ЖЭТФ, 2006, том 129, вып. 2, стр. 378–385

SIZE OF DUST VOIDS AS A FUNCTION OF THE POWER INPUT IN DUSTY PLASMA

V. N. Tsytovich*

Prokhorov General Physics Institute of Russian Academy of Sciences
117942, Moscow, Russia

S. V. Vladimirov**

School of Physics, The University of Sydney
2006, New South Wales, Australia

G. E. Morfill

Max-Planck Institut für Extraterrestrische Physik
85740, Garching, Germany

Submitted 20 December 2005

A dust void is a dust-free region in dusty plasma. Theory demonstrates that the void results from the balance of the electrostatic and plasma (such as the ion drag) forces acting on a dust particle. In dusty plasma experiments, physical properties of the void show clear dependence on the power input into the plasma (in particular, its size increases with the increase of the applied power). Here, the theory and numerical results are presented for such a dependence.

PACS: 52.27.Lw, 52.25.Vy, 52.35.Fp, 52.40.Hf

1. INTRODUCTION

Numerous experiments demonstrate that a commonly observed property of a complex (dusty) plasma is the formation of structured dust/dust-free regions [1–7]. According to the current physical understanding, the dust-free regions, called dust voids, appear in a dusty plasma as a result of the electrostatic force and the drag force acting on dust particles, the latter being due to the plasma ions flowing to the dust [3, 8–11]. The reason for the ion drift is the enhanced plasma ionization in the dust void region as compared to the region occupied by dust, because the latter acts as an effective sink of plasma particles. In general, the ion momentum balance in the void (i.e., in the dust-free region) is determined by the electric force, the ion pressure force, and the friction force of plasma ions with neutral gas atoms. It was shown theoretically [8–11] that a dust void can indeed be formed as a result of the force balance in a dusty plasma. Such voids are usually globally stable for disturbances perpendicular to the void's edge.

The void's boundary appears in experiments as a sharp interface where the dust density abruptly changes. The sharpness of the boundary was theoretically explained in Refs. [8, 9, 11] for various physical situations. Usually, dissipative processes tend to smooth a discontinuity (e.g., in hydrodynamics), but in a dusty plasma, the dust density discontinuity is itself created by dissipative processes related to plasma absorption by dust grains. It was obtained that these processes not only fail to smooth the void's boundaries but, on the contrary, create them. In Refs. [8, 9], the theory of dust voids was proposed for the two limiting cases where the ion friction on the neutral gas atoms is assumed to be small [8] and in the case where the ion-neutral friction is dominating [9]. The «collisionless» void appears when its size is much less than the ion-neutral mean free path; in the opposite case, the void is «collision-dominated» [1].

The dust void structures were also investigated in [11] in the case where the ion diffusion in the neu-

*E-mail: tsytov@lpi.ru
**E-mail: S.Vladimirov@physics.usyd.edu.au;
http://www.physics.usyd.edu.au/~vladimi

tral gas atoms plays an important role. It was demonstrated that this dissipative process not only allows the existence of dust voids (i.e., the absence of dust grains in the void region) with sharp boundaries but can also create new types of (shock-like) discontinuities inside the dust structure.

The ionization source assumed in Refs. [8–11] was homogeneous and proportional to the plasma electron density (as observed in experiments). It was demonstrated that the presence of the plasma ionization supported by an external power input into the plasma is crucially important for the theory of voids because the ionization source creates the ions flowing to the boundary, thus supporting the void.

It was experimentally observed [2, 3, 5–7], that characteristics of the void change with changing plasma parameters such as the input power and/or the gas pressure. Typically, the size of the void increases with the increased power input into the system. When the size increases, the void can change the regime from nearly collisionless to collision-dominated. In this paper, we present a theory for the dependence of the dust void parameters on the power applied to a dusty plasma. The theory is developed for a one-dimensional model, with planar geometry that is symmetric with respect to the center of the void, by numerical investigation of the stationary force balance equations for the void structure.

The outline of the paper is as follows. In Sec. 2, we introduce the model and the main equations written in a dimensionless form; in Sec. 3, we present the dimensionless equations in the dust and void regions, relations at the void boundary, and an equation for the power input; Section 4 contains the numerical results showing the dependence of the void size on the input power, and Sec. 5 contains the main conclusions.

