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MODERATE AND LOW PRESSURE GLOW DISCHARGE IN THE GAP BETWEEN TWO ECCENTRIC TUBES

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The paper considers the positive column of a low and moderate pressure glow discharge located between two dielectric cylindrical walls with noncoincident parallel axes, the discharge current being aligned along the axes. The electron temperature of such discharge plasma was shown to be higher than the one of traditional cylindrical geometry when the outer plasma radii are equal, but the spatial distribution of plasma density in the discharge cross-section can acquire strong inhomogeneity in the azimuthal direction.

Keywords: glow discharge, positive column, eccentric geometry, electron temperature

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ТЛЕЮЩИЙ РАЗРЯД СРЕДНЕГО И НИЗКОГО ДАВЛЕНИЯ В ЗАЗОРЕ МЕЖДУ ДВУМЯ ЭКСЦЕНТРИЧНЫМИ ТРУБКАМИ

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Рассмотрен положительный столб тлеющего разряда низкого и среднего давления в диффузионном режиме, в зазоре между двумя цилиндрическими диэлектрическими стенками с несовпадающими параллельными осями, причем ток разряда направлен вдоль этих осей. Показано, что электронная температура плазмы такого разряда выше, чем в традиционной цилиндрической геометрии при равных внешних радиусах плазмы, но пространственное распределение плотности плазмы в поперечном сечении разряда может приобретать сильную азимутальную неоднородность.

Ключевые слова: тлеющий разряд, положительный столб, эксцентричная геометрия, электронная температура

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Introduction

C In papers [1, 2] we theoretically studied plasma of positive column of low and moderate pressure glow discharge located in the gap between two dielectric coaxial cylindrical tubes; in addition, the longitudinal field E_z and the discharge current were directed along the axis of the tubes. The authors showed that in such a discharge geometry, there is a considerable increase in electron temperature T_e in comparison with the cylindrical geometry even with a small (0.1 and less) ratio of the radii of the inner to the outer wall due to the additional channel of electron losses: electron diffusion to the inner wall. This result is important, in particular, for design of gas-discharge light and UV radiation sources, as it provides an opportunity to increase specific power of the radiation and its efficiency without any noticeable reduction in the discharge volume. All of this is possible by means of a transition from the traditional cylindrical to coaxial discharge geometry only. The results of [1, 2] make it possible to give a physical explanation to the experimental results obtained earlier in articles [3–7].

The results of papers [1, 2] were obtained under the assumption of strictly coaxial, concentric placement of tubes. However, such an ideal case is hard to translate into practice. Manufacturing errors often lead to an axial misalignment: eccentricity of the inner and outer tubes, i.e. to central asymmetry of both the device cross-section, and the profiles of charged particle densities as well.

This paper aimed to evaluate the quantitative influence the eccentricity of the discharge channel cross-section on the spatial distributions of plasma electron densities n and on the electron temperature T_e.

In this article we confine ourselves to the study of a simple case of a positive column of electropositive glow discharge in diffusion mode under low and moderate pressure: when the length of thermal diffusivity of the electrons is more than the outer plasma radius, and electron temperature T_e is constant inside the device cross-section. We assume the direct ionization by electron impact to be the main mechanism of charged particles production, while ambipolar diffusion to the walls being the dominant mechanism of their decay.

Calculation methodology

Fig. 1 shows the discharge channel cross-section in eccentric geometry. The origin (point O) was chosen in the center of the inner circle with radius R_1. The center of the outer circle with radius R (point O_R) is displaced from the origin by distance d. Angle φ is measured from the x axis. The discharge plasma is located between two said circles. The discharge current direction is perpendicular to xy plane.

The equation or spatial distribution of electrons density in the positive column under the conditions indicated above has the following form [8]:

$$D_A \Delta n + \nu_i n = 0,$$

where ν_i, Hz, is ionization frequency; D_A, cm²/s, is ambipolar diffusion coefficient; the values of ν_i and D_A do not depend on spatial coordinates due to assumed constancy of T_e.

