Brownian motion of a lone dust particle in plasma of radio frequency discharge

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Abstract. Experimental data on the Brownian motion patterns of a lone particle in radio frequency discharge plasma under the influence of radiometric force, induced by laser radiation, depending on the type of surface and the material of the particle are presented. It was shown that dust particles in a gas discharge plasma can convert energy of the surrounding medium (laser radiation) into the kinetic energy of motion. The movement of active particle alternates with the changes of random motion and self propulsion.

1. Introduction

Brownian motion is widespread in nature, it is observed in biological and colloidal solutions \cite{1}, in the atmosphere of the Earth and in a plasma with a condensed disperse phase, and even in financial models. The origin of the random motion of microparticles observed by Robert Brown was first explained by Albert Einstein as an enhancement of the statistical fluctuations of the liquid molecules surrounding the particle. In the presented experiments, the motion of a lone dust microparticle in a plasma of a radio frequency discharge of low pressure was studied. Such plasma is widespread and is used in various technological processes \cite{2}. Dust particles in a gas discharge plasma acquire a significant negative charge $\sim 10^3 e$ to $10^4 e$ (where $e$ is the elementary charge) as a result of flows of electrons and ions to its surface \cite{3}. The pressure of the buffer gas in the experiments varies from 0.1 to 10 Pa, thus dissipation due to collisions with molecules or gas atoms plays a significant role. The confinement of charged microparticles was carried out in a plasma trap, where self-consistent action of gravitational, electric and other forces resulted in conditions suited for their levitation.

2. Experiment and results

In figure 1 shows a scheme of the experimental setup, the main elements of which is a gas-discharge chamber with optical windows. Two flat horizontally oriented electrodes are placed inside the chamber. In the central part of the upper electrode there is a hole through of which the insertion of dust particles into the plasma is provided by the injector placed above the hole.

Monodisperse spherical melamine-formaldehyde microparticles of a density $\rho_p = 1.51$ g/cm$^3$ and a diameter $a = 10 \mu$m with a copper-coated surface were used in the experiments. During the experiment, the chamber was pumped out, after which it was filled with buffer gas to a pressure...
Figure 1. Scheme of the experimental setup for the investigation of dust microparticles in the capacitive radio frequency discharge plasma at low pressure.

of 2.5 Pa. We used argon as a buffer gas in our experiments. From the high-frequency generator through an impedance-matching device, a voltage of 300 V with a frequency of 13.56 MHz was applied to the electrodes, resulting in a glow discharge ignited between the electrodes. According to our recent study [4], to visualize and heat the microparticles, we illuminated them by a homogeneous beam of an argon laser with a wavelength of 514 nm. The position of the dust particles was recorded by a high-speed video camera, with a frequency of 100 frames per second, located above the electrode. We observed a lone dust particle movements at different values of the argon laser power applied to the particle. The video recorded in the experiment was processed using a special program which could determine the positions of a dust particle on video frames with sub-pixel accuracy. As a result of the processing of video recordings, their trajectories were obtained in figure 2.

To analyze the motion of a particle, we measured its mean square displacement for different values of laser radiation intensity in figure 3.

It was observed experimentally that the effect of laser radiation with a power up to 0.200 W on melamine-formaldehyde particle did not lead to a noticeable change in its mean square displacement. At the same time, for melamine-formaldehyde particles with a copper coating, the effect of laser radiation of the same power led to an increase of the kinetic temperature and enlarging the region of their motion in figure 4.

