



Dust Cloud Convections in Inhomogeneously Heated Plasmas in Microgravity

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Abstract

Convection is a phenomenon that often occurs in the presence of temperature gradients. In microgravity, free convection can not occur due to the lack of buoyancy. However, during parabolic flights we observed convections of microparticles in a gas discharge within the cylindrical plasma chamber of the setup PK-4. The microparticles and the plasma were exposed to a thermal gradient. There, the cloud convections and dust waves were observed. Analysis by tracking the microparticles' trajectories showed that the vortices were induced by thermal creep, a gas flow that commonly occurs in gases with low pressures at inhomogeneously heated solid interfaces. This effect has driven a gas convection which in turn caused the convection of the microparticle cloud.

Keywords Dusty plasma · Glow discharge · Parabolic flight · Thermal creep flow · Convections

Introduction

A plasma consists of uncharged neutrals, electrons and ions and shows collective behaviour. When microparticles are being inserted into a plasma, one speaks of a complex plasma. This type of plasma is commonly studied under laboratory conditions in low-pressure discharges in noble gases into which microparticles are injected (Fortov et al. 2005). Due to the high mobility of the electrons in comparison to that of the ions, the microparticles gain electrically negative charges of several thousands elementary charges and thus interact with each other via a screened interaction potential

(Morfill and Ivlev 2009). Furthermore, the microparticles possess low velocities because of their relatively low charge-to-mass ratio and as their interparticle distance are in order of a few 100 μm . This allows to observe these many body systems on the level of individual particles in real time with the help of lasers to illuminate and video cameras to capture the reflected light (Fortov et al. 2005; Morfill and Ivlev 2009). Hence, the microparticle observation offers the possibility of tracing back plasma conditions inside the chamber, e.g. given gas flows inside the plasma, or to investigate the physical properties of the complex plasma itself via the study of the microparticles' dynamics or order. Moreover, complex plasmas can be used as model systems for other many particle systems. For example, it is possible to generate a plasma crystal, a system where the microparticles form crystalline structures whose phase transitions from a crystalline to a liquid phase can be observed on single particle level (Thomas and Morfill 1996).

However, under laboratory conditions earth's gravity field confines the microparticles in the plasma's sheath region where strong electric fields are present and counterbalance gravity. There, the microparticles are subjected to inhomogeneous plasma conditions which can lead to a distortion of experiments. In addition, the microparticle clouds there are limited to only a few layers above the balance height due to gravity, so experiments with microparticles cannot take place in the homogeneous bulk plasma. When the microparticles

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need to be situated in homogeneously distributed plasma conditions for experiments, experimenters can apply a thermal gradient. The thermophoretic force exerted by the thermal gradient eventually lifts the microparticles into the bulk plasma (Rothermel et al. 2002). Under low pressure conditions however, the presence of temperature gradients along the plasma chamber walls can cause a gas flow called *thermal creep* resulting in convection of the plasma and thus the microparticle clouds (Mitic et al. 2008; Flanagan and Goree 2009; Schwabe et al. 2011). If these convections are to be avoided it can be beneficial to conduct experiments instead of with temperature gradients in microgravity environments as in sounding rockets (Morfill et al. 1999), parabolic flights (Dietz et al. 2018) or space stations (Schwabe et al. 2020) where the microparticles are in the bulk plasma.

In this work we present an experiment which was conducted during the 71st parabolic flight campaign of ESA in the PK-4^{GI} setup (Dietz et al. 2018). During the microgravity phases we trapped microparticles via a thermal gradient applied by a heating ring in a neon direct current (dc) discharge and observed convections and wave formation of the microparticles. We investigated the microparticle convections in front of the heating ring and identified thermal creep as its cause. This phenomenon was studied theoretically by Maxwell in 1879 (Maxwell 1879) and experimentally by Reynolds (1879).

