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ANALYSIS OF ROTATIONAL MOTION OF DUSTY STRUCTURES IN A MAGNETIC FIELD

Abstract. This article presents the results of experiments on the effect of an external magnetic field created by the Helmholtz coil on the dust structures, which were suspended in the strata of a direct current glow discharge.Observations were carried out in three regions (between the coils (II region), under the coil (III region), and above the coil (I region)). An interesting behavior of dust structures in the stratum was discovered, which was not previously reported in similar works. The dust structure rotates clockwise above the coil and counterclockwise under the coil, while the dust structure located between the coils does not rotate.Monodisperse melamine formaldehyde particles were used as dust particles.The experimental data were processed using the PIV (particle image velocimetry) method at different magnetic field inductions in different areas.An interpretation was proposed that the rotation of dusty structures is due to the influence of the component of the Lorentz force arising from the axial component of the electric field and the radial component of the magnetic field.

Keywords: DC glow discharge, plasma, magnetic field, method of particle image velocimetry (PIV).

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МАГНИТ ӨРІСІНДЕГІ ТОЗАҢДЫ ҚҰРЫЛЫМНЫҢ АЙНАЛМАЛЫ ҚОЗҒАЛЫСЫН САРАЛАУ

Аннотация. Бұл жұмыста Гельмгольц шарғысынан туындайтын магнит өрісінің әсерінің тұрақты токты солғын разряд стратасында ілінген тозаңды құрылымға әсерінің эксперименттік нәтижелері көрсетілген. Зерттеу шарғының ортасында және үстіңгі/төменгі аймағында жүргізілді. Стратадағы тозаңды құрылымның ұқсас зерттеу жұмыстарында байқалынбаған ерекше қозғалысы байқалынды. Зерттеу нәтижесі бойынша тозаңды құрылым шарғының үстіңгі аймағында сағат тілі бойынша, төменгі аймағында сағат тіліне қарама-қарсы айналмалы қозғалысқа ие болса, ал шарғының ортасында тозаңды құрылымның айналмалы қозғалысы байқалынбады. Тозаңды бөлшек ретінде монодисперсті меламинформальдегид бөлшегі қолданылды. Әр түрлі магнит өрісіндегі алынған эксперимент деректері ашық түрдегіMatLAB бағдарламасы негізінде жасақталған PIV әдісі арқылы анализ жасалынды. Тозаңды құрылымның айналмалы қозғалысы электр өрісінің аксиальды құраушысы және магнит өрісінің радиальдықұраушысы нәтижесінде пайда болатын Лоренц күшінің себебінің салдарынан деген болжам ұсынылды.

Түйін сөздер:тұрақты токты газдық разряд, магнит өрісі, PIV әдісі

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АНАЛИЗ ВРАЩАТЕЛЬНОГО ДВИЖЕНИЯ ПЫЛЕВЫХ СТРУКТУР В МАГНИТНОМ ПОЛЕ.

Аннотация. В данной статье представлены результаты экспериментов по влиянию внешнего магнитного поля, создаваемого катушкой Гельмгольца, на пылевую структуру, подвешенную в стратах тлеющего разряда постоянного тока. Наблюдения проводились в трех областях (между катушками, под катушкой и над катушкой). Обнаружено интересное поведение пылевых структур в страте, о котором ранее не сообщалось в аналогичных работах. Пылевая структура вращается по часовой стрелке над катушкой и против часовой стрелки под катушкой, в то время как пылевая структура, расположенная между катушками, не вращается. В качестве пылевых частиц использовали монодисперсные частицы меламинформальдегида. Экспериментальные данные обрабатывались методом PIV (particleimagevelocimetry) на основе программного обеспечения MATLAB с открытым доступомпри различной индукции магнитного поля в разных областях. Была предложена интерпретация, согласно которой вращение пылевых структур обусловлено влиянием составляющей силы Лоренца, возникающей из аксиальной составляющей электрического поля и радиальной составляющей магнитного поля.

