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Characterizing uniform discharge in atmospheric helium by numerical modelling*

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One-dimensional fluid model of dielectric barrier discharge (DBD) in helium at atmospheric pressure was established and the discharge was numerically simulated. It was found that not only the spatial distributions of the internal parameters such as the electric field, the electron density and ion density are similar to those in a low-pressure glow discharge, but also the visually apparent attribute (light emission) is exactly the same as the observable feature of a low-pressure glow discharge. This confirms that the uniform DBD in atmospheric helium is a glow type discharge. The fact that the thickness of the cathode fall layer is about 0.5 mm, much longer than that of a normal glow discharge in helium at atmospheric pressure, indicates the discharge being a sub-normal glow discharge close to normal one. The multipulse phenomenon was reproduced in the simulation and a much less complicated explanation for this phenomenon was given.

Keywords: dielectric barrier discharge, atmospheric pressure glow discharge, glow discharge, numerical simulation

PACC: 5280H, 5280, 5150, 5265

1. Introduction

Dielectric barrier discharge (DBD) is generated by covering at least one of the metallic electrodes in a parallel-plate assembly with a dielectric material and applying a sufficiently large alternating voltage to the electrodes.[1] A large number of randomly distributed transient filaments (streamers) are usually observed in DBD at atmospheric pressure. However, a spatially uniform DBD at atmospheric pressure could be obtained under specific conditions.[2,3] These uniform discharges are often called atmospheric pressure glow discharge (APGD), whatever they are. It is difficult for people to distinguish a uniform discharge from a filamentary discharge by observation of the discharge with naked eyes or with the photographs of an exposure time as long as milliseconds. Indeed, too long an observation time may lead to the integration of the light from numerous discharge filaments with development time of some nanoseconds, giving the illusion of a uniform discharge.[4] Okazaki *et al*[5] proposed the observation of the Lisajous figure of voltage-charges and of the current pulse shapes as a method of distinguishing between a uniform discharge and a filamentary discharge. Massines *et al*[6] believed that the best way to be sure that the discharge filaments do not develop is to take a picture with 10 ns exposure time. Even in the case of a really uniform discharge it is necessary to distinguish a Townsend discharge from a glow discharge. As is well known, a glow discharge at low pressure has the distinctively observable features.[7] From the cathode to the anode a glow discharge normally manifests a stratification into dark and bright layers, i.e., a highly luminous layer called negative glow, a dark layer called Faraday dark, and a weakly luminous layer called positive column. In our previous paper we reported the observation of the transition from a Townsend discharge to a glow discharge in helium at atmospheric pressure by taking pictures with an exposure time of 20 ns.[8] Being responsible for the observable features, the intrinsic features of a glow discharge consist of a cathode layer of a strong field that corresponds to a considerable potential drop known as cathode fall, and a positive column that is a region of electrically neutral plasma with fairly weak field. Since the parameters such as the electric field, the electron density and ion density in the atmospheric plasma are difficult to measure with the commonly used diagnostic

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techniques for the plasmas produced at low gas pressure, much effort has been made to determine these parameters by numerical modelling.[9−17] In this article one-dimensional fluid model of DBD in helium at atmospheric pressure is established and the discharge numerically simulated. Although similar simulations have been performed by other groups, so far as we know none of them is so closely as us to connect the simulation results with the experimental ones. By this way, we show that the discharge is a subnormal glow discharge. In addition, the multipulse phenomenon is reproduced in the simulation and a much less complicated explanation for this phenomenon is given.

2. Model

We consider a uniform DBD in atmospheric helium produced with the same electrode assembly as that used in Ref.[8], i.e., a 5-mm gas gap between two 1-mm thick quartz plates covering two plane-parallel electrodes of 50 mm in diameter. Since the diameter of the electrodes is much larger than the length of the gas gap, a one-dimensional model could, in principle, be used to describe the uniform discharge.