Experimental Design

Experimental Setup

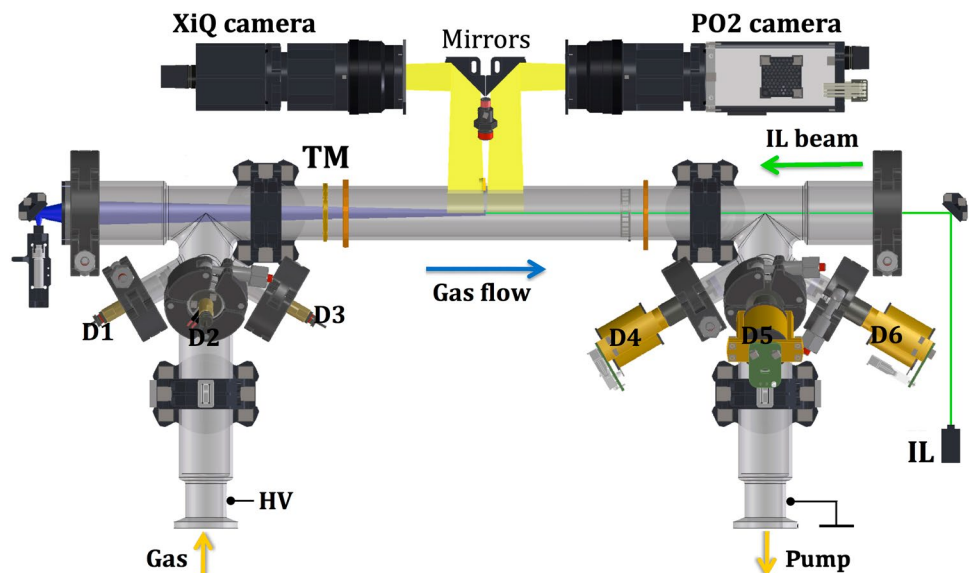
The experiments were performed in University Giessen's parabolic flight model PK-4^{GI} (Dietz et al. 2018) (see Fig. 1), whose experimental setup is similar constructed to the flight

model on the International Space Station (ISS) (Pustylnik et al. 2016). Its plasma chamber consists of an 80 cm long Π -shaped glass tube with an inner diameter of 3 cm. For experiments the tube is filled with either neon or argon. With the help of two hollow high voltage electrodes located at the ends of the tube a dc discharge can be realized with an actively controlled current of maximum 3.1 mA. The gas-vacuum system, whose gas inlets and outlets are attached to the electrodes, controls and regulates the gas pressure during experiments at values between 5 or 250 Pa. Spherical, monodisperse microparticles made of either melamine formaldehyde or silicon dioxide are injected via dispensers mounted on the glass tube with particle radii of 1.3 to 11 μm . The microparticles are illuminated with a planar laser sheet with a wavelength of 532 nm which possesses a thickness of 90 μm in focus. The reflected light of the microparticles can be recorded by a CMOS camera (field of view 2048 x 2048 pixels, framerate up to 90 fps, spatial resolution 11.8 $\mu\text{m}/\text{pixel}$) and a CCD camera (field of view 1600 x 1200 pixels, framerate up to 35 fps, spatial resolution 14.2 $\mu\text{m}/\text{pixel}$) (Note that on the ISS setup instead of one CMOS camera and one CCD camera two CCD camera with the same specifications as described are being used). Both cameras are mounted on a translation stage which allows to move them along and perpendicular to the glass tube. This gives us the possibility to generate tomographic 3D scans of the particle clouds.

When the microparticles have reached the experiment area there are several ways to manipulate the microparticle clouds and the plasma:

- a ring electrode mounted inside the glass tube which can compress and expand the microparticle clouds
- two radio frequency coils (one with a fixed position and the other one is driveable) mounted around the glass

Fig. 1 Sketch of the setup used during the parabolic flight



tube, can be used individually or at the same time with the option to combine it with the dc discharge

- a heating wire mounted around the glass tube which exerts a thermophoretic force onto the particles via an adjustable temperature gradient
- a laser with a wavelength of 808 nm and output power up to 20 W which can induce shear flows
- a configuration of the electrodes to a polarity switching which causes an ac discharge with frequencies between 100 and 5000 Hz

For a more detailed description of the PK-4 setup see Pustynnik et al. (2016).