Using a reduced coordinate $X = r / R$ and defining $\xi = R\sqrt{\nu_i / D_A}$, we obtain:

$$\frac{\partial^2 n}{\partial X^2} + \frac{1}{X}\frac{\partial n}{\partial X} + \frac{1}{X^2}\frac{\partial^2 n}{\partial \varphi^2} + \xi^2 n = 0. \tag{1}$$

We seek the solutionof Eq. (1) as a product of two functions:

$$n = \mathrm{P}(r)\Phi(\varphi).$$

Then Eq. (1) takes the form

$$\frac{X^2 \mathrm{P}''}{\mathrm{P}} + \frac{X\mathrm{P}'}{\mathrm{P}} + \xi^2 X^2 = -\frac{\Phi''}{\Phi} = k^2,$$

where k is a constant value.

Consequently, $\Phi'' = -k^2\Phi$, or

$$\Phi(\varphi) = C_1^{(k)} \cos(k\varphi) + C_2^{(k)} \sin(k\varphi). \tag{2}$$

From a physical point of view, $\Phi(\varphi)$ is a periodic and even function by φ with the period of 2π. Therefore, k can have only integer values: $k = 0$,

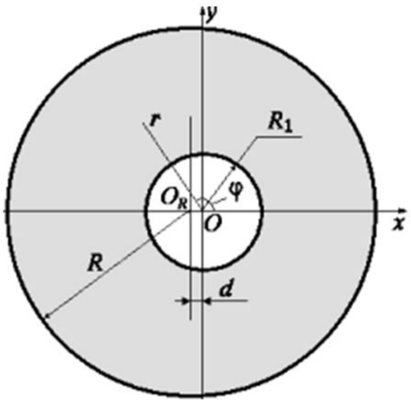

Fig. 1. Discharge channel cross-section (shaded area) in eccentric geometry: x, y and r, φ are Cartesian and cylindrical coordinate systems; d is eccentricity of the outer circle with respect to the inner one (their radii are equal to R and R_1, respectively)

1, 2,..., while $C_2^{(k)} = 0 \; \forall k$.

Function P(r) satisfies the expression

$$\mathrm{P}(r) = B_{k1}\mathrm{J}_k\left(\xi X\right) + B_{k2}\mathrm{N}_k\left(\xi X\right), \qquad (3)$$

where $\mathrm{J}_k(x)$, $\mathrm{N}_k(x)$ – Bessel and Neumann functions of k^{th} order.

As general solution of Eq. (1) we obtain the following expression in the discharge cross-section:

$$n\left(X,\varphi\right) = \sum_{k=0}^{\infty}\left\{C_k \cos\left(k\varphi\right) \times \right. \\ \left. \times\left[\mathrm{J}_k\left(\xi X\right) + B_k \mathrm{N}_k\left(\xi X\right)\right]\right\}, \qquad (4)$$

where $B_{k1} = 1, B_{k2} \equiv B_k$ due to homogeneity of Eq.(1).

Boundary conditions on the inner circle correspond to the zero values:

$$n(\rho,\varphi) = 0 \; \forall\varphi, \qquad (5)$$

where ρ is a reduced radius of the inner wall ($\rho = R_1 / R$); the boundary conditions on the outer wall are the same:

$$n(X_R,\varphi_R) = 0 \; \forall\varphi_R \in [0, 2\pi), \qquad (6)$$

where X_R is the reduced radial coordinate of a point on the outer circle having the angle of its vision from the origin φ_R.

Values X_R and φ_R are connected by the relation (see Fig. 1):

$$X_R^2 + a^2 - 2X_R a\cos(\pi - \varphi_R) = 1,$$

where $a = d/R$, or

$$X_R = \sqrt{1 - a^2\sin^2\varphi_R} - a\cos\varphi_R. \qquad (7)$$

The angle φ_R, like φ, is measured from x axis counterclockwise, and its angular point lies in the origin.

It follows from Eqs. (4) and (5) that

$$B_k = -\frac{\mathrm{J}_k\left(\xi\rho\right)}{\mathrm{N}_k\left(\xi\rho\right)} \; \forall k \in [0, 1, 2, ..., \infty).$$

Then

$$n(X,\varphi) = \sum_{k=0}^{\infty} C_k \cos(k\varphi)\,\Omega_k(\xi, X), \qquad (8)$$

where we have introduced a notation

$$\Omega_k(\xi, X) = \mathrm{J}_k\left(\xi X\right) - \frac{\mathrm{J}_k\left(\xi\rho\right)}{\mathrm{N}_k\left(\xi\rho\right)}\mathrm{N}_k\left(\xi X\right).$$

It follows from boundary conditions (6) that

$$\sum_{k=0}^{\infty} C_k \cos(k\varphi_R)\,\Omega_k(\xi, X_R) = 0, \qquad (9)$$

where values φ_R and X_R are connected by the relation (7).