Our model includes the self-consistent solution of Poisson equation for the electric field, the continuity and momentum equations for the electrons and ions. The kinetic description in the model is very simple as only atomic helium ions and electrons are taken into account. The impurities as well as their Penning ionization by helium metastables are neglected for simplicity. By using the drift-diffusion approximation, we obtain the governing equations as follows.

$$\frac{\partial E}{\partial x} = \frac{e}{\varepsilon_0} \cdot (n_\mathrm{i} - n_\mathrm{e}), \tag{1}$$

$$\frac{\partial n_\mathrm{e}}{\partial t} - \frac{\partial}{\partial x}\left(n_\mathrm{e}\mu_\mathrm{e}E + D_\mathrm{e}\frac{\partial n_\mathrm{e}}{\partial x}\right) = G - L, \tag{2}$$

$$\frac{\partial n_\mathrm{i}}{\partial t} + \frac{\partial}{\partial x}\left(n_\mathrm{i}\mu_\mathrm{i}E - D_\mathrm{i}\frac{\partial n_\mathrm{i}}{\partial x}\right) = G - L, \tag{3}$$

where E is the electric field, n the number density, μ the mobility, and D the diffusion coefficient. The subscript e and i denote electron and ion; G and L are the generation term and loss term, respectively

The loss term L is determined by the electron-ion recombination with a rate coefficient β, i.e., $L = \beta \cdot n_\mathrm{e} \cdot n_\mathrm{i}$. The generation term could be calculated with the formula

$$G = \alpha \cdot \mu_\mathrm{e} \cdot E \cdot n_\mathrm{e} + G_0, \tag{4}$$

where α is the rate coefficient of the direct electron impact ionization, G_0 is generation rate of the volume photoionization by cosmic rays and γ rays from the radioactive substances in the earth. According to the measurements by Chinese Academy of Radiation Protection, we have $G_0 = 4.95{\cdot}\mathrm{cm}^{-3}{\cdot}\mathrm{s}^{-1}$ in atmospheric helium in Beijing area.

Most of the data for transport parameters and reaction rate are taken from the literature and listed in Table 1.

Table 1. Summary of rate coefficient.

Process	Value of rate coefficient	references
electron mobility	$\mu_\mathrm{e} = \dfrac{0.86\times10^6\mathrm{cm}^2\cdot\mathrm{Torr}\cdot\mathrm{V}^{-1}\cdot\mathrm{s}^{-1}}{p} = 1.132\times10^3\cdot\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$	[7] p.11
ion mobility	$\mu_\mathrm{i} \approx 10\cdot\mathrm{cm}^2\cdot\mathrm{V}^{-1}\cdot\mathrm{s}^{-1}$	[7] p.26
electron diffusion	$D_\mathrm{e} = \dfrac{kT_\mathrm{e}}{e}$, $\mu_\mathrm{e} = 1.132\times10^3\mathrm{cm}^2/\mathrm{s}$ when kT_e=1 eV	[15]
ion diffusion	$D_\mathrm{i} = \dfrac{kT_\mathrm{i}}{e}$, $\mu_\mathrm{i} = 0.52\times10^2\mathrm{cm}^2/\mathrm{s}$ when kT_i=0.052 eV	[15]
$\mathrm{He}^+ - \mathrm{e}$ recombination	$\beta = 10^{-7}{\cdot}\mathrm{cm}^3/\mathrm{s}$	[18]
secondary electron emission	$\gamma = 0.1$	[15]
electron direct impact ionization	$\alpha = A\cdot p\exp\left[B\,(p/E)^{1/2}\right]$	[7] p.56
	$A = 4.4\mathrm{cm}^{-1}\mathrm{Torr}^{-1}$, B= 14V/(cm·Torr)$^{1/2}$	

The boundary conditions for Poisson equation are given in terms of the electric field at the interface between the gas gap and the dielectric barrier.

$$\varepsilon_\mathrm{r}\varepsilon_0 \cdot E_\mathrm{dielectric} + \sigma_0 = \varepsilon_0 \cdot E_\mathrm{plasma}, \tag{5}$$

where σ_0 is the surface density of charges deposited on the dielectric surface, ε_0 and ε_r are the vacuum permittivity and the relative permittivity of the dielectric barrier, respectively. In our case ε_r is about 3.8 for the

quartz plate.

As for the boundary conditions for the continuity equations, the secondary electron emission from the dielectrics through ion impact was taken into account. As a result of the charge deposited on the dielectric surface, the voltage boundary conditions can be derived by considering an equivalent circuit in which the equation capacitor of gas gap is in series with the equivalent capacitor of the dielectrics.

