are indicated, and note that E_b, the electric field in the external region of the corona, has a magnitude $E_b \ll E_a$. In this case we define scales δL_a from Eqs. (4), such as

$$\delta L_a \left|\frac{\partial E_a}{\partial r}\right| \ll E_a, \quad \delta L_a \ll L_{aM} \ll L_{bM}, \tag{17}$$

and therefore the volume $(\delta L_a)^3$ may be taken as a region of quasiuniformity of the local field E_a. Let us make some numerical estimates corresponding to experimental conditions,[11] with a pressure $p = 760$ Torr, a voltage $U = 25$ kV, an interelectrode space $L \simeq 4$ cm, and pin radii $d_M = 0.3$–0.1 cm. Then the average electric field becomes $\bar{E} \simeq 6$ kV/cm and $E/p \simeq 8$ V/cm Torr. Near the tips, the local corona field can reach magnitudes $E_a = 50$–150 kV/cm, $\delta L_{aM} \ll 0.1$ cm, and $E_a/p \simeq 70$–200 V/cm Torr. In the external zone of the discharge the smaller electric field E_b is more uniform than in the corona region. Consider now phenomena occurring in the turbulent-gas portions while passing through three distinct discharge zones.

(1) The sheaths. A plasma is formed in the gas entering the area where the electric field is strong. The sheaths adjacent to the pins have a thickness of the order of the Debye

length l_d, which is small when compared with any characteristic size. Even the smallest scale of the turbulence λ_0 [see Eq. (1)] can be much larger than this thickness. This means that the influence of a turbulent flow is negligible, and we will exclude the sheaths from further consideration in this paper.

(2) The quasineutral corona zone. As the corona field E_a is located in space with the scale L_a (see Fig. 4), only relatively small and high-frequency turbulent eddies with scales λ and frequencies ω can markedly influence the transport coefficients and other properties of the plasma which are formed in the corona region; in this case λ and ω have to satisfy the conditions

$$\lambda_0 < \lambda < L_a; \quad \omega_0 > \omega > \tau_a^{-1}. \tag{18}$$

Therefore, the significant influence of the turbulence on the plasma properties in the corona region is possibly only for flows which satisfy the conditions

$$\lambda_0 \simeq l\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{-3/4} \ll L_a, \quad \omega_0 \simeq \frac{\Delta v}{l}\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{3/4} \gg \tau_a^{-1}; \tag{19}$$

or

$$\frac{\mathrm{Re}}{\mathrm{Re}^*} \gg \left(\frac{l}{L_a}\right)^{4/3}. \tag{20}$$

Un-ionized gas portions entering the corona discharge rapidly acquire new turbulent-plasma properties as the gas is affected by the strong and nonuniform electric field, i.e., (a) the gas portions passing the corona zone are ionized under the short-term action of the strong electrical field (the electron and ion concentrations N_e and N_i and electron energies $\bar{\epsilon}_e$ are sharply increased), (b) energy distributions in the newly formed moving plasma are nonequilibrium and nonsteady, (c) the properties of the moving plasma characterized by N_e, $\bar{\epsilon}_e$, etc., are nonuniform and change quickly from point to point and from instant to instant, (d) fluxes of energetic electrons and avalanches pass through the moving gas, (e) turbulent pulsations of the gas interact with plasma oscillations and fluctuations, and so on. All these phenomena very much complicate the gas description in the corona discharge.