2. THE MODEL

We consider the one-dimensional model as sketched in Fig. 1. The overall approach assumes a planar geometry that is symmetric with respect to the center of the void located at $x = 0$. The ion drift velocity is zero at the center. When a void appears, its center is at $x = 0$. The void's edge corresponds to x_v. The dust region corresponds to $x > x_v$ where the dust number density n_d is finite (and positive).

To describe a collision-dominated structure with the size much larger than the ion-neutral mean free path, we use the dimensionless variables given by [9, 11]

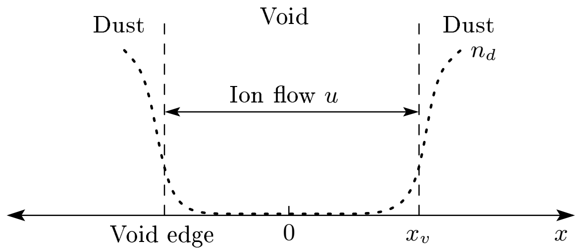

Fig. 1. Sketch of the one-dimensional simulation region. A dust cloud fills all space except for a void region of the full width $2x_v$ with the center at $x = 0$. The edge of the void is x_v

$$\begin{aligned} &n \to \frac{n_i}{n_{00}}, \quad n_e \to \frac{n_e}{n_{00}}, \quad P = \frac{n_d Z_d}{n_{00}}, \\ &u \to \frac{u_i}{\sqrt{2} v_{Ti}}, \quad v_{Ti}^2 = \frac{T_i}{m_i}, \\ &E \to \frac{eE\lambda_{in}}{T_i}, \quad x \to \frac{x\tau}{\lambda_{in}}, \\ &z = \frac{Z_d e^2}{aT_e}, \quad \tau_d = \frac{T_d e^2}{T_e^2 a}, \end{aligned} \tag{1}$$

where n_i, n_e, and n_d are the dimensional ion, electron, and dust number densities, respectively, Z_d is the dust charge in the units of the electron charge (the dust is assumed to be charged negatively), u_i is the ion drift velocity, $v_{Ti} = (T_i/m_i)^{1/2}$ is the ion thermal velocity, T_e and T_i are the electron and ion temperatures, T_d is the dust kinetic temperature in energy units (all temperatures are assumed to be homogeneous and constant), $\tau = T_i/T_e$ is the ion-to-electron temperature ratio, assumed to be small, τ_d is the dimensionless dust temperature (also assumed to be small), E is the electric field, λ_{in} is ion-neutral mean free path, a is the dust size, and z is the dimensionless dust charge. Finally, n_{00} is the ion critical density used for normalization of the plasma electron and ion densities,

$$n_{00} = n_0 \frac{\lambda_{Di}^2}{a} \frac{\tau}{\lambda_{in}} = \frac{\tau T_i}{4\pi e^2 \lambda_{in} a}, \tag{2}$$

where

$$\lambda_{Di} = \left(\frac{T_i}{4\pi n_i e^2} \right)^{1/2}$$

is the ion Debye length.

The total set of the balance equations is given by:

1. The electron momentum equation for the electron pressure force balanced by the electric field force,

$$\frac{dn_e}{dx} = -n_e E. \tag{3}$$

This equation leads to Boltzmann distribution of plasma electrons.

2. The ion momentum equation for the ion pressure force balanced by the electric field force, the friction on the dust force and the friction on the neutral-atom force,

$$\tau\frac{dn}{dx} = n(E - \alpha_{dr}uzP - u(2 + \alpha_n|u|)), \tag{4}$$

where $\alpha_{dr} = \alpha_{dr}(u, \tau/z)$ is the dust-ion drag coefficient, which is calculated with both the capture force and the Coulomb scattering force [9] of plasma ions by dust particles taken into account. Here, we neglect the udu/dx term because it is small for the considered subsonic ion drift velocities (we note that in our dimensionless units, this term contains an additional factor τ); our numerical calculations confirm this assumption. In the limits $\tau \ll 1$ and $1 \ll (\tau/z) \ll (a/\lambda_{Di})$, α_{dr} depends only on the ion drift velocity and is given by