Ключевые слова: тлеющий разряд, плазма, магнитное поле, PIVметод

Introduction

Plasma with charged microparticles (dust particles) is formed in technological installations for etching, sputtering, deposition and synthesis of nanoparticles [1-2], in the wall region of experimental installations for controlled thermonuclear fusion [3] and in various installations for laboratory studies of processes and properties dusty plasma [4].It is an interesting and necessary task to study dusty plasma under various influences. One such action, a magnetic field, is used to control dusty structures in a plasma system.The first application of such exposure is associated with the removal of dust particles from technological installations.Currently, several scientific centers around the world are engaged in research using a magnetic field in a dusty plasma. The University of Iowa with the DPD device in [5] and the University of Kiel with the Matilda II device [6] are actively involved in research activities.They used weak magnetic fields of 10 to 20 mT to control the properties of the plasma. In these studies, the magnetic field was not considered to have a direct effect on the microparticles.At the same time, this magnetic field expanded the area in the plasma where microparticles could get trapped. In addition to these studies, experiments were also carried out in which a magnetic field was used to indirectly affect a cloud of suspended particles.This was the case in the experiments of Nunomura from Japan. In a study by Nunomura et al. [7] an axial magnetic field B = 87.5mT was applied to dusty plasma with electron cyclotron resonance at low pressure (p = 3.1 × 10-4 Torr). Here, the entire cloud was observed to participate in global rotation, which appears to be due to E × B ion drift.A similar effect appears in experimental observations carried out by Sato and colleagues, it was reported that at magnetic field strengths up to B = 1 T, but at much higher neutral gas pressures p = 70-220mTorr [8]. As in Nunomura's experiments, a general rotation of the dusty plasma cloud was observed when exposed to a magnetic field.It is noted that other groups have made similar observations, including studies of: rotating dust clusters reported by Cheung [9] (magnetic field strength 10 mT), rotating dust rings reported by Konopka (magnetic field strength 15 mT) [10], rotating dust structuresreported by KarasevV.Yi (magnetic field strength 40 mT) [11] and toroidally rotating dust structures in the anode plasma reported byPiel et al. (magnetic field strength 60 mT) [12].

As shown above, in most research centers a high-frequency discharge is used to generate plasma, since plasma instability is not observed in such types of discharge. In this work, a stratified DC glow discharge in a glass tube was used as the type of discharge. Plasma instabilities often appear during such discharges. Accordingly, a glow discharge is considered an inconvenient type of discharge in a magnetic field. A narrowing current channel (insert) is often used to suppress instabilities, such as oscillation of striations. The insertis located inside the discharge tube. A distinctive feature of this work is that by changing the discharge parameters, we found the optimal discharge condition without an insert, where instability does not manifest itself during the experiment in a magnetic field. The experiment investigated the rotational motion of dust structures in the horizontal plane. Processing of experimental data was carried out using the PIV (particle image velocimetry) method based on MatLab software that is in the public domain [13].

Experimental setup

To study the effect of a magnetic field on duststructures in a DC glow discharge, an experimental setup was created schematically shown in Fig.1.

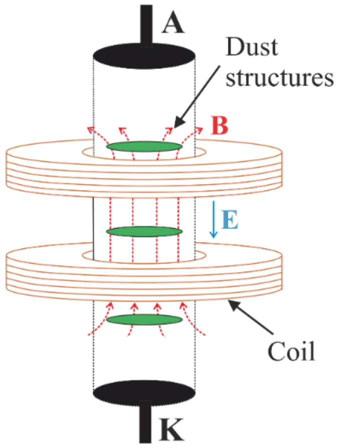


Figure 1. Experimental setup

The experimental setup is a vertically oriented discharge tube.We used argon gas to fill the tube.When voltage is applied from a high-voltage power source to the electrodes, a stratified glow discharge (plasma) is ignited. The strata act as a dust trap, since the electric field is strong enough to compensate for the gravitational force. Dust particles that are in the container, which is located on the upper side of the tube, falling downward forms a dust structures in the stratum.Dust particles are illuminated with a solid-state green diode laser and their movement is recorded in the CCD camera.The magnetic field was created using a Helmholtz coil.The highest value of the induction of the longitudinal magnetic field, equal to 23 mT, at which the standing striations were preserved, was obtained by us for a discharge into argon at low pressures and at low currents.Parameters of experiment are given below.Plasma parameters were determined using a Langmuir probe.

Pressure of gas	0.23 torr
Current	1.3 mA
Induction of magnetic field	0-23 mT
Concentration of plasma particles	10^15 m^-3
Temperature of electrons	4 eV

Processing and analysis of experimental data

Particle Image Velocimetry (PIV) is a well-known dusty plasma technique that is used to process and analyze experimental data.The essence of the method is to measure the average motions of a group of particles by comparing a pair of images separated in time by a known interval.Video captured on an CCD camera (25 frames per second) is split into several frames viaVirtualDub program. Each experimental measurement was taken in 10 seconds and processed using a publicly available method.After processing the method, we can obtain a qualitative analysis of the experimental data. Also we can determine the rotational property (angular velocity, vector direction, displacement and other characteristics). For example, Figure 2 shows the original file and the file after processing by a known publicly available method. As can be seen from the figure, the characteristic of the rotational motion of dust structures in the horizontal plane is clearly shown.