Consider semiphenomenologically the problem of plasma diffusivity in the corona zone and its space scale under turbulent conditions. The ambipolar diffusion described by Eq. (11) takes place in the plasma regions with space scales Δl_{At} satisfying the relations

$$\Delta l_{At} > \lambda_0 \quad if\ \lambda_0 > l_d, \quad \text{or} \quad \Delta l_{At} > l_d \quad \text{if } l_d > \lambda_0, \tag{21}$$

where the ratio λ_0/l_d depends on Re/Re*, N_e, and $\bar{\epsilon}_e$, which are different at various points of the discharge. Turbulent (but not ambipolar) diffusion described by Eqs. (5)–(9) takes place within the regions with space scales Δl_t satisfying the conditions

$$l_d > \Delta l_t \gg \lambda_0. \tag{22}$$

The conditions (21) are fulfilled, for example, in the corona region near the pins for the configuration pictured in Figs. 1 and 4 (see also Secs. II and IV). However, when the gas is removed from the strong-field zone by convection or diffusion and enters weaker-electrical-field regions, N_e, N_i, and $\bar{\epsilon}_e$ decrease and l_d increases and can become large enough to satisfy the condition $l_d > \lambda_0$. Thus relations (22) or the intermediate cases can only occur in a region external to the corona discharge, where N_e and $\bar{\epsilon}_e$ can be relatively small. This means that every portion of the moving gas can keep high values for N_e and $\bar{\epsilon}_e/\bar{\epsilon}_i$ only for the limited times t_r and t_ϵ, where $t_\epsilon < t_r$. Note that the relevant time for N_e is characteristically the recombination time. Only within this time t_r can the diffusivity of the charged particles in the moving gas be determined by the turbulent ambipolar coefficients D_A; therefore, the time interval t_r can also serve as a characteristic time for estimates of the space scale L_{at} of the turbulent corona zone. In this zone, concentrations of charged particles are high enough, and conditions (21) are fulfilled; hence Eqs. (11) and (13) for the ambipolar turbulent diffusivity are valid. Thus the effective ambipolar turbulent diffusion length ΔL_{Aa} and the drift velocity w_{At} are respectively

$$\Delta L_{Aa} \simeq (6t_r D_A)^{1/2} \simeq \left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)^{1/2} \Delta L_{AM}, \tag{23}$$

$$w_{At} \simeq \frac{\Delta L_{Aa}}{t_r} \simeq \left(6\frac{\mathrm{Re}}{\mathrm{Re}^*}\frac{\bar{\epsilon}_e}{\bar{\epsilon}_i}\frac{D_{iM}}{t_r}\right)^{1/2}, \tag{24}$$

where the condition $w_A > v$ is assumed to be fulfilled; for example, this takes place for the turbulent ambipolar diffusion of positive ions under the considered conditions (see Sec. II). Here

$$\Delta L_{AM} \simeq (6t_r D_{AM})^{1/2} \simeq [6t_r(\bar{\epsilon}_e/\bar{\epsilon}_i)D_{iM}]^{1/2}, \tag{25}$$

and it represents the corresponding diffusion length for the nonflow conditions. D_{AM} is given by Eq. (12).

In the corona region, where $E_a(r)$ is high and nonuniform, $\bar{\epsilon}_e \gg \bar{\epsilon}_i$, and both $\bar{\epsilon}_e$ and $\bar{\epsilon}_i$ depend on the coordinate r. The effective length of the corona region under turbulent conditions is (see Fig. 4)

$$L_{at} = \tfrac{1}{2}\bar{d} + \Delta\tilde{L}_{Aa}, \quad \text{if } w_{At} > v, \tag{26}$$

where $\frac{1}{2}\bar{d}$ is the corona space scale under nonturbulent conditions. In the corona area, where E_a, E_a/p, and the ratio $\bar{\epsilon}_e/\bar{\epsilon}_i$ are high enough, turbulence of a magnitude Re/Re* can greatly enhance w_{At}, ΔL_{Aa}, and L_{at}. The spreading of charged particles in the direction perpendicular to the flow increases the crosssection of the corona region of every pin up to the value

$$\bar{S}_{at} \simeq \pi\Delta\tilde{L}_{Aa}^2\left(1 + \frac{\bar{d}}{2\Delta\tilde{L}_{Aa}}\right)$$

or

$$\bar{S}_{at} \simeq 6\pi\widetilde{\left(\frac{\mathrm{Re}}{\mathrm{Re}^*}\right)\left(\frac{\bar{\epsilon}_e}{\bar{\epsilon}_i}\right)D_{iM}t_r} \quad \text{if } \tfrac{1}{2}\bar{d} \ll \Delta L_{Aa}. \tag{27}$$

Here the tilde over the symbols means that the corresponding values are averaged over the small corona regions, where relatively high electron concentrations and energies and their associated ambipolar diffusivity take place.