$$\alpha_{dr}(|u|) = \left(\frac{\mathrm{erf}(|u|)}{2|u|^3} - \frac{\exp(-u^2)}{\sqrt{\pi}u^2}\right)\ln\Lambda, \tag{5}$$

where $\ln\Lambda$ is a generalization of the Coulomb logarithm with the collective plasma effects, the finite dust size, and the ion scattering on large angles by dust particles taken into account. Next, α_n in (4) is a numerical coefficient describing the nonlinearity of the friction force on the neutral atoms, which is typically of the order 1, and we therefore set $\alpha_n = 1$ in further numerical computations here. This value of α_n is based on the experimental dependence of the ion mobility on the electric field in a low-temperature plasma [12], which demonstrates that with the increase of the electric field E, the mobility starts to depend on E and $u \propto \sqrt{E}$ for large field, i.e., the ion friction force on the neutral atoms is proportional to u^2.

3. The dust momentum equation (balancing the dust pressure force by the electric field force and the ion drag force)

$$\tau_d\frac{d}{dx}\left(\frac{P}{z}\right) = -P(E - n\alpha_{dr}uz). \tag{6}$$

If we neglect the dust pressure force, we obtain the simple relation between the electric field force and the ion drag force acting on dust particles:

$$E = \alpha_{dr}(|u|)nuz. \tag{7}$$

4. The ion continuity equation determining the ion flow velocity and containing the ionization source and the dissipation sink on the dust component (written as an equation for the ion flux)

$$\frac{d\Phi}{dx} = \frac{n_e}{x_i} - \alpha_{ch}Pn, \tag{8}$$

where Φ is the total dimensionless ion flux (see Eq. (10) below), x_i is the dimensionless ionization length (see [8, 9]), and α_{ch} is the capture coefficient, also appearing in the dust charging equation (11), which in the limit $\tau \ll 1$ depends only on the ion flow velocity:

$$\alpha_{ch}(|u|) = \frac{\mathrm{erf}(|u|)}{4|u|}. \tag{9}$$

5. The ion flux relation including the convective flux and the diffusion flux

$$\Phi = nu - \tau\alpha_D\frac{dn}{dx}, \tag{10}$$

where α_D is the diffusion coefficient of ions on neutral particles; it is given by

$$\alpha_D = 1/3\sqrt{2} = 0.236$$

if estimated as

$$\lambda_{in}v_{Ti}/3 \quad \text{for} \quad T_i \approx T_n$$

(T_n is the neutral gas temperature in energy units). We note that the diffusive flux leads to the second-order derivative of the ion density in the ion continuity equation (8). The diffusion is negligible when $\tau \sim 0$; in that case, $\Phi = nu$, and the pressure term in the ion momentum equation also disappears.

6. The dust charging equation obtained from the balance of charging plasma currents on the dust grains

$$\frac{1}{z}\frac{dz}{dx} = -\frac{1}{z+1}\left(E + \frac{1}{n}\frac{dn}{dx} + \frac{1}{\alpha_{ch}}\frac{d\alpha_{ch}}{du}\frac{du}{dx}\right). \tag{11}$$

In the limit $\tau \ll 1$, the charging coefficient α_{ch} (as well as the drag coefficient α_{dr}) is a function of the ion drift velocity only.

7. The Poisson equation. It is used only in the void region. In the dust region, it gives an algebraic equation determining P as a function of n, n_e, u, and z (see Eq. (14) below). We have

$$\frac{dE}{dx} = \frac{1}{d^2}(n - n_e), \tag{12}$$

where

$$d^2 = \frac{a}{\lambda_{in}} \tag{13}$$

is the (square root of the) ratio of the dust particle size to the ion-neutral mean free path.

A similar system of equations was used previously in Ref. [11] (by keeping the ion diffusion term) and in Refs. [8, 9] by neglecting the ion diffusion on neutrals, $\alpha_D \to 0$, as well as the dust pressure $\tau_d \to 0$ when Eq. (6) describes sharp boundaries ($P = 0$ at one side of the boundary and $E = nuz\alpha_{dr}$ at the other side of the boundary), and/or the ion friction on neutrals. We note that the present system of the balance equations was first written in the full form in Ref. [11] and an important point here is the explicit expression for τ_d containing no parameter that can change in the appearing structures.