The initial conditions for n_e and n_i at the time $t = 0$ was determined to be $n_e(x,0) = n_i(x,0) = n_0 = 7 \times 10^3/\mathrm{cm}^3$ by using the formula $G_0 = \beta \cdot n_0^2$, which means that the production of the charged particles due to the background radiation is balanced by the electron-ion recombination, leading to a constant number density of the seed electrons uniformly distributed in the gas gap before the voltage is applied to the electrodes.

Based on the finite differential method and Newton iteration method, the equations were numerically solved. The charged particle fluxes are approximated using the Scharfter–Gummel scheme.[19]

3. Results and discussion

In the experiment of DBD, the applied voltage, V_a, and the discharge current, i_d, are the only electrical parameters that can be directly measured. However, the voltage applied to gas gap, V_g, could be calculated by using the following formulas:[14]

$$V_g(t) = V_a(t) - V_m(t), \tag{6}$$

$$V_m(t) = \frac{1}{C_{quartz}} \int_{t_0}^{t} i_d(t) \cdot dt + V_m(t_0), \tag{7}$$

where C_{quartz} is the equivalent capacitance of the quartz plates, and V_m the voltage due to the charges deposited on the quartz plates.

In order to check the validity of the established model and the numerical method, it is better to make a comparison between the experimental and numerical results of the electrical parameters. Figure 1 shows such a comparison.

The numerical simulation was performed under the same discharge conditions as that of the experiment in which an alternating voltage with a frequency of 30 kHz and amplitude of 1300 V is applied to the electrodes. In both cases a single current pulse with a pulse width of 1–2 μs and an amplitude of about 32 mA is observed per half-cycle of the applied voltage. Furthermore, the breakdown appears at a gap voltage of about 1.1 kV in both cases. Since the numerical results of the electrical parameters agree very well with the experimental ones, the validity of the established model and the numerical method is verified.

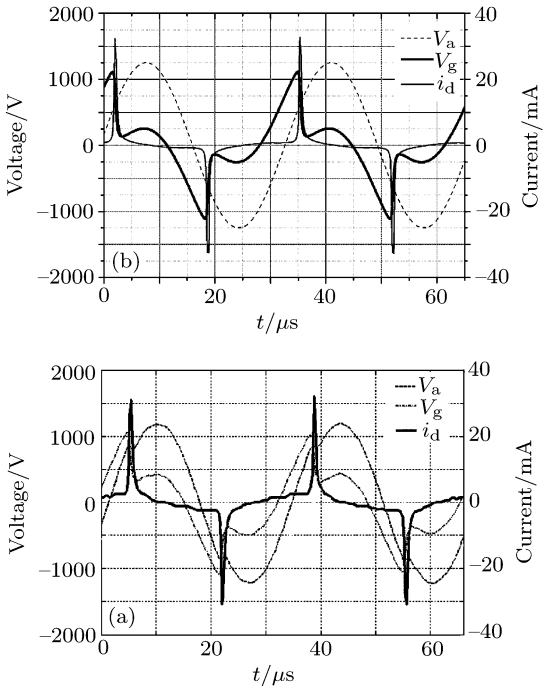


Fig.1. Comparison between the experimental and numerical results of the electrical parameters, (a) results from simulation, (b) results from experiment.

The spatial distribution of the electric field as well as the electron and ion densities are presented in Fig.2. Figure 2 (a) shows the numerical results obtained at the time when the discharge current is maximal. As comparison, Fig.2(b) shows the distributions of the same parameters in a low-pressure glow discharge.[7] In both cases the cathode is on the left.

In Fig.2(a) the whole gap from the cathode to the anode could be divided into three specific regions. The first region is the cathode fall layer, a high field region in which the maximum field reaches a value slightly below 10 kV/cm. In this region the ion density peaks to $1.9 \times 10^{11} \cdot \mathrm{cm}^{-3}$. It is this high ion density close to the cathode that makes the cathode fall layer a high field region. The thickness of the cathode fall is about 0.5 mm. The second region corresponds to negative glow and Faraday dark. In this region the electric field is very weak in the boundary to the cathode fall layer and increases linearly with the distance from the cathode until reaching a constant value about 1 kV/cm. The extension of this region is 2.5 mm. The last region is the positive column, a region of electrically neutral plasma with a constant field of about

1 kV/cm and $n_e = n_i \approx 10^{10} \cdot \mathrm{cm}^{-3}$. The thickness of this region is about 2 mm.