However, in regions external to the corona discharge where $r > L_{at}$, the concentrations of charged particles cannot be high enough to produce ambipolar diffusion through-out. Here diffusion can be described by the transition turbulent coefficient D_{tr}, which is the turbulent analog of the transition diffusivity under nonflow conditions[22] and which can be substantially less than the ambipolar turbulent diffusivity D_A in the corona zone. Now consider some numerical estimates of the values D_a, w_{At}, ΔL_{Aa}, and $\bar{S}_{at}$ in the corona region. Let $\mathrm{Re}/\mathrm{Re}^* = 3\times 10^3$, $\bar{\epsilon}_e/\bar{\epsilon}_i \simeq 10^2$, $D_{iM} = 0.2$ cm^2/sec, $t_r \simeq 10^{-6}$ sec, and $\frac{1}{2}\bar{d} \simeq 0.2$ cm. Then from Eqs. (11)–(13) and (24), $D_A \simeq 0.6\times 10^5$ cm^2/sec and $w_{At} \simeq 6\times 10^5$ cm/sec. The value w_{At} is of the order of the ion drift velocity for large E/p, and much larger than the flow velocities used in the experiments[11] ($v \simeq 10^4$ cm/sec). But w_{At} is $10-10^2$ times less than the free-electron drift velocities. In this case the diffusion length ΔL_{Aa} and the corona space and time scales are $\Delta L_{Aa} \simeq 1.9$ cm $\gg \frac{1}{2}\bar{d}$, $L_{At} \simeq 2$ cm, $4\bar{S}_{at}/\pi\bar{d}^2 \simeq 10^2$, and $\tau_a \simeq 2\times 10^{-4}$ sec. Therefore, turbulence has the effect of greatly spreading the charged particles from the small region near the pins in all directions and thereby creates a more homogeneous distribution of charged particles in the corona. This means that turbulence fattens the corona region considerably, as $L_{at} \simeq \frac{1}{2}\bar{d}$ and $w_{At} \gg v$. Since $L_{at} \gtrsim r_p \simeq b_p^{-1/2}$ ($r_p \simeq 1$ cm), the corona zones of neighboring pins can overlap and create a more or less homogeneous corona discharge common for all pins (as observed under no-flow or laminar-flow conditions[11,27]).

(3) The external zone. The external quasineutral zone has a length

$$L_{bt}(v) = L - L_{at} = L - \tfrac{1}{2}\bar{d} - \Delta L_{at}(v) \tag{28}$$

and a residence time

$$\tau_{bt}(v) \simeq L_{bt}/v = \tau - \tau_a(v), \tag{29}$$

both of which depend on v.

The electrical field E_b is considerably lower and more uniform in this region, i.e., $E_b \ll E_a$ and $|\partial E_b/\partial r| \ll |\partial E_a/\partial r|$. Hence, the electron energy $\bar{\epsilon}_e$ and concentration N_e and associated rate coefficients are much less than those in the corona zone, making the diffusion coefficients D_b in the external zone also less than D_{Aa} in the corona zone. The diffusion length is