3. EQUATIONS IN THE DUST AND VOID REGIONS, AT THE VOID BOUNDARY, AND FOR THE POWER INPUT

3.1. Equations in the dust region

In the dust region, the Poisson equation gives the value of P as a function of other parameters in the dust region,

$$P(u,n,n_e,z) = \frac{n - n_e + d^2\alpha_{dr}(|u|)u^2nz\left[\dfrac{\alpha_{dr}(|u|)nz}{z+1} + \dfrac{R(u,z)}{\tau}(nz - 2 - |u|)\right]}{1 + R(u,z)d^2\alpha_{dr}(|u|)nz\left(\dfrac{u^2}{\tau}\alpha_{dr}(|u|)z - \alpha_{ch}(|u|)\right)}, \tag{14}$$

where the parameter $R(u,z)$ is related to the dependence of the dust drag coefficient α_{dr} and the charging coefficient α_{ch} on the ion flow velocity u,

$$R(u,z) = 1 + u\frac{1}{\alpha_{dr}(|u|)}\frac{d\alpha_{dr}(|u|)}{du} - \frac{1}{(1+z)}\frac{u}{\alpha_{ch}(|u|)}\frac{d(\alpha_{ch}(|u|))}{du}. \tag{15}$$

These relations complement the balance equations given in the previous section. We note that as $d \to 0$, it follows from expression (14) that

$$P = n - n_e, \tag{16}$$

which is nothing else but the local quasi-neutrality condition. In the other limit as $\tau \to 0$ for finite d, we obtain

$$P = n - \frac{2 + |u|}{z\alpha_{dr}(|u|)}. \tag{17}$$

We use these (or similar) relations below.

Furthermore, we obtain the ion continuity equation

$$\frac{du}{dx} = \frac{R_1(u,n,n_e,z)}{R(u,z)}, \tag{18}$$

the ion momentum (force balance) equation

$$\frac{dn}{dx} = \frac{un}{\tau}\left(\alpha_{dr}(|u|)z(n - P(u,n,n_e,z)) - 2 - |u|\right), \tag{19}$$

the electron momentum (force balance) equation

$$\frac{dn_e}{dx} = -unn_ez\alpha_{dr}(|u|), \tag{20}$$

and the dust charging equation

$$\frac{dz}{dx} = R_2(u,n,n_e,z). \tag{21}$$

In Eqs. (18) and (21), we have

$$R_1(u,n,n_e,z) = \frac{\alpha_{dr}(|u|)znu^2}{1+z} - \frac{zu^2}{\tau(1+z)}\left(\alpha_{dr}(|u|)z(n - P(u,n,n_e,z)) - 2 - |u|\right) + \frac{n - n_e - P(u,n,n_e,z)}{d^2\alpha_{dr}(|u|)zn} \tag{22}$$

and

$$R_2(u,n,n_e,z) = -\frac{z}{z+1}\left[\frac{1}{\alpha_{ch}(|u|)}\frac{d\alpha_{ch}(|u|)}{du} + \frac{R_1(u,n,n_e,z)}{R(u,z)}\frac{u}{\tau}\alpha_{dr}(|u|)z(n - P(u,n,n_e,z)) + \alpha_{dr}(|u|)znu\right]. \tag{23}$$

3.2. Equations in the void region

In the void region, we use the balance equations in which the ion diffusion and the dust pressure effects are neglected, while the ion pressure effects are included. The equations used in the void region are the ion continuity equation

$$\frac{du}{dx} = -\frac{u}{\tau}\left(E - u(2 + |u|)\right) + \frac{n_e}{nx_i}, \tag{24}$$

the ion momentum (force balance) equation

$$\frac{dn}{dx} = \frac{n}{\tau}\left(E - u(2+|u|)\right), \tag{25}$$

the electron momentum (force balance) equation

$$\frac{dn_e}{dx} = -n_e E, \tag{26}$$

and the Poisson equation

$$\frac{dE}{dx} = \frac{1}{d^2}\left(n - n_e\right). \tag{27}$$

3.3. Equations for the virtual void boundary

First, we here use the new concepts of the virtual dust charge and the virtual void boundary that should be used [11] in the absence of dust. The virtual dust charge indicates that if a dust particle is placed in some region in a plasma, it is charged corresponding to the virtual charge at that point. We note that forces acting on the dust grain move it if the chosen position does not satisfy the equilibrium force balance condition (as in the experiments in [7]). This concept is close to the concept of field strength in electrodynamics: the force acts on a charge only when the charge is actually placed at the point where the field exists.

