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Behavior of Dust in an Inductively-Heated Plasma Jet with Application to Planetary Science

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Motivation

Alumina particles have been injected into Argon and Helium gas plasma jets created by the inductively-heated plasma generator IPG6-B at Baylor University [1] and dust behavior has been observed using both low- and high speed camera systems. These preliminary experiments prove the capability of the facility for applied research in complex plasmas [2] and using dust as a diagnostic [3]. Furthermore it allows the application of the facility to research the behavior of dust in planetary and astrophysical environments [4]. These include the processes in protoplanetary disks, e.g. rim formation on chondrules [4], behaviour of dust within planetary rings [5] as well as studies of dust in lunar [6] or martian [7] environments or the solar wind. The results of the study of dusty plasma flows can therefore provide critical insight into the processes in such environments.

Experimental Setup

Figure 1: IPG6-B facility in operation with argon and an electrostatic probe

All experiments were conducted within the IPG6-B experimental facility at Baylor University [1], [8], [9]. The facility consists of a 1.2 m^3 vacuum tank with a diameter of 0.9 m connected to a vacuum system capable of maintaining a base pressure of 2 Pa. This vacuum tank is connected to an inductively-heated plasma generator (IPG), which is capable of producing an inductively coupled discharge with electrical powers between 150 and 15000 W in various gases such as air, Argon, Helium and Nitrogen [9]. In the experiments presented here, Argon was used. A manually operated dust shaker, filled with **alumina particles of 20µm** diameter, is placed inside the vacuum chamber within a distance of 300mm from the exit of the discharge tube of the plasma generator and on the center axis of the cylindrical vacuum tank (Figure 1). A pressure of 50 Pa is maintained with dust in the shaker introduced into the system by tapping the handle with an engineering hammer. The dust is illuminated using a high-power tungsten lamp through a quartz-glass window. A camera on the opposite side of the tank films the dust using a highly magnifying tele-microscope lens. In this setup, the dust is visible against the background lighting. When the dust shaker is operated, the falling dust particles can be observed using the camera system. Interaction of the dust with both an argon gas jet at a velocity of approximately 100m/s and a plasma jet at a similar velocity has been observed. The argon plasma has an electron temperature of 1eV and an electron density of 10^{19} m^{-3} [9], [10].

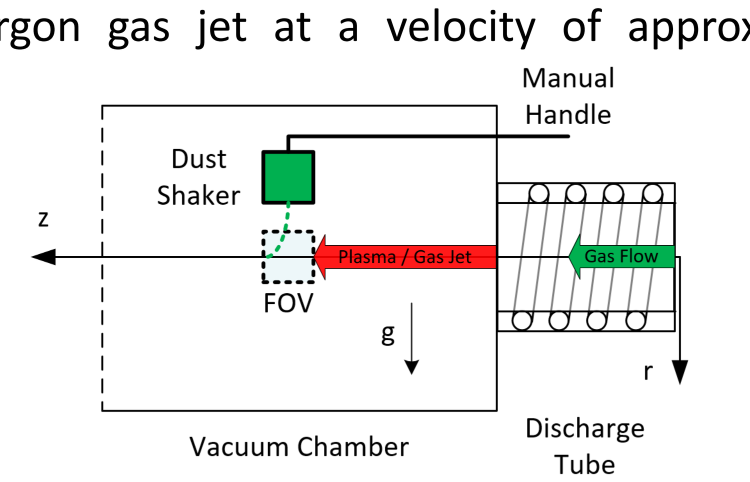

Figure 2: Schematic of the experiment with plasma generator, dust shaker and field of view of the camera (not to scale)

Experimental results

Dust in free fall in Vacuum (no gas flow)

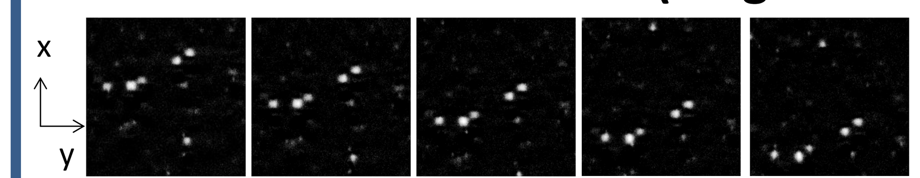

Figure 3: Image series of falling alumina dust in argon at 50 Pa

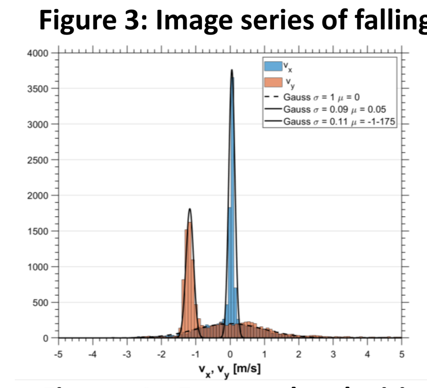

Figure 4: Extracted velocity distributions v_x v_y (in m/s)