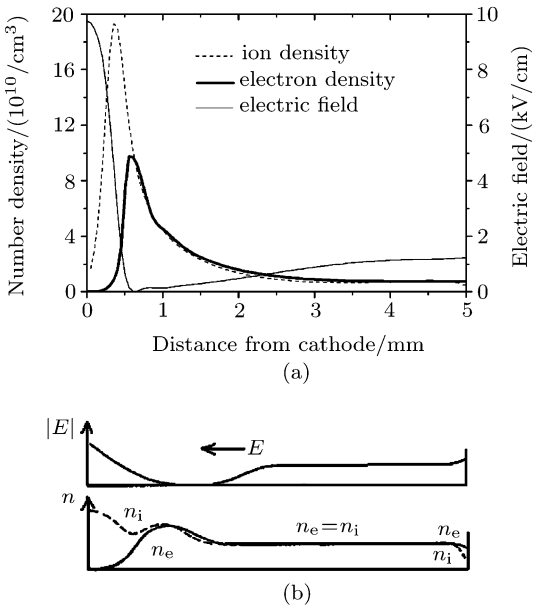


Fig.2. Spatial distribution of the electric field as well as the electron and ion densities. (a) Results from the numerical simulation of a uniform DBD in atmospheric helium. (b) Results of a low-pressure glow discharge.

Figure 3 is the discharge photograph of atmospheric helium taken at the time when the discharge current is maximal. The whole gap from the anode to the cathode could be divided into three layers: a weak luminous layer, followed by a relatively dark layer, and finally a highly luminous layer. This is exactly the same structure as that of low-pressure glow discharge in which these three layers are, respectively, called positive column, Faraday dark space, and negative glow.

From Figs.2 and 3 it is clear that not only the spatial distributions of the internal parameters are similar to that of a low-pressure glow discharge, but also the visually apparent attribute (light emission) is exactly the same as the observable feature of a low-pressure glow discharge. This confirms that the uniform DBD in atmospheric helium is a glow type discharge.

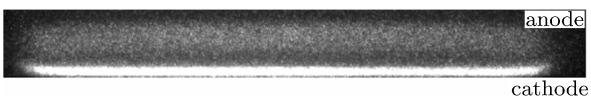


Fig.3. Discharge photograph of atmospheric helium taken at the time when the current is maximal.

Just as what had been found in the experiment,[8] it was noticed from the results of the simulation that the thickness of the cathode fall layer was about 0.5 mm, much longer than 0.07 mm, the thickness of the cathode fall layer for a normal glow discharge in helium at atmospheric pressure. It could be concluded that the glow-like DBD in helium at atmospheric pressure is a sub-normal glow discharge close to normal one. The reason for this is that the dielectric barrier quenches the discharge before the normal glow discharge is reached.

Figure 4 presents the temporal and spatial evolutions of the electric field, the electron density and ion density during a time about a half cycle of the applied voltage. The electric field peaks at the cathode region forming a cathode fall only for a short time about 1 μs, corresponding to the time of discharge pulse. As the dielectric is charged up, the gas voltage decreases, leading to the decrease of the field in