In the absence of dust grains, the void boundaries can be obtained as virtual boundaries. The virtual dust voids bounded by the virtual surface can be stable as well as unstable. Experimental observations of real dust voids and a few particles staying on the virtual void surface for long time correspond to a stable virtual void, i.e., a stable virtual void boundary. The dust charge at the virtual void surface is virtual. This means that if we introduce a grain at this surface, it acquires the charge equal to the virtual dust charge. Although the model in [8, 9], which deals with the boundary conditions at the void surface and assumes the jump of the dust density at the void boundary, can in principle predict the virtual void size, the virtual dust charge can be obtained only at the void surface in this approach. Here, we use the concept of the virtual dust charge to calculate the void boundaries and the actual dust density distributions.

The boundary conditions for the void boundary are given by the continuity equation of the electric field

$$E(x_v) = n(x_v) z_v u(x_v) \alpha_{dr}(|u(x_v)|) \tag{28}$$

and the charging equation

$$\exp(-z_v) = \frac{2\sqrt{\pi}}{\tau m_i/m_e}\alpha_{ch}(|u(x_v)|) z_v \frac{n(x_v)}{n_e(x_v)}. \tag{29}$$

They give the position x_v of the void boundary and the dust charge z_v at the void boundary. We can therefore obtain the ion density $n_v = n(x_v)$, the electron density $n_{e,v} = n_e(x_v)$, the ion drift velocity $u_v = u(x_v)$, and the parameter $P_v = P(u_v, n_v, n_{e,v}, z_v)$ at the boundary.

3.4. Equation for the power input

The value for the power input provided by the ionization source can be obtained from ion continuity equation (24) by integrating it over the void size. We obtain

$$Q_i = 2\int_0^{x_v} \frac{n_e(x)}{x_i} dx. \tag{30}$$

The factor 2 is written here because the calculations are performed from the center of the void for the half-space $x \geq 0$ and therefore for a half of the void (see Fig. 1). All values are found as a function of the ionization distance, which is modeled as

$$x_i = 2(1 - m/6), \quad 0 \leq m \leq 5. \tag{31}$$

Thus we obtain the dependences on the parameter m, which are subsequently converted to the functions of Q_i, and the interpolated curves are given.

4. NUMERICAL RESULTS

The above equations (where the ion diffusion and the dust pressure effects are neglected while the ion pressure effects are included) were first solved for the set of the parameters $\tau = 0.05$, $x_i = 2$, $d = 0.2$, and $n_0 = 2$. These values are close to typical parameters of complex plasma experiments such as in Ref. [9]. The assumptions adopted are sufficient for the problem considered because we can easily obtain both the void structure and the dust structure, without any problems occurring with the point $u = 0$ in this approximation. We assume that $x = 0$ is in the center of the void and start numerical calculations from this point in the void region for $x > 0$ to find the boundary x_v of the void.

We thus obtain the main parameters of the void boundary: $x_v = 0.19004$, $z_v = 2.82089$, $n_v = 2.32804$, $n_{e,v} = 1.91211$, $E_v = 0.45031$, and $u_v = 0.07948$. Then we can find the jump P_v of the parameter P at the void's edge, i.e., the value of P at the dust side of the boundary. From Eqs. (14) and (15), we obtain $P_v = 0.3686$. This is positive and therefore the condition $P_v > 0$ is satisfied, i.e., a sharp dust void boundary exists. All the parameters found at the boundary can