$$\Delta L_{bt} \simeq (6D_b\tau_b)^{1/2}, \tag{30}$$

where D_b depends on the conditions in the external zone and can vary from the ambipolar diffusivity D_{Ab} to D_t, as determined by Eqs. (5) and (9). This zone may be subject to sufficient radiation from the corona region so that photoionization and excitation can increase the conductivity σ. Intensive diffusion (and convection) which spreads charged particles may (a) increase L_{at} and decrease L_b; (b) prevent the formation of large local densities of charged particles, and therefore hinder the creation of streamers; consequently, a sharp increase in the turbulent-transport coefficients may enhance discharge stability in the agreement with experimental data[11]; (c) create better conditions for more pronounced ionization and excitation and increase the yield of charged particles; and (d) increase the electrical field E_b (with decreasing L_b). The latter phenomena promote enhancement of the electrical conductivity σ_b in the external zone and consequently reduce its resistance $R_b \simeq \sigma_b^{-1} L_b$ and lead to large increases of the current and the power consumption.

VIII. INFLUENCE OF TURBULENCE ON POWER INPUT

We wish now to calculate the current I_t and power consumption W_t in the discharge, where

$$I_t = U_t/R_t, \quad W_t = I_t U_t; \tag{31}$$

$$R_t = R_{at} + R_{bt}, \quad R_{at} \simeq L_{at}/\sigma_A S_{at}, \quad R_{bt} \simeq L_{bt}/\sigma_{bt} S_{bt}; \tag{32}$$

$$S_{at} = n_{pt}\bar{S}_{at} \quad \text{if } \bar{S}_{at} < b_p^{-1}, \text{ or } S_{at} \gtrsim S \quad \text{if } \bar{S}_{at} > b_p^{-1}, \tag{33}$$

where R_{at} and R_{bt} are the resistances of the corona zone and the external zone, respectively, σ_{at}, σ_{bt} and S_{at}, S_{bt} are the conductivities and cross sections of these zones, $S_{bt} \gtrsim S_{at}$ (as can be seen in Fig. 4), and $S = n_p b_p$ is the electrode crosssection. The external zone gives the main contribution to the total effective discharge resistance R_t, which may be represented by

$$R_t = \frac{L - L_{at}}{S_b \sigma_{bt}}\left(1 + \frac{R_{at}}{R_{bt}}\right), \quad R_{at} < R_{bt}. \tag{34}$$

Then

$$I_t = \sigma_{bt}\frac{U_t - S_{bt}}{L - L_{at}}\left(1 + \frac{R_{at}}{R_{bt}}\right)^{-1}, \tag{35}$$

$$W_t = \sigma_{bt}\frac{U_t^2 S_{bt}}{L - L_{at}}\left(1 + \frac{R_{at}}{R_{bt}}\right)^{-1}, \tag{36}$$

where U_t is voltage, and

$$S_{bt} \simeq \pi n_{pt}\Delta L_{Aa}^2\left(1 + \frac{\bar{d}}{2\Delta L_{Aa}} + \frac{\Delta L_{bt}}{\Delta L_{Aa}}\right)^2. \tag{37}$$

Hence, the current and power consumption under turbulent conditions are

$$W_t \sim I_t \simeq \sigma_{bt}\frac{\pi U_t n_{Pt}}{L - L_{at}} 6\frac{\mathrm{Re}}{\mathrm{Re}^*}\frac{\bar{\epsilon}_e}{\bar{\epsilon}_i}\frac{\bar{U}_i}{NS_i} \times t_r\left(1 + \frac{\bar{d}}{2L_{Aa}} + \frac{L_b}{L_{Aa}}\right)^2\left(1 + \frac{R_{at}}{R_{bt}}\right)^{-1}, \tag{38}$$

where S_i is the cross section of ion-neutral collisions, $\bar{U}_i$ is the mean ion velocity, and N is the number density of gas particles. Now one can see that the current I_t and the power consumption W_t are (a) inversely proportional to the density N or pressure p, as $N \sim p$, and (b) increasing functions of the velocity v as Re, L_{at}, and n_{Pt} increase and $L - L_{at}$ decreases with flow velocity. These facts are in agreement with observations.[11,27]

