STUDY ON SIMILARITY OF GLOW DISCHARGE AT LOW PRESSURE BY NUMERICAL SIMULATION

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ABSTRACT

The similarity law was not always valid because of the occurrence of the forbidden processes (e.g. stepwise ionization, charge exchange) for which the similarity law might be violated. In order to exam the validity of the similarity relations of low pressure glow discharge,a fluid model of gas discharge was established with the forbidden processes. The dimension ratio of the gap A and B was set at 2:1, the pressures for the gap A and B were 60Pa and 120Pa, respectively. The discharge parameters (such as electric potential, electric field, space charge density, electron density and ion density) in two geometrical similar gaps were comprehensively investigated. The simulation results indicated that the discharge was identified as a typical glow discharge. The impact of the forbidden processes caused small deviations, but was not significant in our case. The physical parameter relations of the two similar gaps were found to be in agreement with the theoretical ones derived by the similarity law.

1.INTRODUCTION

The similarity law was first noticed by Townsend in 1915 and was extended later by Holm to account for the maintenance of current between geometrically similar electrodes [1-2]. The similarity law represents a useful tool in the analysis of gas discharge since it can help us to use known properties of the discharge at one pressure to extrapolate features of discharges at many pressures of interest[3]. In gas discharge physics, the product of the electric field strength ***E*** and the electron mean free path λ expresses the energy gained by the electron between two consecutive collisions, and the product of pressure *p* and the gap length *d* is proportional to the number of collisions between electrodes. Therefore, if the scaling factors ***E***/*p* and *pd* are kept constant, the electron multiplication can be fixed and the similar discharges at different pressure *p* will be obtained. Many recent studies have been reported in the literature regarding the application of similarity law [4-6]. However, the similarity relations are not always valid because of the occurrence of the forbidden processes in discharges [7]. If the influence of the forbidden processes on the similarity law is not noticeable, the similarity relations will still be valid for the similar gaps. The deviations caused by the forbidden processes are necessary to be examined.

In this paper, many physical parameters were obtained based on a fluid discharge model in which the discharge processes, such as the elastic, ionization at single collision, excitation, and the stepwise ionization, were included. Discharges in similar gaps were both identified as glow discharges. Relations of the physical parameters(e.g. electric potential, electric field, space charge density, electron density and ion density) of two similar gaps were all checked. Similarity relations of glow discharge by numerical simulation were found to be in agreement with those derived by similarity law.

2. MODEL

Two parallel plane electrodes are shown in Fig.1 where U_S is the DC voltage source, *I* is the discharge current, *U* is the voltage drop of the discharge gap, *R* is the ballast resistor. For gap A, d＝20cm, r=10cm, p＝60Pa, and for gap B, d＝10cm, r＝5cm, p=120Pa. The dimensional ratio of the two gaps is 2. The line o_1-o_2 is central axis and the line a-b indicates a gas boundary.

As a preliminary study, argon was chosen as the working gas for simplicity. Three type particles were considered, such as the atom Ar, excited argon atom Ars and ion Ar^+. The processes of elastic, excitation, and ionization were included in the model. In the gaps,the plasma reactions are R1:e+Ar→e+Ar; R2:e+Ar→e+Ars; R3: e+Ar→2e+Ar^+; R4:e+Ars→2e+Ar^+. All the reaction rates are calculated with the cross sections by electron impact in Fig.2.

At the cathode, the secondary electron emission is the main mechanism sustaining the glow discharges. The secondary electron emission coefficient γ was set as 0.1 [8]. The cathode material is assumed as iron and the work function is 4.48J. For the gas boundary a-b in Fig.1, we assumed zero gradient boundary condition for electrons. The excited argon atoms Ars and ions $Ar^+$are absorbed due to the surface reactions:Ars→Ar and Ar^+→Ar. The gas temperature T was set to 300K since the low pressure glow discharge approximates to the room temperature. The number density of the primary electron before discharge was assumed as $10^7 cm^{-3}$. The U_S was chosen as 250V and the ballast resistors R=100kΩ for the two gaps. The parameter relations of the similar gaps from the simulation results were compared with the similarity relations listed in Table 1.