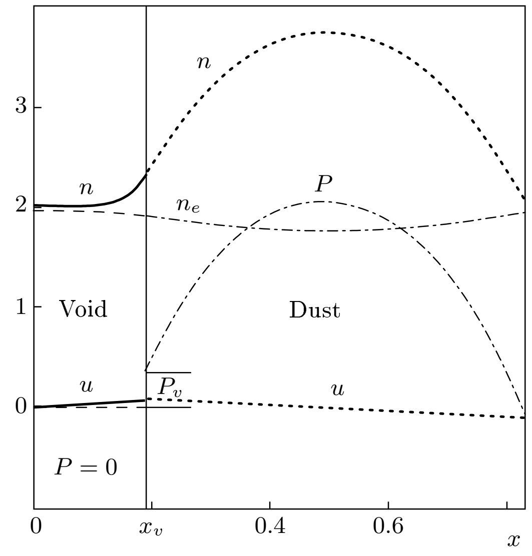

Fig. 2. Distribution of the main dimensionless parameters in the void and the dust regions in the case where the ion diffusion is neglected. The assumed values of the normalized plasma parameters are $\tau = T_i/T_e = 0.05$, $x_i = 2$, $d = (a/\lambda_{in})^{1/2} = 0.2$, $n_0 = 2$, and $n_{0e} = 0.98$. At the dust boundary, the parameter P as well as its derivatives are discontinuous. At the end of the structure, where $P = 0$, the derivative of P is also discontinuous

now be used to solve the equations in the dust region up to the point $P = 0$, together with the boundary conditions at the void's edge.

The solution is presented in Fig. 2. We can see that at the dust–void boundary, the parameter P is discontinuous (together with its derivatives). At the end of the structure, where $P = 0$, the derivative of P is also discontinuous. It is important that the sign of the ion velocity u changes inside the dust region. It can be seen that the solution in the dust region has no singularity at $u = 0$, which is related to the fact that the electric field, being proportional to u (due to the dust balance equation), vanishes for $u = 0$. Also, no point where the equality $R = 0$ is possible, is reached inside the dust region.

We note that for another set of the initial parameters, R can be equal to zero inside the dust region. The expression R appears in denominators (e.g., see (18)) when solving the system of equations for du/dx and dn/dx. The possibility of a singularity (i.e., $R = 0$) means that the one-dimensional approach adopted in the present study might not be sufficient to describe the dust dynamics. We note that in the two-dimensional case where the same system of equations with nonzero dust velocity describing formation of dust vortices has the additional term $\mathbf{v}_d dz/d\mathbf{r}$, no such singularities appear for dust rotation. Thus, $R = 0$ in the one-dimensional case corresponds to the possibility of generation of dust vortices in the two-dimensional consideration. The absence of such a singularity for the results shown in Fig. 2 suggests that for the set of parameters used, the dust vortices cannot be excited in the dust region.

In the case where the second surface is not a free surface (as was assumed for the point $P = 0$ shown in Fig. 2), and, for example, the wall with the floating potential appears, the dust region does not continue to $P = 0$ and another jump of P can occur before that point, leading to a near-wall dust void. Within the near-wall void, the ion flow velocity is directed to the dust region in the vicinity of it, then it changes its sign once more at some point, and is directed towards the wall near the wall. We note that only in this case the boundary conditions for the floating potential at the wall can be satisfied. Here, we do not explore the possibility of the near-wall dust void and consider only the free second surface with $P = 0$.

Next, we allow for changes in the ionization rate according to (31) to study the dependence of the dust void size on input power (30). All values of the plasma and dust parameters are found as functions of m. Then these functions are converted to functions of the applied power Q_i, and the corresponding interpolated curves are given.

Figure 3 shows the dependence on the applied power of the size of the void x_v, as well as the jump P_v of the parameter P and plasma parameters such as the dimensionless ion density, dust charge, and the ion flow velocity at the void's edge (presented as $n_v - 2$, $z_v - 2.5$, and u_v curves, respectively). Here, $\tau = 0.05$ and $d = 0.2$; the other parameters are the same as in Fig. 2. We note the general increase of the dust void size x_v for larger power input, which is in agreement with experimental results. The increase of the void is accompanied by the increase of the jump P_v of the parameter P at the void boundary, which corresponds to larger dust densities. We note that the dust charge at the boundary is decreased, which is due to a larger input of ions into the dust charging compared with the input of plasma electrons. Indeed, we can see that the ion density and velocity increase at the void boundary with the increase of the power input into the system.