Thermal Manipulation

During the parabolic flights, we exposed microparticle clouds in a neon dc discharge with an electrode current of 1 mA to a temperature gradient, which was regulated to stop the particles in front of the heater via the thermophoretic force. The CMOS camera captured images of the microparticles in the planar sheet along the longitudinal axis of the chamber during the experiment runs. The stopped microparticle clouds showed a region of dust waves travelling in direction of the temperature gradient and a region of two vortices divided by the longitudinal axis (see Fig. 2). In the following, we will study in two experiment runs with microparticles with a diameter of 6.8 μm at a gas pressure of 50 respectively 100 Pa the convection of the dust clouds, to investigate whether it was thermal creep driven. It should be mentioned that the first reported experiment on thermal creep in complex plasmas was performed in Mitic et al. (2008) in PK-4, as in our work. The apparatus was oriented in such a way that the thermophoretic force exerted was directed opposite to the direction of gravity to balance it, thus the particles could be levitated. The manipulated microparticles in Mitic et al. (2008) had a diameter of 6.1 μm and were injected into in a neon plasma at a pressure of 50 Pa. The plasma discharge was driven by a polarity switching at a frequency of 1 kHz with a current of 1 mA. Due to the polarity switching discharge, the microparticles in Mitic et al. (2008) were not affected by a longitudinal electric field, unlike our experiment. Moreover, no dust waves were observed at all in Mitic et al. (2008).

Analysis

In our analysis, the section of interest was the one where convection dominated microparticle motion (see Fig. 2). There, we first tracked the trajectories of individual microparticles using *Python*-based open source software *Trackpy* (Allan et al. 2019). Afterwards we determined the gas flow profile

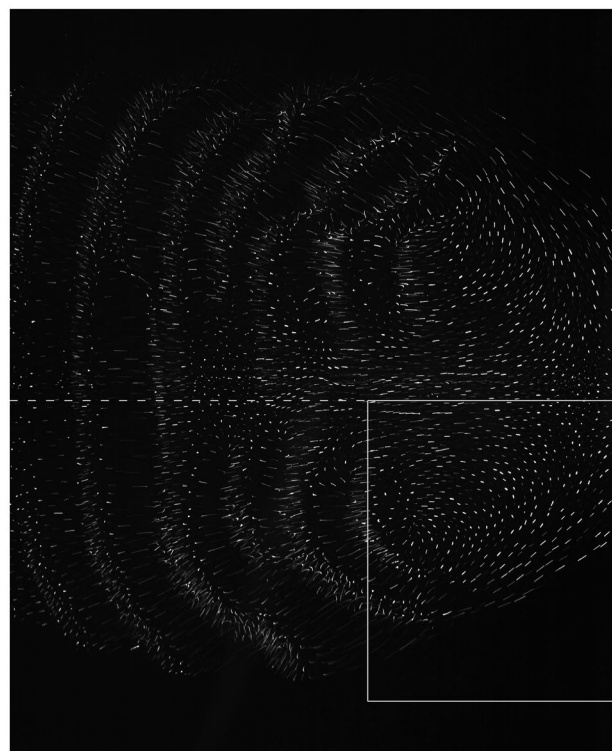


Fig. 2 Brightness and contrast enhanced image of dust density waves and dust cloud convection at a pressure of 100 Pa, a direct current of 1 mA, and a microparticle radius of 3.4 μm . Note that at the right edge of the figure is the heat coil, which creates a thermal gradient to the left side of the image. The horizontal dashed line represents the longitudinal axis. The displayed image section is 2048 x 2048 Px and 24 mm x 24 mm. The gray highlighted area denotes the investigated range of thermal creep flux (600 x 825 Px, respectively 7.08 mm x 9.74 mm)

by considering, similarly to Mitic et al. (2008), the following forces acting on the microparticles: the electric force, the neutral drag force and the thermophoretic force.

In Mitic et al. (2008) the interparticle forces were neglected because they were assumed to be weak, which we consider likewise in our analysis.