Eq. (8), provided we find coefficients C_k and eigenvalues ξ from Eq. (9), is an exact solution of problem (1) for the eccentric case. But if we set satisfaction of the boundary conditions (6) in all points of the outer circle, then to find coefficients C_k we need to solve a system of linear algebraic equations (9) of unlimited size.

Although, we should note that for $a \to 0$, when both the value of the gap between the walls and solution (8) do not depend on angle φ, and only one term remains in the sums (8) and (9) – namely by $k = 0$. In addition, Eq.(9) transforms into a transcendental equation for eigenvalue ξ in the purely coaxial case:

$$\Omega_0(\xi,1) = \mathrm{J}_0(\xi) - \frac{\mathrm{J}_0(\xi\rho)}{\mathrm{N}_0(\xi\rho)}\mathrm{N}_0(\xi) = 0, \tag{9a}$$

and expression (8) transforms into an equation

$$n(X,\varphi) \propto \Omega_0(\xi, X). \tag{9b}$$

Therefore, it is reasonable to assume that in the eccentric case for small deviations from the coaxial one, i.e., when a value is small, but finite ($a << 1$), we could take a finite number of terms M in the sums (8) and (9) to obtain an approximate solution of (1)[1]:

$$n(X,\varphi) \approx \sum_{k=0}^{M-1} C_k \cos(k\varphi)\Omega_k(\xi,X), \tag{10}$$

$$\sum_{k=0}^{M-1} C_k \cos(k\varphi_R)\Omega_k(\xi, X_R) = 0. \tag{11}$$

Next, suppose M rays come from the origin O at angles

$$\varphi_j = \pi j/(M-1),\ \ j = 0, 1, \ldots, (M-1)$$

and divide the upper semi-circumference of the inner circle $X = \rho$ into $M - 1$ identical sectors. These rays cross the upper semi-circumference in the points with a reduced radial coordinates (see Eq. (7)):

$$X_j = \sqrt{1 - a^2\sin^2\left(\frac{\pi j}{M-1}\right)} - a\cos\left(\frac{\pi j}{M-1}\right), \tag{12}$$

including the points on X axis for $\varphi = 0, \pi$.

To find an approximate solution, let us demand satisfaction of zero boundary conditions (6) not in all of points of the outer semi-circumference, but only in M of its upper points $\{X_j, \varphi_j\}$. Since the above boundary conditions are satisfied in its symmetrically located lower points by default, these zero conditions are finally satisfied in ($2M - 2$) points on the entire outer semi-circumference. Then expression (11) transforms into the following:

$$\sum_{k=0}^{M-1} C_k \cos(k\varphi_j)\Omega_k(\xi, X_j) = 0; \quad j = 0, 1, \ldots, M-1, \tag{13}$$

which is a homogenous system of linear algebraic equations (linear system) having square matrix $M\times M$ with respect to a finite number M of coefficients C_k.

For the solution of system (13) to be non-trivial, its determinant must equal zero. From here we can find approximate values of the first M eigenvalues of problem (1). As function $n(X,\varphi)$ describing the density should never be less than zero between the circles (i.e. in the space occupied by the discharge plasma), only the eigenfunction corresponding to the smallest eigenvalue will have physical sense. It is the one we further substitute into Eq. (13).

Due to homogeneity of Eq. (1), its solution can be calculated up to a constant factor only. Therefore, we can compute coefficients C_k in relative units, assuming, for example, $C_0 = 1$. Then, the matrix column of linear system (13) that contains $C_0 = 1$ is moved to the right-hand side of the linear system. Thus, system (13) is transformed from a homogenous into a inhomogeneous, but overdetermined linear system containing M equations and ($M - 1$) unknown coefficients C_1, C_2, ..., C_{M-1}, which numerical values can be computed using the method of least squares.