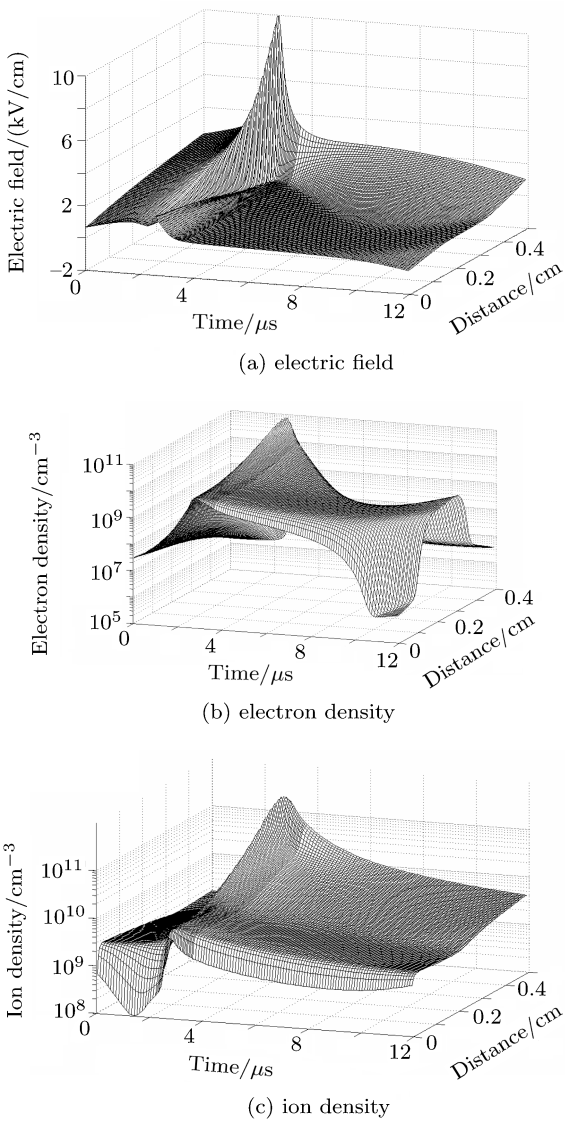


Fig.4. Temporal and spatial evolutions of the electric field, the electron density and ion density during a half cycle of the applied voltage.

the cathode fall. It is important to find that the electron density in the gap before discharge is in the range of $10^6 - 10^7 \mathrm{cm}^{-3}$. This considerable amount of electrons may work as seed electrons for the next discharge to initiate at low electric field, which is crucial for gaining a uniform discharge rather than a filamentary discharge.

As was observed in our experiment, the multipulse effect also existed in our simulation. When the amplitude of the applied voltage slightly exceeds the breakdown voltage of the helium gap, the current waveform shows a single pulse per half cycle of the applied voltage. An increase in the amplitude of the applied voltage leads to a sudden appearance of a second current pulse. Further increasing the voltage may also bring about a third current pulse. This phenomenon is usually called 'multipulse effect'. It has been observed in experiments[20−22] or in simulations,[13,22,23] and different interpretations in connection with the effect have been given. While Akishev *et al*[22] attributed it to a negative differential resistance in the cathode fall region of the discharge, Golubovskii *et al*[22] suggested that a lag between the production of ions and resonant atoms nearby the anode and following photo- or ion-electron emission at cathode is responsible for the multipulse effect. From

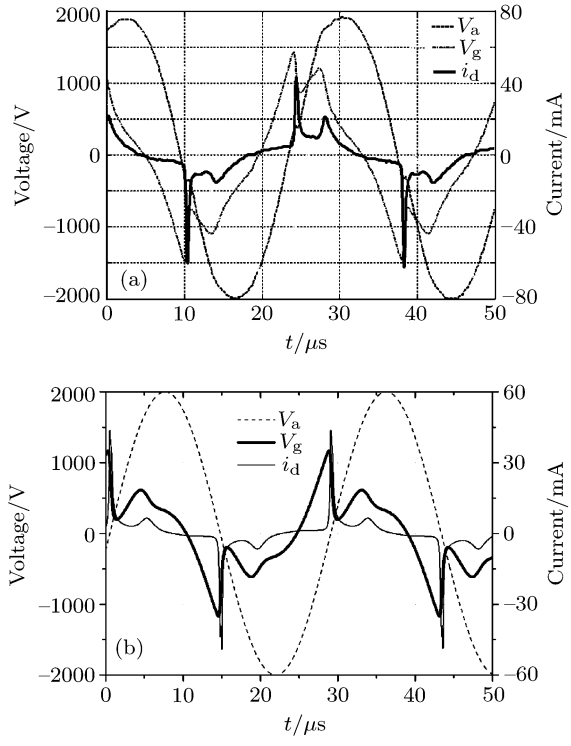


Fig.5. Observation of double current pulses at an applied voltage of 20 kV in amplitude, (a) results from the experiment, (b) results from the simulation.

the results of our simulation as well as experiment, as shown in Fig.5, we believe that both Akishev and Golubovskii *et al* have made a simple thing complicated.