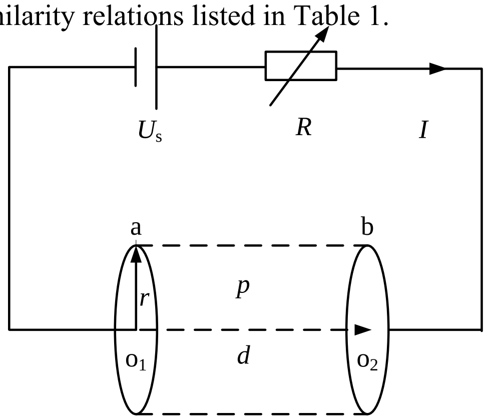


Fig. 1 Schematic of the discharge gaps

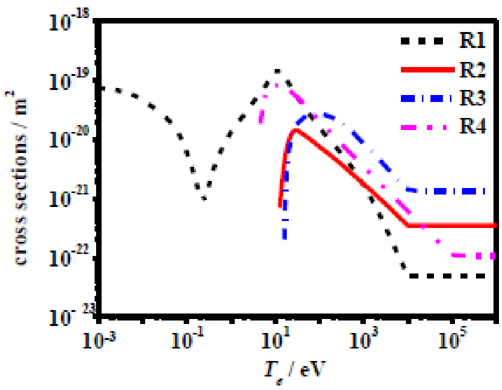


Fig. 2Cross sections of argon by electron impact

Table 1 Typical similarity relationsof the discharge parameters [1-2, 7]

No	Parameter	Similarity Relation
SL1	Electric potential	$U_1=U_2$
SL2	Electric field	$E_1=E_2/k$
SL3	Ion density	$N_{i1}=N_{i2}/k^2$
SL4	Electron density	$N_{e1}=N_{e2}/k^2$
SL5	Charge density	$\rho_1=\rho_2/k^2$

3. RESULTS AND DISCUSSION

The distributions of the electric potential along the axis px (Pa.m) were shown in Fig.3. The position, px=0, indicates the cathode and px=20 was the anode. It was found that the cathode voltage drop was 119V in the gap A and 117V in the gap B. In both cases, there is an obvious voltage drop region near the cathode (px=0). The voltage drop region is usually called as cathode fall layer which is a typical feature of glow discharge. According to the theory of glow discharge, the length of the cathode fall layer is constant once the gas type and cathode material are selected. In order to check the validity of the simulation results, the voltage drop from the simulation was compared with the experimental measurements. According to the experimental results in Ref.[9] , the cathode voltage fall is about 165 volts for argon glow discharge with iron cathode and the corresponding length of cathode fall layer, pdc, is about 0.44 Pa.m. The cathode voltage fall of the simulation in our case was about 135 volts, and the pdc was about 0.588Pa.m. The calculation results were approximate to the experimental ones. Since many complicate factors impact on the gas discharge processes, the simulation results were often not exactly the same with the experimental data. It was considered that the simulation results are believable.

In Fig.3, the values of pd_C in the similar gaps were almost the same.The voltage of the gap A and B are 158.8 volts and 155.5 volts, respectively. The distributions of the electric potential in the similar gaps were in good agreement similarity relation SL1 in Table 1.

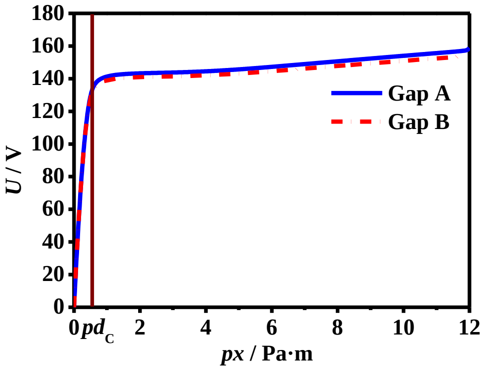


Fig.3 Distributions of electric potential along the axis px between similar gaps

The parameter relation of electric field between the similar gaps was check in Fig.3. In order to show the electric field relation clearly in the similar gaps, the reduced electric fields along the axis *px* were adopted. Near the cathode, the electric fields *E*/*p* ($V\cdot m^{-1}\cdot Pa^{-1}$) both reached the maximum of 4.11. Apart from the cathode, the electric fields decreased linearly, which is in consistent with the glow discharge theory in Ref.[9]. It was pointed out that the distribution of the electric field is very similar with the electric field distribution in a plate shaped sheath. In the rest region of the gaps, the electric field value was very small, not zero. The reduced electric fieldincreased to 0.2 at the anode. The distributions of ***E***/*p* were almost coincident along the axis *px*, so the SL2, $E_1=E_2/k$, can be verified since the pressure ratio was 1:*k* in the similar gaps.