The corresponding current and the energy consumption without turbulence are

$$I_M = \frac{U_M}{R_{aM} + R_{bM}} = \sigma_{bM}\frac{U_M - S_{bM}}{L - L_{aM}}\left(1 + \frac{R_{aM}}{R_{bM}}\right)^{-1}, \tag{39}$$

$$W_M = \sigma_{bM}\frac{U_M^2 S_{bM}}{L - L_{aM}}\left(1 + \frac{R_{aM}}{R_{bM}}\right)^{-1}, \tag{40}$$

where $S_M = n_{PM}\bar{S}_M$, $\bar{S}_M \simeq \frac{1}{4}\pi\bar{d}^2$ is the effective cross section of the channel associated with each pin, and U_M is the voltage. Consider the ratios η_1 and η_2:

$$\eta_1 \equiv \frac{I_t}{I_M} \approx \frac{\sigma_{bt} S_{bt}}{\sigma_{bM} S_{bM}}\left(\frac{L - L_{aM}}{L - L_{at}}\right)\frac{U_t}{U_M}, \tag{41}$$

$$\frac{R_{at}}{R_{bt}} < 1, \quad \frac{R_{aM}}{R_{bt}} < 1,$$

$$\eta_2 \equiv \frac{W_t}{W_M} = \frac{U_t}{U_M}\eta_1, \tag{42}$$

or in accordance with Eqs. (23), (27), and (37),

$$\eta_2 = \frac{I_t}{I_M}\frac{U_t}{U_M} \approx \frac{24}{\bar{d}^2}\left(\frac{U_t}{U_M}\right)^2 \frac{\text{Re}}{\text{Re}^*}\frac{\bar{\epsilon}_e}{\bar{\epsilon}_i}\frac{1-L_{aM}/L}{1-L_{at}/L}\frac{\sigma_{bt}n_{Pt}}{\sigma_{bM}n_{PM}}\frac{U_i}{NS_i} \times t_r\left(1+\frac{\bar{d}}{2\Delta L_{Aa}}+\frac{\Delta L_b}{\Delta L_{Aa}}\right)^2, \tag{43}$$

where

$$\frac{S_{bt}}{S_{bM}} \simeq 4\frac{n_{Pt}}{n_{PM}}\frac{\Delta L_{Aa}^2}{\bar{d}^2}\left(1+\frac{\bar{d}}{2\Delta L_{Aa}}+\frac{\Delta L_{bt}}{\Delta L_{Aa}}\right)^2 \gg 1, \tag{44}$$

$$L_{aM} \ll L_{at} \approx L, \quad \frac{L-L_{aM}}{L-L_{at}} > 1, \tag{45}$$

$$\frac{n_{bt}}{n_{bM}} > 1, \quad \text{and} \quad \sigma_{bt} > \sigma_{bM}. \tag{46}$$

Hence, the ratios η_1 and η_2 can be expected to be considerably larger than unity. These expressions show that the current and energy consumptions may increase sharply with turbulence, facts which correspond to experimental observations. We can add to these numerical estimates for η_1 and η_2; it has been estimated above that $4\Delta L_{Aa}^2/\bar{d}^2 \approx 10^2$ and $L_{at} \approx 0.5\,L$. Therefore, the ratios η_1 and η_2 determined in Eqs. (41) and (42) are equal: $\eta_1 \approx \eta_2 \gtrsim 10^2$, and also correspond to the experimental values $\eta_1^{(e)} \approx \eta_2^{(e)} \approx 250$ of Ref. 11.

IX. EFFECTIVE NUMBER OF PINS WORKING UNDER TURBULENT CONDITIONS

The power consumption W_t or W_M depends on the numbers n_{Pt} or n_{PM}, respectively. It has been mentioned that a corona discharge can be very uniform in space and time without flow, i.e., that not all the pins are active in the discharge. Turbulence can activate all the pins without external ballasting. Let us consider the following cases.