The calculation showed that the values of coefficients C_k quickly decrease with the growth of k, so when $a \le 0.2$ and $\rho \le 0.5$, this proves the validity of the assumption that finiteness of the number of terms (10) and (11) brings no significant error in the solution of $n(X,\varphi)$. Fig. 2 demonstrates the quality of fulfillment of boundary conditions (9) for seven and two points of the upper semi-circumference and, re-

[1] The validity of this assumption is proved in further calculations.

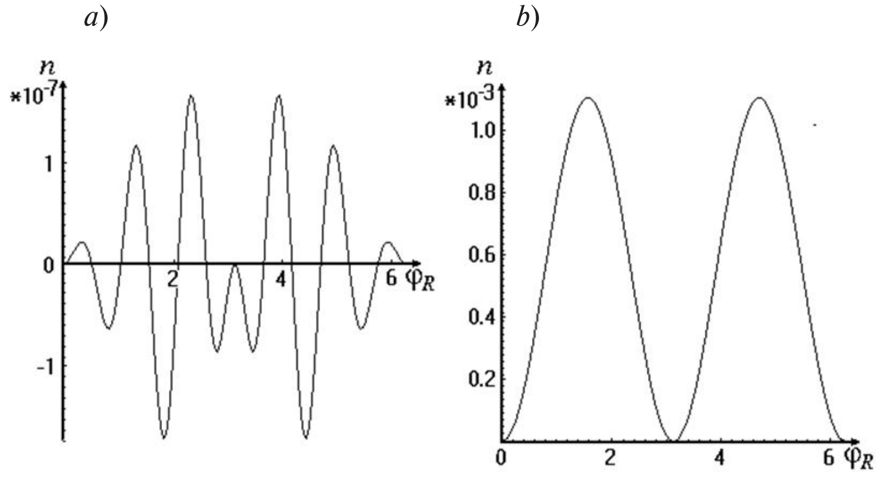

Fig. 2. Graphs of fulfillment of boundary conditions (9) at the outer circle if they are established exactly in ($2M-2$) points of the border; the cases presented are for $M = 7$ (*a*) and 2 (*b*); function $n(X,\varphi)$ at the maximum is assumed to be equal to 1

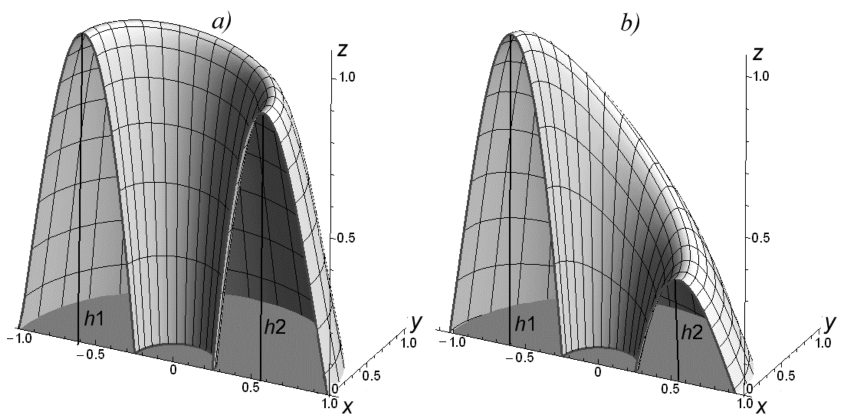

Fig. 3. 3D-distributions of function $n(X,\varphi)$ in the upper semi-circumference, i.e. when $y \geq 0$ (see Fig. 1) for the eccentricity values $a = 0.01$ (*a*) и 0.04 (*b*); reduced radius of the inner wall

spectively, for seven and two terms of sum (10). It can be seen that despite the small amount of points, boundary conditions (9) have satisfactory fulfillment at the entirety of the outer border: a difference in the solutions of $n(X,\varphi)$ for seven and two terms of (10) turns out to be inessential, and in the eigenvalues – in the third decimal place.

After calculating coefficients C_1, C_2, ..., C_{M-1} variable $n(X,\varphi)$ is normalized to 1 at the maximum, while values C_0, C_1, ..., C_{M-1} are recalculated once more.

Calculation results

Fig. 3 presents examples of solutions according to the described procedure.