The electric force of the DC plasma can be divided into an axial and a radial component. The axial component of the electric field in neon is given by $E_{\parallel} \approx 2.1 \text{ V/cm}$ (Khrapak et al. 2013). The radial electric field is given by the stationary solution of ambipolar diffusion for a cylindrical geometry (Lieberman and Lichtenberg 2005):

$$E_{\perp} = \frac{2.405k_B T_e J_1(2.405 \cdot r/R)}{eR J_0(2.405 \cdot r/R)} \quad (1)$$

Here k_B is the Boltzmann constant, T_e the electron temperature, e the elementary charge, R the inner radius of the plasma chamber, r the radial distance from the longitudinal axis of the plasma chamber, and J_0 and J_1 are Bessel functions of the first kind. We use the reduced charge $z \approx 0.3$

from Antonova et al. (2019) to calculate the charge number $Z = 4\pi\epsilon_0 k_B T_e a z / e^2$, where ϵ_0 is the vacuum permittivity and a the microparticle radius. Therefore, we can calculate the electric force $\vec{F}_e = Q \cdot \vec{E}$ via the microparticle charge $Q = -Z \cdot e$.

Due to the relative motion to the moving background gas, which is due to the thermal creep, the microparticles experience a neutral drag force which is:

$$\vec{F}_n = -\delta \frac{4\pi}{3} n_n v_{th_n} a^2 m_n (\vec{v}_p - \vec{v}_f) \quad (2)$$

Epstein (1924) with δ , a numerical factor, which in our case of diffuse reflection with accumulation of neutral gas particles on the microparticles is 1.393 (Epstein 1924), the neutral gas density, n_n , the mass of a single neutral gas atom, m_n , $v_{th_n} = \sqrt{8k_B T / \pi m_n}$, the thermal velocity of the neutral gas atoms at the gas temperature T , the microparticle radius, a , the microparticle velocity, \vec{v}_p , and \vec{v}_f , the gas flow velocity (Epstein 1924).

Since there is a temperature gradient in the plasma, the thermophoretic force must be taken into account:

$$\vec{F}_{th} = -3.33 \frac{k_B a^2}{\sigma} \nabla T, \quad (3)$$

where σ is the gas kinetic cross section for atomic scattering, which is $2.1 \cdot 10^{-19} \text{ m}^2$ for neon (Varney 1952) and ∇T the temperature gradient (Rothermel et al. 2002). To determine the temperature gradient, the temperature distribution along the glass wall was measured using implemented temperature sensors along the outer plasma chamber wall with 5 temperature sensors during each experiment run (see Figs. 3 and 4).

The forces presented can be summarized in the following equation of motion:

$$m_p \ddot{\vec{r}} = \vec{F}_e + \vec{F}_n + \vec{F}_{th}, \quad (4)$$

where $m_p = \rho 4/3 \pi a^3$ is the microparticle mass with mass density of melamine formaldehyde $\rho = 1.519 \text{ g/cm}^3$ and $\ddot{\vec{r}}$ is the microparticle acceleration. We determine the microparticle velocity distribution (see Fig. 5) by first tracking the microparticle trajectories in 60 frames. The section of interest is then divided into bins of 50×50 pixel, in which the average microparticle velocities are calculated. The microparticle trajectories can be used to further calculate the velocity profile of the gas flow via the equation of motion (4). Similar to the velocity distribution, the gas flow velocities are averaged in bins to obtain the gas flow velocity distribution (see Fig. 6).