(1) The space between pins $r_p \approx b_P^{-1/2}$ satisfies the condition

$$r_p \gg \bar{d} + 2\Delta L_{At}, \quad \text{where} \quad b_P \approx n_P/S.$$

In this case, the regions of diffusion spreading of separate discharge zones relating to neighboring pins do not overlap, and the effective cross sections of the conducting channel is less than the full cross section, i.e.,

$$S_{at} \approx (\tfrac{1}{2}\bar{d} + \Delta L_{Aa})^2 \pi n_{Pt} < S,$$

the effective cross section and homogeneity of corona discharges can increase with increasing flow velocity. This growth promotes the rapid increase of current and power consumption.

(2) The space r_P between neighboring pins satisfies the opposite condition, i.e.,

$$r_P \approx b_P^{-1/2} \ll 2\Delta L_{Aa} + \bar{d}.$$

In this case, the regions of spreading from neighboring pins overlap and form a corona common for all pins, but the effectiveness of each pin can decrease if every pin works effectively for $r'_P > r_P$. Here, the actual effective cross section S'_{at} is less than the possible cross section of the conducting zone (under the condition that every pin works effectively):

$$S'_{at} < \pi n_{pt}(\tfrac{1}{2}\bar{d} + \Delta L_{Aa})^2,$$

and increasing the flow velocity does not lead to a great increase of the effective cross section (S'_{at}) and does not cause any sharp enhancement of energy consumption.

(3) The optimum condition for any given velocity is likely to be

$$\pi n_P(\tfrac{1}{2}\bar{d} + \Delta L_t)^2 \simeq S. \tag{47}$$

From here we expect the optimum number of pins n_P for a given S, E_a and v to be

$$n_P \simeq S\pi^{-1}(\tfrac{1}{2}\bar{d} + \Delta L_{At})^{-2}. \tag{47a}$$

Now increasing or decreasing of either velocity, E_a, $\bar{\epsilon}_e$, or b_P leads to the previous two cases.

X. SUMMARY AND CONCLUSIONS

The considered questions and established relations show that the turbulent gas speedily moving through the corona region with a strong and nonuniform electric field acquires new turbulent-plasma properties which need special attention. We have focused on a particular set of problems and conditions in order to arrive at experimentally observable conclusions, and even here the situation is quite complicated. The gas turbulence together with newly acquired plasma properties (ionization, relatively high electron energies, etc.) lead in particular to a great enhancement of the transport coefficients, of the current I_t, and of the energy consumption W_t. In Eqs. (38) and (43) the biggest influence arises from the factor Re/Re* associated with the gas turbulence and from the ratio $\bar{\epsilon}_e/\bar{\epsilon}_i$ connected with the high electric field E_a in the corona region. It must be recalled that the measurable effect of turbulence on the current and on the power input[11,27] represents a substantial increase in accordance with the above conclusions. The division of the discharge region into two main regions with the space scales L_a and L_b turns out to be quite useful and is dictated by the differences of physical phenomena occurring in these zones.

It should be kept in mind that our work is a preliminary consideration of the problem, but that even without exact knowledge of some parameters we can clearly point out the effects of turbulence. Our qualitative and semiquantitative results are no substitute for the required kinetic- and turbulent-plasma-theory solutions which are most complicated; the kinetic theory of the discharge under a very nonuniform electric field has not been developed even under no-flow conditions. We do know, however, that the establishment of stationary distributions is not very likely under highly nonuniform fields and that turbulence and the short residence time under a flow situation aggravates the problem. Here, a pulsed-discharge approach may be fruitful in describing the short-term action of the electric field. We are hopeful that this first step in the description of the problem will have defined the general features well enough for the next steps to be undertaken.

ACKNOWLEDGMENT

The second author would like to thank the Lady Davis Fellowship Trust for having made this work possible.