We should note the high sensitivity of the form of $n(X,\varphi)$ to eccentricity: there is a considerable inhomogeneity of $n(X,\varphi)$ by the angle even at small values of a (see Fig. 3). The greater ρ, the stronger the inhomogeneity at the same value of a. Quantitatively it can be characterized by a ratio between the minimum and the maximum values of function $n(X,\varphi)$ on the "ridge" (see Fig. 3). A graph of this ratio $h2/h1$ vs a is shown on Fig. 4, *a*.

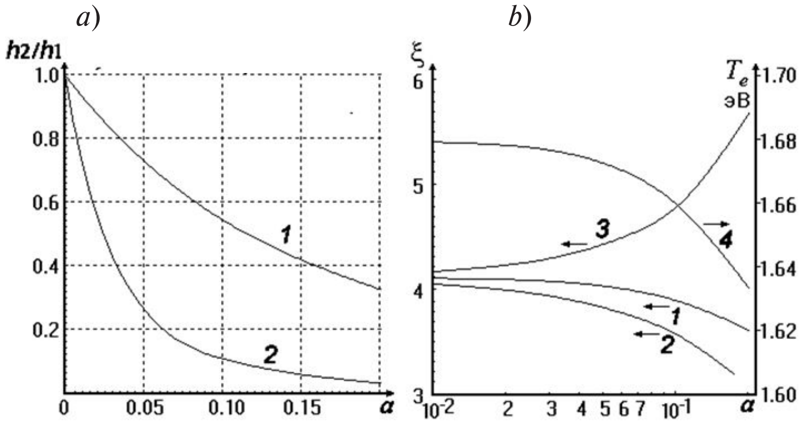

Fig. 4. Dependencies of the ratio $h2/h1$ (*a*), as well as eigenvalues ξ and plasma electron temperature T_e (*b*) on the eccentricity *a* of the gas-discharge tube.
Ratio $h2/h1$ (see Fig. 3) shows inhomogeneity of $n(X,\varphi)$ when $\rho = 0.05$ (*1*) and 0.25 (*2*). We also present diagrams of eigenvalues for eccentric (*1*) and coaxial (*2*, *3*) cases with gaps $1 - \rho + a$ (*2*) and $1 - \rho - a$ (*3*); value of T_e (*4*) is calculated for Ar plasma at the pressure of 1 Torr and $R = 1$ cm for the eccentric case

Discussion of results

In the coaxial case, the width of the gap between the walls $b = 1 - \rho$ is constant and does not depend on φ. Due to central symmetry, in the coaxial case there is no other direction of the orthogonal to the current diffusion flow, except for the radial one.

The eigenvalue $\xi = R\sqrt{\nu_i/D_A}$ determines the value of temperature T_e, which in the case under consideration (low pressure)is constant across the whole positive column cross-section and corresponds to the equality of the rates of electrons production by direct ionization in the volume and their losses due to ambipolar diffusion to the walls in the radial direction [9, 10]. If we know the eigenvalue ξ, we can estimate the value of T_e both for the coaxial and eccentric discharge geometry using the following expression:

$$\xi = 8191CpR\sqrt{1+\frac{1}{2}\frac{W_i}{T_e}}\sqrt[4]{\frac{T_e}{W_i}}\exp\left(-\frac{1}{2}\frac{W_i}{T_e}\right),$$

where W_i, eV, is ionization potential of gas atom; p, Torr, is gas pressure; R, cm, is radius of the outer wall; C is a constant, which values are tabulated in papers [9, 10] for various gases.

We deduced the presented expression in this paper using the relation obtained in papers [9, 10] which connects the value T_e with the tube radius and gas type for the cylindrical geometry of the positive column of glow discharge in diffusion mode.

For the eccentric case in the considered conditions of positive column, the value of T_e for small eccentricity has only weak deviation from the ideal coaxial case. An example of dependence of T_e on a for an Ar discharge at $p = 1$ Torr, $R = 1.00$ cm and $R_1 = 0.25$ cm is shown in Fig. 4,*b* (curve *4*). The value of T_e decreases only insignificantly from 1.68 eV at $a = 0$ (coaxial geometry) down to 1.63 eV, when eccentricity $a = 0.2$. Let us note that, for the cylindrical geometry in the same conditions, the value of T_e would only amount to 1.51 eV.