While dropping dust particles within an vacuum at 50 Pa, the horizontal velocity was 0 m/s while the vertical velocity was around 1 m/s

Dust interaction with an argon plasma

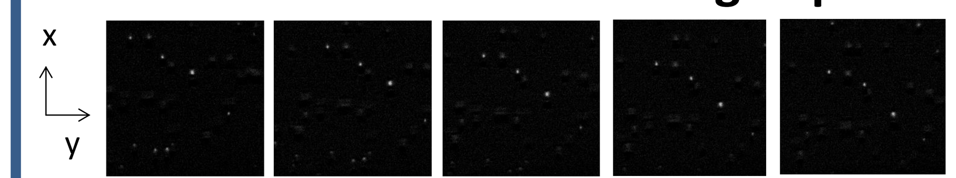

Figure 7: Image series of falling dust in an argon plasma

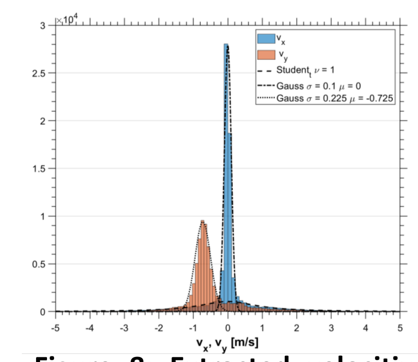

Figure 8: Extracted velocity distributions v_x v_y (in m/s)

While dropping dust particles within an quiescent argon plasma, the horizontal velocity was 0 m/s while the vertical velocity was around 1 m/s

Dust interaction with an argon gas jet

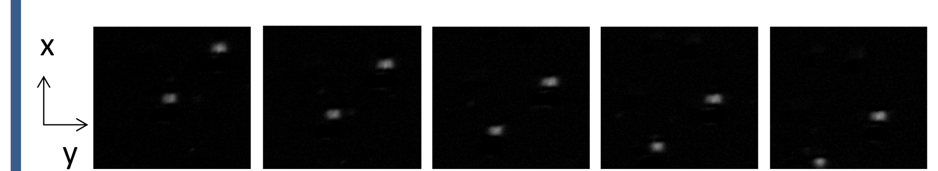

Figure 5: Image series of alumina dust in an argon gas jet

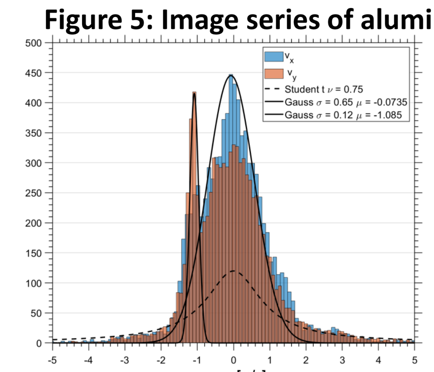

Figure 6: Extracted velocity distributions v_x v_y (in m/s)

Interaction with an argon (neutral) gas jet shows a much wider velocity distribution and also a small horizontal velocity component

Dust interaction with an argon plasma flow

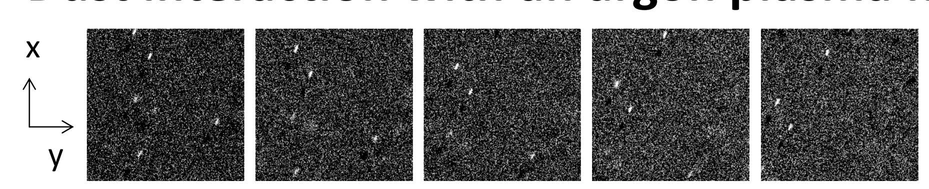

Figure 9: Image series of alumina dust in an argon plasma flight

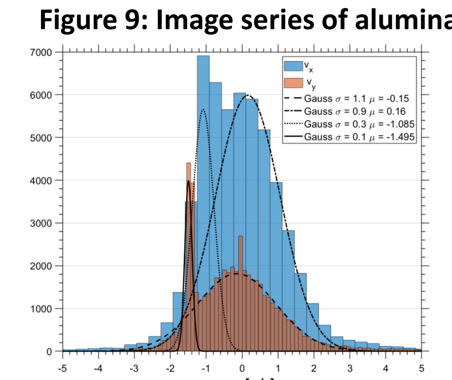

Figure 10: Extracted velocity distributions v_x v_y (in m/s)