[1] L.S. Polak and Y.K. Khait, Dok. Akad. Nauk USSR **156**, 920 (1964).
[2] Y.L. Khait, Zh. Prikl. Mekh. Tekh. Fiz. **N4**, 54 (1965) [Sov. J. Appl. Mech. Tech. Phys. **N4**, 54 (1965)].
[3] *Kinetics and Thermodynamics of Chemical Reactions in Low-Temperature Plasma*, edited by L.S. Polak (State Publishing Office, Nauka, Moscow, 1965).
[4] *The Application of Plasmas to Chemical Processing*, edited by R.F. Baddour and R.S. Timmins (MIT, Cambridge, Mass., 1967).
[5] *Reactions Under Plasma Conditions*, edited by M. Venugopolan (Wiley, New York, 1971).
[6] *Fundamentals of Plasma Chemistry*, edited by A.T. Bell and Y. Holaahan (Wiley-Interscience, New York, 1973).
[7] F.K. McTaggert, *Plasma Chemistry in Electrical Discharges* (Elsevier, Amsterdam, 1967).
[8] A.C. Eckerbeth and F.S. Owen, Rev. Sci. Instrum. **43**, 995 (1972).
[9] J.W. Davis and C.O. Brown, AIAA Preprint No. 72-722, 1972 (unpublished).
[10] B. Karlovitz, Pure Appl. Chem. **5**, 557 (1962); also D.A. Allen, I. Fells, and F.J. Fletcher, J. Phys. D **4**, 1710 (1971).
[11] O. Biblarz and R. Nelson, J. Appl. Phys. **45**, 633 (1974).
[12] J. Schwartz and Y. Lavy, AIAA J. **13**, 647 (1975).
[13] D.H. Douglas-Hamilton and P.S. Rostler, AVCO-Everett Report, Project No. 9752-02, 1977 (unpublished).
[14] J. Shwartz and E. Wasserstrom, Isr. J. Technol. **13**, 122 (1975).
[15] Shih I. Pai, *Viscous Flow Theory, II—Turbulent Flow* (Van Nostrand, Princeton, N.J., 1959).
[16] L.D. Landau and E.M. Lifshitz, *Fluid Mechanics* (Addison-Wesley, Reading, Mass., 1959), Chap. III.
[17] Y. Khait, *Kinetics and Thermodynamics of Chemical Reactions in Low Temperature Plasma* (State Publishing Office, Nauka, Moscow, 1965), p. 167.
[18] V.L. Ginsburg, *Propagation of Electromagnetic Waves in Plasma* (State Publishing Office, Nauka, Moscow, 1966).
[19] I.P. Shkarovsky, T.W. Johnson, and M.P. Bachynsky, *The Particle Kinetics of Plasmas* (Addison-Wesley, Reading, Mass., 1966).
[20] Y. Khait, L.S. Polak, and E.N. Tchervotchkin, *Proceedings of 4th All-Union Conference on Physics and Generators of Low Temperature Plasma*, (Alma-Alta Polytechnic Institute, Alma-Alta, USSR, 1970), p. 40.
[21] L.S. Polak, Y.L. Khait, and E.N. Tervotchkin, High Energy Chem. **5**, 308 (1971).
[22] E. Nasser, *Fundamentals of Gaseous Ionization and Plasma Electronics* (Wiley-Interscience, New York, 1971); also, S.C. Brown, *Introduction to Electrical Discharges in Gases* (Wiley, New York, 1966).
[23] G.A. Dawson and W.P. Winn, Z. Phys. **183**, 159 (1965).
[24] F.B. Vurzel, Y.L. Khait, L.S. Polak and E.N. Tchervotchkin, High Energy Chem. **5**, 105 (1971).
[25] Y. Khait, Non-Stationary Heat and Mass Transfer in Plasma Chemical Processes, Moscow Petrochemical Synthesis Institute, USSR Academy of Sciences, 1972 (unpublished).
[26] Y. Khait, 82nd National Meeting of AIChE, Atlantic City, 1976 (unpublished).
[27] O. Biblarz, J.L. Barto, and H.A. Post, Isr. J. Technol. **15**, 59 (1977).