In Fig. 4, the dependence of the dust void size x_v, of the jump P_v, and of the plasma parameters (presented as $n_v - 2$ and $z_v - 2.5$ curves) at the void's edge on the applied power is presented for other values of plasma parameters, i.e., for $\tau = 0.1$ and $d = 0.1$. We

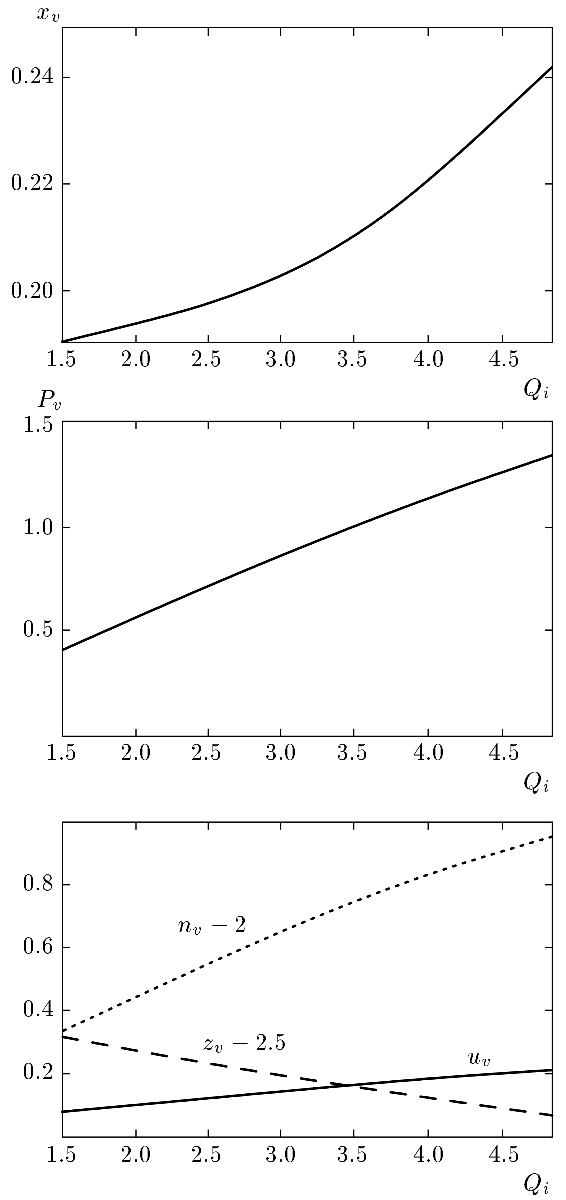

Fig. 3. Dependence of the size of the void x_v, the jump P_v of the parameter P, and the plasma parameters (presented as $n_v - 2$, $z_v - 2.5$, and u_v curves for the normalized ion density, normalized dust charge, and the normalized ion drift velocity, respectively) at the void's edge on the applied power Q_i. The assumed values of the normalized plasma parameters are the same as in Fig. 2, in particular, $\tau = 0.05$ and $d = 0.2$