Interaction with an argon plasma jet shows a much wider velocity distribution and a clearly visible horizontal velocity component

Discussion

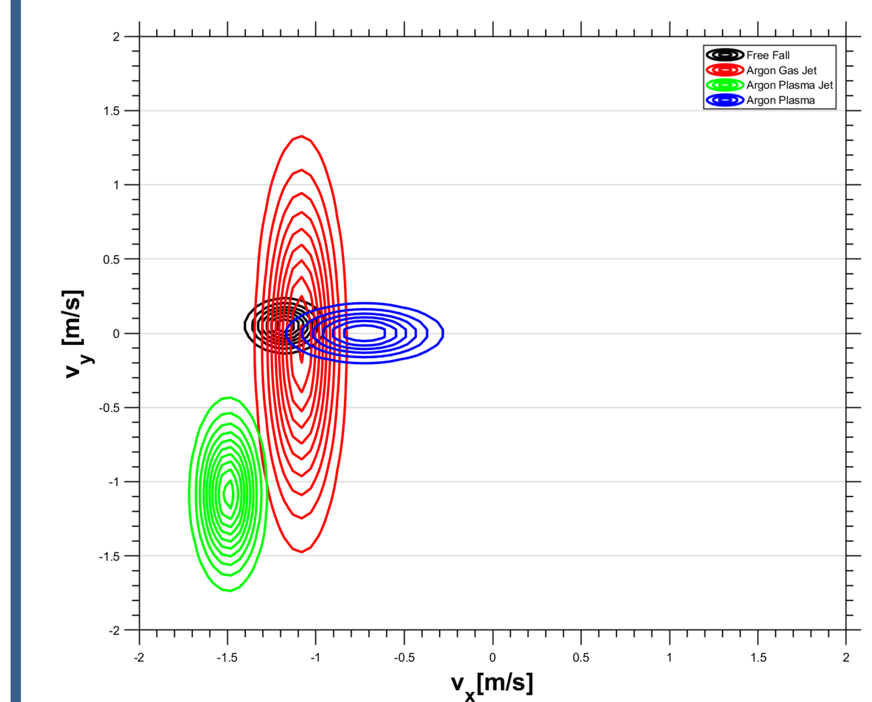

Figure 11: Comparison of normalized velocitiy distributions v_x v_y (in m/s) for the 4 experimental conditions

As shown in Figure 11, comparison of the velocity distributions from the extracted particle trajectories shows significant differences for every case. It can be seen, that in the gas without any flow, the horizontal component of the velocity vector is almost zero, while there is a difference in vertical velocity between the neutral gas and plasma case. For the interaction with flow, the case are even easier to distinguish. For a plasma flow, the horizontal component is much higher, while the distribution in the neutral gas jet case seems to be more widened.

Theory

In a multiphase flow, a dust particle interacts with the gas through drag forces. Within a complex plasma, since the dust particles are charged due to free electrons within the dusty plasma system, additional interaction forces also rapidly become important. The interaction can be described by

$$m_p \frac{\partial v}{\partial t} = F_E + F_B + F_{D,n} + F_{D,i} \qquad (1)$$

where F_E describes the electrostatic force, F_B describes the electromagnetic force and $F_{D,n}$ describes the drag due to neutrals and $F_{D,i}$ the drag due to ions. Due to their mass, field strengths which can influence micrometer-sized particles must be significant. However even if such fields cannot be achieved, lower field strengths can still affect the plasma and therefore the entrained dust due to its entrenched nature and interaction with the plasma. Particle image velocimetry (PIV) can be applied to achieve information about these interactions by monitoring the flow. Compared to conventional PIV used as a diagnostic for gas flows, with charged dust, crucial information on electric and magnetic fields can be achieved using the described method.

Conclusion

Dust velocities have been calculated in a simplified manner using the known exposure time of 500µs and known resolution of 50µm per pixel and yield the results shown in Figure 4. Due to the limitations of the framerate of the camera system, only streaks of moving particles can be observed and a single particle could not be observed for multiple frames. Other than the results observed for condition 3, all of these results are expected and explainable. That the dust moves in the direction of the discharge tube under condition 3 might be caused by temperature or density gradients within the vacuum chamber and the argon plasma. Even if no additional gas flow is present, the particles might be 'dragged' due to the gas flow induced by such gradients. Preliminary experiments with alumina dust particles having an average size of 20µm have been conducted within the IPG6-B facility. It has been shown that dust is observable within the facility and responds to different experimental conditions. Future work includes the improvement of the camera setup and a more sophisticated evaluation of the data.

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