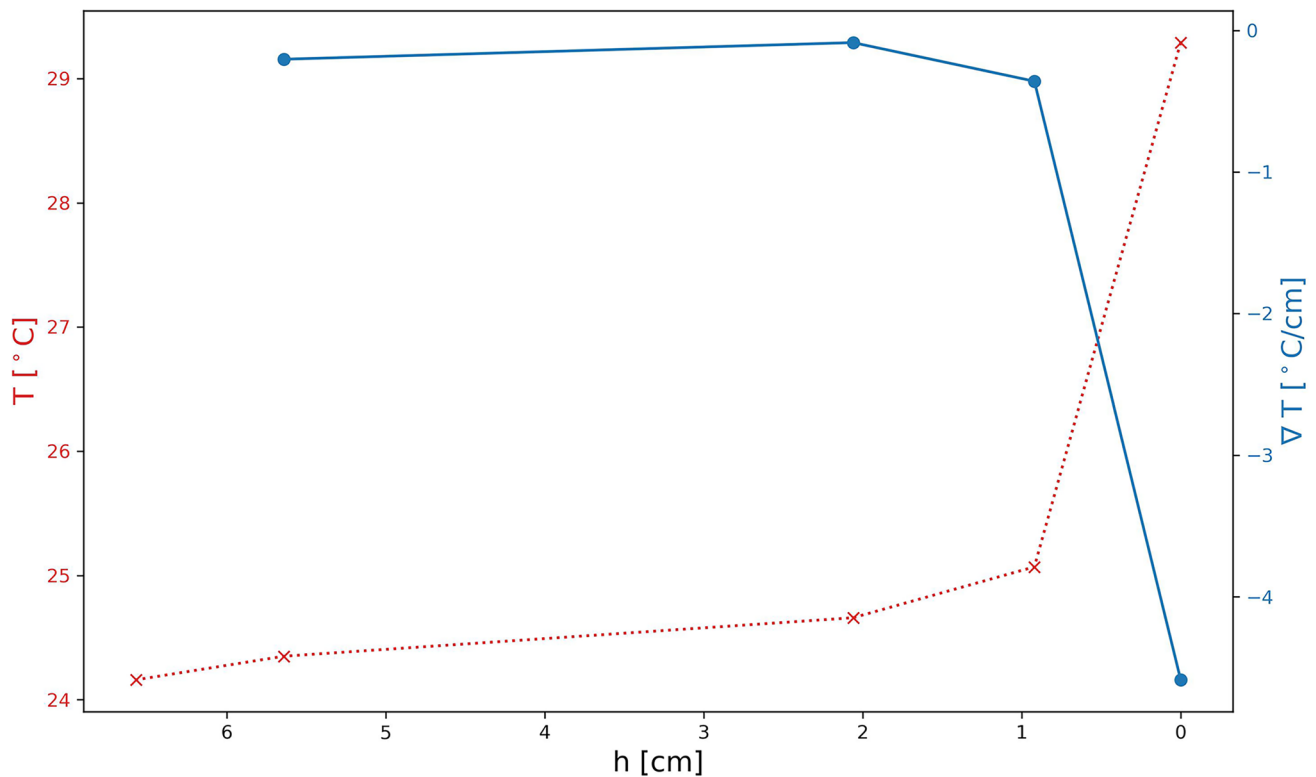


Fig. 3 Corresponding temperature (red dotted) and temperature gradient distribution (blue solid) along the glass wall of the experiment run shown in Fig. 2 at 100 Pa. h denotes the axial distance from the thermal manipulator