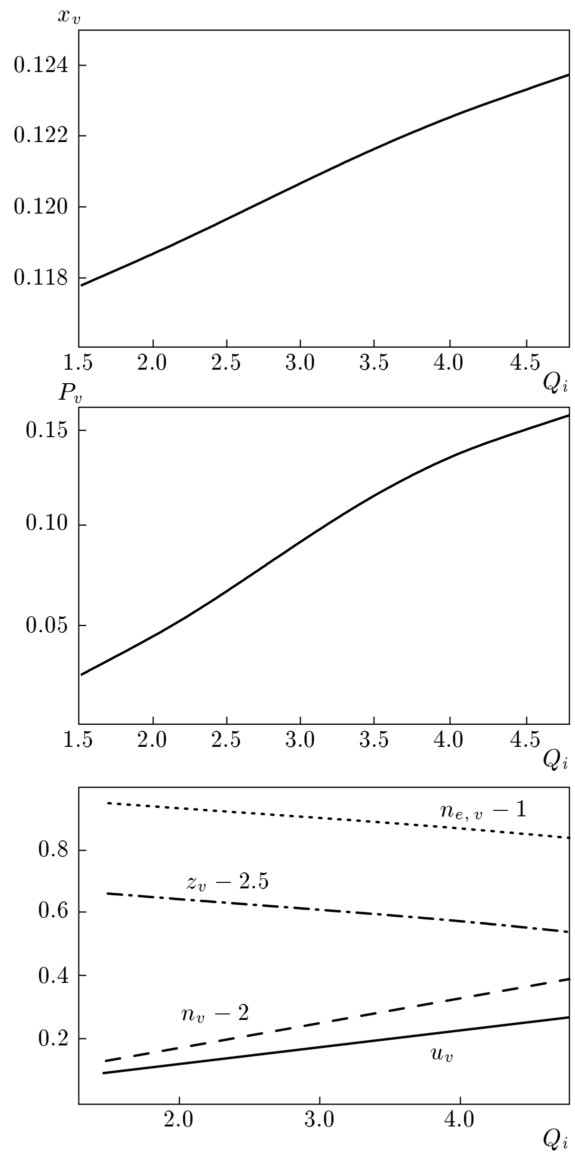

Fig. 4. Dependence of the size of the void x_v, the jump P_v of the parameter P, and the plasma parameters (presented as $n_{e,v} - 1$, $n_v - 2$, $z_v - 2.5$, and u_v curves for the normalized electron density, ion density, dust charge, and the ion drift velocity, respectively) at the void's edge on the applied power Q_i. The assumed values of the normalized plasma parameters are $\tau = 0.1$ and $d = 0.1$, the others are the same as in Figs. 2 and 3

note that in this figure, we also add the dependence of the electron density at the void's edge $n_{e,v}$ (presented as $n_{e,v} - 1$) on the power input into the system. We see that all general features of the applied power dependences are similar for different plasma parameters (we have also checked other values of the plasma parameters). In particular, the tendency of the increasing dust void size with the increasing power input into the systems is the same. We also note the decreasing electron density at the void's edge, which also contributes to the decrease of the dimensionless dust charge as the power input into the system increases.

5. CONCLUSION

To conclude, we have investigated the behavior of the main parameters of a dust void on the power applied to a dusty plasma system. We have demonstrated that the size of the dust void increases with increasing the power input. This is in agreement with experimental observations, e.g., in Ref. [3]. We have obtained the dependence of the main plasma and dust parameters at the void boundary on the applied power for various plasma conditions.

The authors thank J. Goree for attracting our attention to the problem and fruitful discussions. V. N. T. expresses thanks for hospitality during his stay at the University of Sydney (support of the Australian Research Council) and at the Max-Planck Institute for Extraterrestrial Physics, Garching. The work of S. V. V. was partially supported by the Australian Research Council and the Max-Planck Society.

REFERENCES

1. S. V. Vladimirov, K. Ostrikov, and A. A. Samarian, *Physics and Applications of Complex Plasmas*, Imperial College, London (2005).
2. G. Praburam and J. Goree, Phys. Plasmas **3**, 1212 (1996).
3. D. Samsonov and J. Goree, Phys. Rev. E **59**, 1047 (1999).
4. G. E. Morfill, H. M. Thomas, U. Konopka, H. Rothermel, M. Zuzic, A. Ivlev, and J. Goree, Phys. Rev. Lett. **83**, 1598 (1999).
5. A. Melzer, A. Homann, A. Piel, V. A. Schweigert, and I. V. Schweigert, in *Physics of Dusty Plasmas*, ed. by M. Horanyi, S. Robertson, and B. Walch, AIP Conference Proceedings, AIP, Woodbury (1998) Vol. 446, p. 167.
6. R. P. Dahiya, G. V. Paeva, W. W. Stoffels, E. Stoffels, G. M. W. Kroesen, K. Avinash, and A. Bhattacharjee, Phys. Rev. Lett. **89**, 125001 (2002).
7. C. Zafiu, A. Melzer, and A. Piel, Phys. Plasmas **10**, 1278 (2003).
8. J. Goree, G. E. Morfill, V. N. Tsytovich, and S. V. Vladimirov, Phys. Rev. E **59**, 7055 (1999).
9. V. N. Tsytovich, S. V. Vladimirov, G. E. Morfill, and J. Goree, Phys. Rev. E **63**, 056609 (2001).
10. S. V. Vladimirov and K. Ostrikov, Phys. Rep. **393**, 175 (2004).
11. V. N. Tsytovich, S. V. Vladimirov, and G. E. Morfill, Phys. Rev. E **70**, 066408 (2004).
12. L. S. Frost, Phys. Rev. **105**, 354 (1957).