It is related to the fact that melamine-formaldehyde microparticles with a copper coating can effectively absorb laser radiation, resulting in the increase of their surface temperature [5]. This, in turn, causes a photophoretic effect and an increase of the kinetic energy of the chaotic motion of particles due to the gaining of an additional momentum from collisions with neutrals. From the slope of the curve, the part can be determined by the characteristic of the diffusion of the particle. Asymptotics $t^1$ refer to the diffusion, $t^2$ refer to the ballistic regime and $t^{3/2}$ refer to intermediate regime [6]. In figure 5 shows the mean square displacements of a lone microparticle with a metallic coating for different values of laser radiation intensity. Note that the absence of ballistic regime for melamine-formaldehyde particles and melamine-formaldehyde particles with copper coating at laser power 0.085, 0.105 and 0.200 W, we can explain by the low spatial resolution of video camera and apparition artifacts. The obtained data is consistent with visual observation, where the tracks of microparticles consist of linear segments of different length, specific to ballistic motion, which are randomized over long periods and are characterized by Brownian behavior.
Figure 2. Trajectories of a lone dust melamine-formaldehyde microparticle during 1 s, levitating in the near-electrode region of a radio-frequency discharge of low pressure under action of laser radiation with a power of 0.085, 0.105 and 0.200 W.

Figure 3. Mean-square displacement of a lone dust particle under influence of laser radiation with a power of 0.085, 0.105 and 0.200 W. Thin solid, dotted and dashed lines show asymptotics $t^2$, $t^{3/2}$ and $t^1$, respectively. Here $\langle \rangle$ represents the ensemble average.

Based on the presented observations, we consider that the dynamics of different particles changes with increase of laser power. Depending on the experimental conditions, the particle behavior can correspond to the Brownian motion of active or passive “particles in the trap”. Active Brownian particles are capable of taking up energy from their environment and converting
Figure 4. Trajectories of a lone dust particle of melamine-formaldehyde with a copper coating for 1 s levitating in the near-electrode region of a low-pressure radio frequency discharge under the action of laser radiation with a power of 0.082, 0.105 and 0.200 W.

Figure 5. Mean-square displacement of a lone dust particle covered by copper under influence of laser radiation with a power of 0.082, 0.105 and 0.200 W. Thin solid, dotted and dashed lines show asymptotics $t^2$, $t^{3/2}$ and $t^1$, respectively. Here $\langle \rangle$ represents the ensemble average.

it into directed motion; they feature an interplay between random fluctuations and self propulsion [7]. For the active Brownian motion, the particle trajectory is characterized by linear segments,
which are changed to chaotic shifts caused by collisions with neutrals. Such behavior is typical also for living systems, for example, the movements of bacteria in the liquid, for certain colloidal suspensions, etc. An uncoated particle moves randomly under laser radiation of any power: 0.085, 0.105 and 0.2 W, in figures 2 and 4, so that the directed movement of the particle does not prevail over the random one, which might be indicated as “passiveness”. The trajectories of the coated particle are similar to the trajectories of the uncoated particle at low values of the laser radiation power (0.082 and 0.105 W). At the same time, increasing of the laser power up to and beyond 0.2 W leads to a change in the motion state (the trajectory becomes circular) and to a growth of the velocity (up to \( \sim 1000 \mu\text{m/s} \)) of the coated particle, suggesting that the directed motion of the coated particle starts dominating over random one, which is an evidence in favour of its “activity”. We can see in figure 4 that the random motion of active particle alternates with self propulsion.

3. Conclusion
The motion of a lone charged microparticle, which levitates in the plasma of a capacitive high-frequency discharge at low pressure under laser action, is studied experimentally. For particles of various materials and properties of their surfaces the character of their motion via the parameters of the experiment is determined. It is shown that dust particles in a gas discharge plasma can convert energy of the surrounding medium (laser radiation) into the kinetic energy of motion. The mechanism of motion for microparticles with a metallic surface is related with photophoresis. Absorption of laser radiation by the metal surface of the particle creates a radiometric force, which in turn makes the particle movement. We observed experimentally the active Brownian motion (directed or irregular) caused by the action of radiometric force for various charged microparticles in the low-pressure plasma. For particles with a metal coating, as the result of the action of photopheresis force, a direct motion with velocities up to \( \sim 1000 \mu\text{m/s} \) was observed.

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