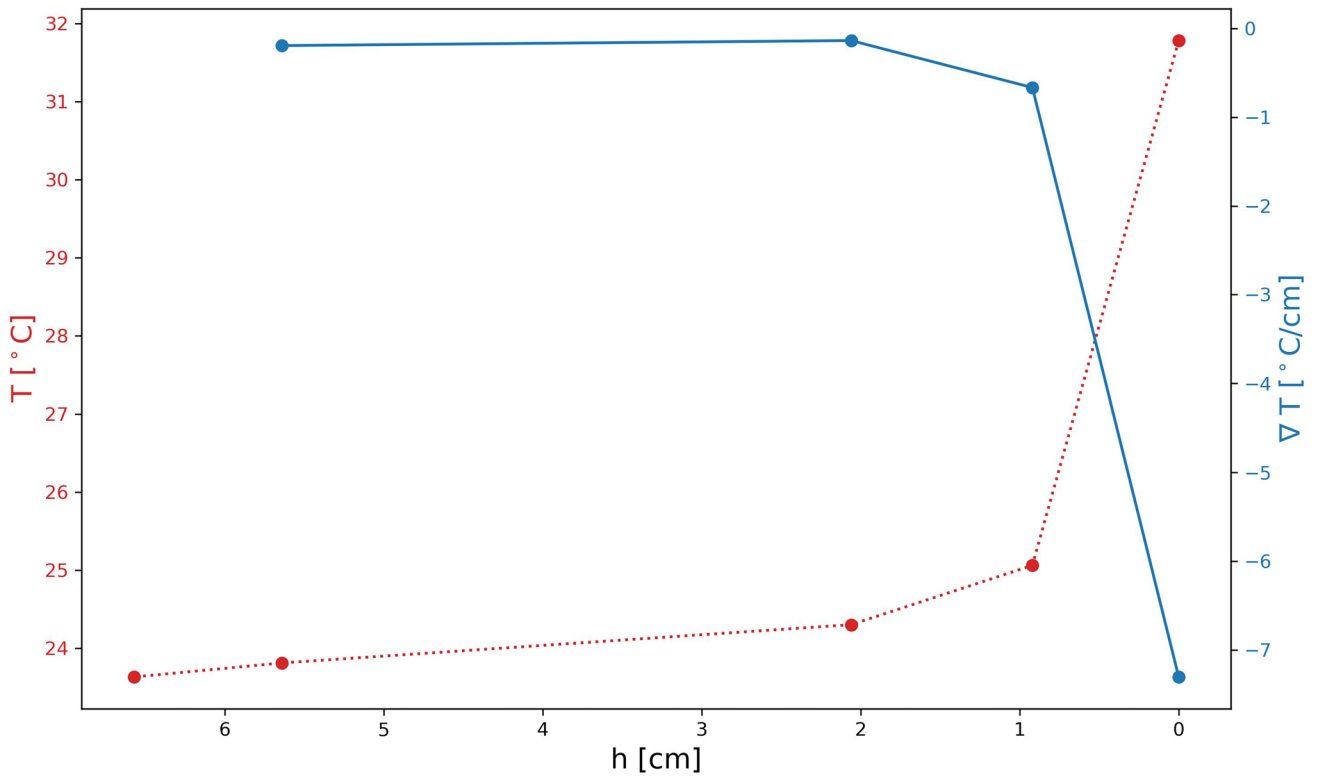


Fig. 4 Corresponding temperature (red dotted) and temperature gradient distribution (blue solid) along the glass wall of the experiment run at 50 Pa. h denotes the axial distance from the thermal manipulator

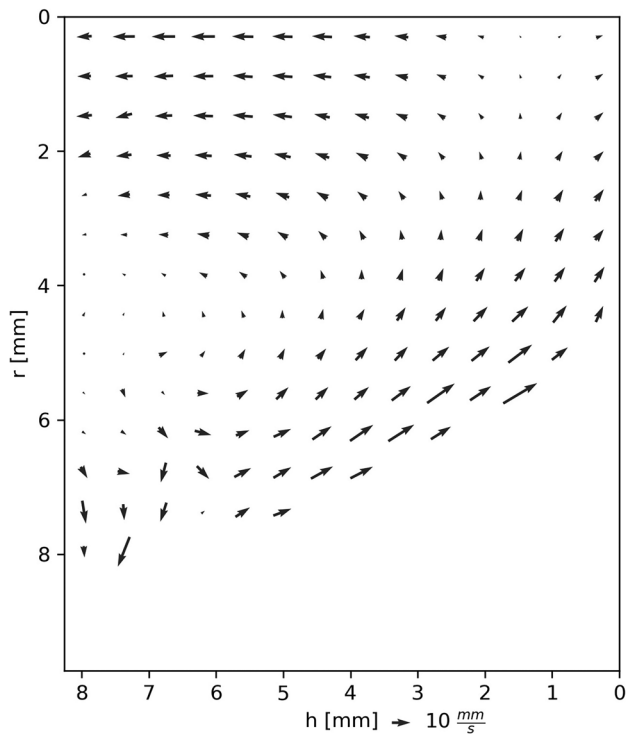


Fig. 5 Velocity distribution of microparticles with a radius of 3.4 μm at a pressure of 100 Pa and a direct current of 1 mA. h denotes the longitudinal distance to the heating ring. The velocity distribution shown was taken from the section of interest in Fig. 2