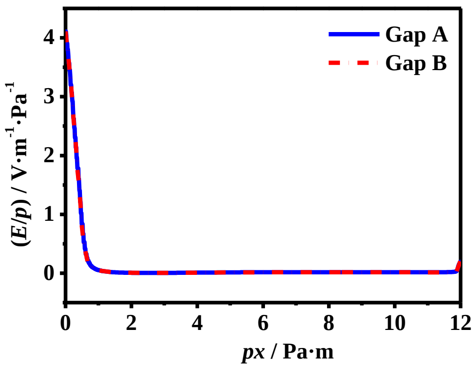
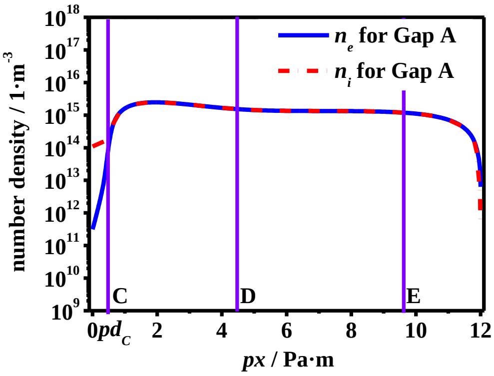
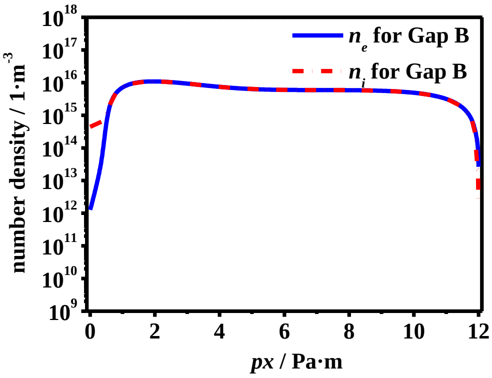


Fig.4 Distributions of electrical field along the axis between similar gaps

The electron and ion densities for Gap A and B were shown in Fig.5. Take gap A for example, the gas gap was divided into four sections in Fig.5. The first region is the cathode fall layer from *px*=0 to $px=pd_c$, in which the ion density was much larger than the electron density. The difference of the ion density and electron density formed a space charge region which we will show later. The second region CD is usually called the negative glow zone where the number densities of charged particle reach at the maximum. In this region, the excitation and ionization are very intense and the glow can be generated by excited atoms. In the section DE, the number densities of the electron and ion are identical and kept constant as *px* increased. The section DE is positive column which is one typical feature of glow discharge. The fourth part from E to the anode is called as anode zone where the electron density is greater than the ion density. The results were in accordance with the glow discharge simulation in Ref.[10].



(a) *Gap A*

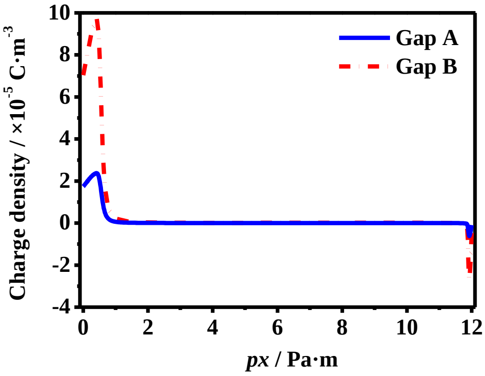


(b) *Gap B*

Fig.4 Spatial distributions of the electron and ion densities in the similar gaps

In order to check the parameter relations of the densities of the electron and ion, number densities in four positions were compared between gap A and B. For the electron distribution in gap A, densities in *px*=0,*px*=2,*px*=7 and *px*=12 were 3.15×10^{11}, 2.47×10^{15}, $1.34\times10^{15}$and 6.29×10^{12}. The electron densities for gap B at the corresponding positions were 1.27×10^{12}, 1.09×10^{16}, 5.92×10^{15}, and 2.64×10^{13}, respectively. The density ratios of the gap A and B were 1:4.03, 1:4.41, 1:3.95 and 1:4.20 in the four positions mentioned above. According to the comparing results, the electron density relations did not strictly obey the theoretical relations in Table 1. Similar results for ion were also obtained by comparison. The causes leading to the deviations of similarity relations were considered as the forbidden processes such as the stepwise ionization.

In glow discharges, the electric field near the cathode was often strengthened by the space charge.Distributions of the space charge density ($C\cdot m^{-3}$) in the similar gaps A and B were shown in Fig.4. The space charge density was positive near the cathode where the ion density is larger than the electron density. To the opposite, the space charge density near the anode was negative. The maximums of the positivespace charge densities near the cathode were 2.37×10^{-5} and 9.69×10^{-5} for gap A and B. The maximum values of the negative space charge densities near the anode were 6.19×10^{-6} and 2.68×10^{-5}. The ratios of the space charge densities were $1{:}k^2=1{:}4.09$ for the maximums of the positive charge and 1:4.33 for the negative ones between the gap A and B. The similarity relation SL5 was almost correct though the forbidden processes were included in the discharge processes.



4. CONCLUSIONS

The similarity law relations for glow discharge at low pressure were checked based on the numerical simulation method. The simulation results were verified with the experimental measurement and the discharge in the similar gaps was identified as glow discharge. The similarity relation of the electric potential and electric field were in good agreement with the theoretical relations SL1 and SL2. However, there are small deviations in similarity relations such as SL3 and SL4. The causes leading to the deviations from the theoretical relations were considered as the stepwise process which will violate the similarity law. The influence of the forbidden processes will be researched both theoretically and experimentally next.

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