It is well known that DBD works in such a way that when the dielectric considered as a capacitance is charged up by the discharge current and thus reduces the gas voltage to a great extent, the discharge turns off. Thereafter, the gas voltage will increase as the applied voltage increases. If the amplitude of the applied voltage is high enough, a second breakdown will happen, leading to the appearance of the second current pulse. This is just what we can be observed in Fig.5.

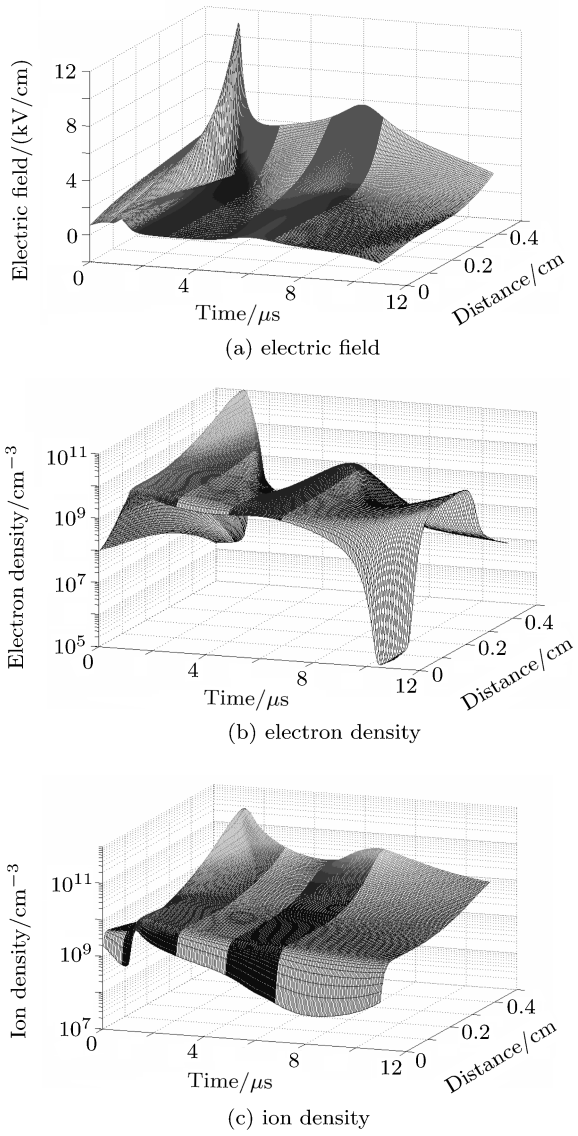


Fig.6. Temporal and spatial evolutions of the electric field, the electron density and ion density during a half cycle of the applied voltage in the case of double current pulses.

From Fig.5 we can see that the second breakdown voltage of the gas gap as well as the amplitude of the

second current pulse is much lower than the first one. This phenomenon could be easily explained with the simulation results shown in Fig.6. The time lag between the first and the second current pulses is about 5 μs, so short that a large amount of charged particles produced in the time of the first current pulse are still in the gas gap. The electron density before the second breakdown is in the range of $10^8 - 10^9 \mathrm{cm}^{-3}$, two orders higher than that before the first breakdown. It is this much more electrons as seed electrons that makes the second breakdown occurring at a field slightly below 6 kV/cm, much lower than 11 kV/cm for the first breakdown. Since the second current pulse develops at a much lower electric field, the amplitude of the current pulse should be much lower.

4. Conclusions

Since the numerical results of the electrical parameters agree very well with the experimental ones, the validity of the established model and the numerical method is verified. Not only the spatial distributions of the internal parameters such as the electric field, the electron density and ion density are similar to that of a low-pressure glow discharge, but also the visually apparent attribute (light emission) is exactly the same as the observable feature of a low-pressure glow discharge. This confirms that the uniform DBD in atmospheric helium is a glow type discharge. The fact that the thickness of the cathode fall layer is about 0.5 mm, much longer than that of a normal glow discharge in helium at atmospheric pressure, indicates that the discharge is a sub-normal glow discharge close to normal one. The multipulse phenomenon can be reproduced in the simulation and a much less complicated explanation for this phenomenon has been given.

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