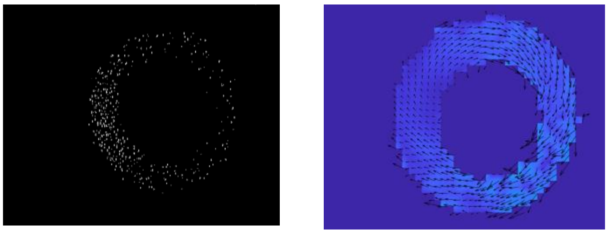
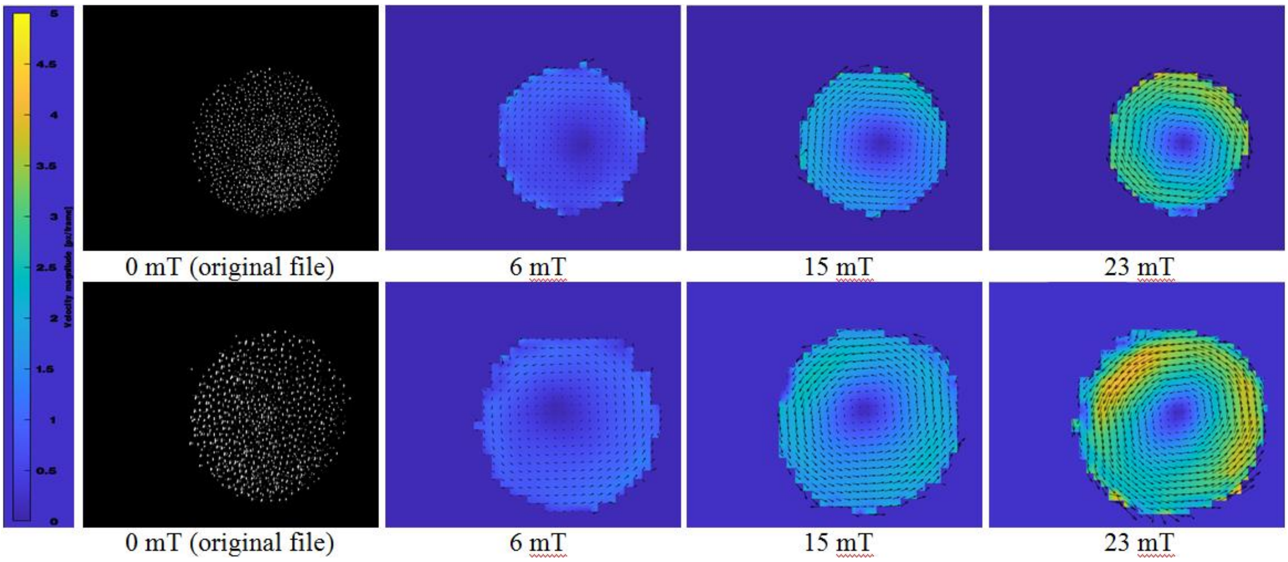


Figure 2. Frames before and after processing

Results of experiment & Discussion

The observations were carried out in three configurations of the magnetic field: below/above the coils (I and III regions) and between the coils (the second region). When the magnetic field was turned on, the dust particles in regions I and III had a rotational motion in the horizontal plane. Clockwise and counterclockwise motions were observed in regions I and III, respectively, while the dust structure in region II did not rotate. In this article, using the method, the first and third regions were processed, since in these regions the dynamic behavior of dust structures is observed.As can be seen from the Figure 3, with an increase in the magnetic field induction, the angular velocity of dusty structures increases in both regions.It can also be seen that the dusty structure does not rotate as a solid, since different rotational properties are observed in different radial segments.The maximum angular velocity reaches 6 px/frame at 23 mT.Table 2 shows the values of the angular velocities and sizes of dust particles at different induction of the magnetic field for all regions. It was also observed that the size of the dust structures changes in the first and third regions with increasing magnetic field. But in the second region, that is, between the coils, where the magnetic field lines are parallel, the size of the dust structures does not change.



0 mT (original file) 6 mT 15 mT 23 mT

0 mT (original file) 6 mT 15 mT 23 mT

Figure 3. Rotational motion of dust structures processed using the PIV methodin the I and III regions. On the left corner is an indicator of the angular velocity value.

Table 2. Dependence of angular velocity (rad/s) andsize of dust structure (cm) on induction of magnetic field(mT) at different region

B (mT)	0	5.7	10	15	19	23
I region (negative)	0	0.06	0.14	0.19	0.25	0.27
	1.2	1.2	1.3	1.4	1.5	1.6
II region	0	0	0	0	0	0
	1.4					
III region (positive)	0	0.08	0.2	0.28	0.3	0.44
	1.2	1.1	1.2	1.3	1.4	1.5

Magnetic induction **B** can be considered as the sum of longitudinal $\mathbf{B}_{\parallel}$ (vertically along the tube) and transverse components $\mathbf{B}_{\perp}$.The rotational movement took place in crossed electric and magnetic fields; where the radial component of the ion flux, which is deflected in the vertical magnetic field leads to the appearance of the azimuthal force of ion drag [14].In the first and third region, the magnetic field has a radial component. In the first region, the magnetic field is directed from the center to the wall, and in the third from the wall to the center.Therefore, in regions I and III, the duststructure rotates in opposite directions. The reasons for the absence of rotational motion in region II are associated with the fact that the lines of the magnetic field and the directional velocity of charged particles do not intersect.

Conclusion

The dust structures in the first and third regions were in different configurations of the magnetic field lines. In the first region, the magnetic field lines diverge from the center of the tube, and in the third region they converge to the center. Therefore, dust structures in these areas rotate in opposite directions. The rotational motion of dusty structures occurs due to the flow of ions which has a different direction due to the configuration of the magnetic field. Using the PIV method, it was found that the angular velocity increases with increasing magnetic field. Also, the size of dust structures was determined for different regions at different magnetic field inductions.

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