In an eccentric discharge, the value of T_e also remains constant in the volume of positive column, which means that the ionization rate is constant in the entirety of the volume. However, the width of the gap between the walls b at $a > 0$ does not remain constant with the change of the angle φ. It changes from $b_{min} = 1 - \rho - a$ at $\varphi = 0$ to $b_{max} = 1 - \rho + a$ at $\varphi = \pi$ (see Fig. 1), therefore the rate of radial diffusive removing should depend on the angle φ: it should be maximal at b_{min} and minimal at b_{max}. The calculations show that the eigenvalue ξ for $a > 0$ (see Fig. 4,*b*, curve *1*) has intermediate value between

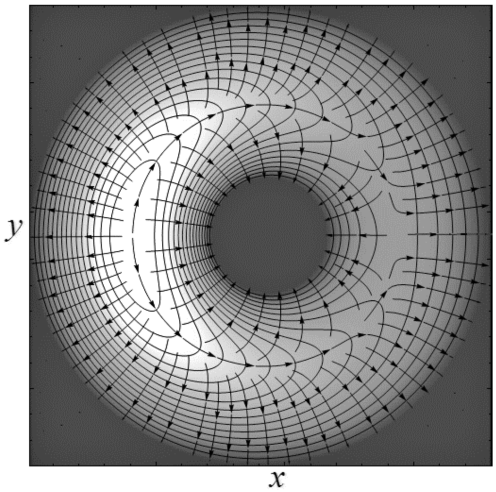

Fig. 5. Spatial distribution of $n(X,\varphi)$ (expressed by brightness and contours), as well as directions of electron flows in plasma cross-section (arrowhead lines) in eccentric discharge geometry for $\rho = 0.25$ and $a = 0.04$. The "compensating" flow goes in azimuthal direction over the ridge of the $n(X,\varphi)$ distribution

the ones for two control coaxial cases: with the gaps equal to b_{max} and b_{min} (curves *2* and *3*, respectively). This means that for the eccentric case, in the neighborhood of angle $\varphi \approx 0$ (where the gap is the narrowest) the ionization rate turns out to be insufficient to compensate for the radial diffusive removing of the particles to the walls, while in the area of $\varphi \approx \pi$ (widest gap) it is excessive.

This result should lead to the following effects:

firstly, to increasing of electron (and ion) density and its gradient in the neighborhood of widest gap, and to decreasing of the said parameters in the narrowest gap in comparison with the coaxial case $a = 0$, i.e. to the occurrence of azimuthally inhomogeneous distribution of $n(X,\varphi)$ (see Fig. 3);

secondly, for the density distributed in this manner, there is an azimuthal gradient $\mathrm{grad}_{\varphi}[n(X,\varphi)]$ and a corresponding diffusion electron flow in the azimuthal direction that "pumps" the electrons from the wide gap into the narrow one on both sides of the inner wall (Fig. 5). This flow compensates for the excessive generation of electrons in the wide gap, as well as the extra electron losses due to diffusive removing to the walls in the narrow gap; by such a way the balance of charged particles can be throughout ensured. However, the inhomogeneity of $n(X,\varphi)$ from the angle φ still remains, since the said flow compensating for the imbalance of the rates of production and decay of charged particles in different areas of positive column cross-section can take place only in the presence of the azimuthal density gradient. It is necessary to note that the presence of a gradient of electron densities directed on average from the narrow gap to the wide one will cause a constant electric field directed on average along x axis. It should retard the described electron diffusion in the azimuthal direction to the ambipolar one.

Conclusion

Summing up, the absence of central symmetry of the spatial distribution of the positive column plasma density in the eccentric discharge geometry can be considered as a characteristic feature of plasma in this geometry, which is in fact responsible for maintaining the charged particles balance of plasma in the entire volume dedicated to it. Insignificant eccentricity has only little impact on the value of electron temperature T_e. However, to retain acceptable azimuthal homogeneity of the discharge after the transition from the cylindrical to coaxial geometry, it is necessary to provide good accuracy of the gas-discharge device manufacturing: the distance between the axes of the inner and the outer cylindrical walls should not exceed 1–2% of the width of the gap between the walls.

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