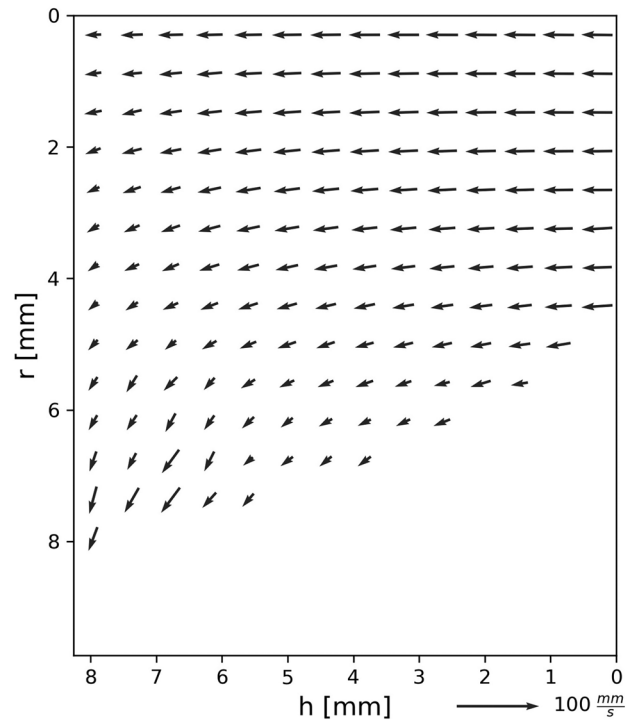


Fig. 6 Gas flow velocity distribution determined using microparticles with a radius of 3.4 μm at a pressure of 100 Pa and a dc current of 1 mA. The distribution of gas flow velocity shown was obtained from the section of interest in Fig. 2

Table 1 Summarized parameters of the experiment with temperature gradient. T_e was taken from Pustyl'nik et al. (2016) and Z_d was calculated via the reduced charge $z \approx 0.3$ (Antonova et al. 2019). ΔK_{TC} is the error of the thermal creep coefficient K_{TC}

p [Pa]	a [μm]	T_e [eV]	K_{TC}	ΔK_{TC}	Z_d
50	3.4	7.8	0.8	0.00010	5525
100	3.4	7.1	1.0	0.00016	5029

To further determine if a thermal creep was present, we used (Maxwell 1879)

$$\vec{v}_{tc} = K_{tc} \nu \nabla_{\parallel} (\ln T_W) \quad (5)$$

where v_{tc} denotes the creep flow velocity along the wall surface, K_{TC} denotes the thermal creep coefficient, ν denotes the kinematic viscosity of the background gas, ∇_{\parallel} denotes the tangential gradient along the wall, and T_W denotes the temperature at the wall (Maxwell 1879). If thermal creep flow is present, K_{tc} is between 0.75 and 1.2 (Bakanov 1992). Thus we calculate $K_{tc} = |\vec{v}_{tc}| / |\nu \nabla_{\parallel} (\ln T_W)|$ with the temperature distributions from Figs. 3 and 4 and calculate the kinematic viscosity of the neon background gas $\nu = \eta / \rho$, where the kinematic viscosity is $\eta = 0.553 \sqrt{m_n k_B T} / \sigma$ (Reif 1987) and $\rho = pM / (\bar{R}T)$, the mass density of the neon background gas with the molar mass M and the gas constant \bar{R} . To determine the thermal creep velocity near the boundary we use the determined gas flow velocity distributions as in Fig. 6 to retrieve the flow velocity along the longitudinal axis of the chamber $v_h(r=0)$. Afterwards, the thermal creep velocity is calculated via the gas flow profile distribution for thermal creep $v_h(r) = v_{tc}(2r^2/R^2 - 1)$ (Landau and Lifshitz 1987). Therefore, we obtained $v_h(r=0) = -v_{tc}$ to finally determine K_{tc} and to show that in both of our experiment runs a thermal creep flow is present.

The experiment's parameter and determined thermal creep coefficients are summarized in the Table 1.

Conclusion

We performed experiments in a dc neon plasma at low pressures with dust clouds manipulated by temperature gradients in a microgravity environment. Microparticle convection was investigated by following the trajectories of individual microparticles to conclude, using the equation of motion of the particles, that a gas flow was present. The gas flow, called thermal creep, was caused by the inhomogeneous heating along the glass chamber walls.

In Mitic et al. (2008) it was suggested that this phenomenon of microparticle cloud convection can be caused in microgravity, which has been proven in our work. In contrast

to Mitic et al. (2008), we observed dust waves in addition to convections. We suspect that the orientation of the temperature gradient in the direction of gravity suppresses the development of the waves.

In addition, we propose to investigate in the future under which pressure conditions the convections are suppressed.

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Author Contribution Andreas S. Schmitz prepared the experiments. Andreas S. Schmitz, M. Kretschmer and Markus H. Thoma conducted the experiments. Andreas S. Schmitz and Ivo V. Schulz analyzed the data. Andreas S. Schmitz wrote the manuscript.

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Data Availability The data of this study are available from the authors upon request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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