1. Introduction

1.1 Historical background

Tonks and Langmuir (1929) were the first ones who used the term ‘plasma’ to describe the inner region of a glowing ionized gas produced by means of an electric discharge in a tube. The term plasma represents a gas containing many interacting charged particles (electrons and ions) and neutrals. In outer space, a lot of matter exists in the form of a plasma, e.g. stars and nebulas. In some cases the plasma coexists with dust particles (nebulas). These particles can range from nanometers up to microns in diameter. They are also seen as building blocks for planet formation. These dust particles are in most cases not neutral, they obtain either a positive or negative charge due to interaction with the surrounding plasma and photon flux. In space the dust particles usually obtain a positive charge due to photo-ionization. A dust particle embedded in a plasma becomes generally negatively charged by the collection of electrons. A mixture of charged dust particles, electrons, ions and neutrals is called a ‘dusty’ or complex plasma. The historical background of dusty plasmas is quite old. In old manuscripts, bright comets have been described, like the famous comet of Halley. These comets are excellent examples for the study of dust-plasma interactions in space. A simple and nice example of dust-plasma interaction on a laboratory scale is an ordinary flame. The fact that a flame is considered as a plasma may seem as a surprise. However, strictly it is not. What makes it it close to being a plasma is the presence of very small particles (\(\sim 100\AA\)) of unburnt carbon. The yellow light emitted by the typical hydrocarbon flames is due to incandescence of these small dust particles heated to well over 1000 degrees Celsius. The thermionic emission of electrons from the dust particles elevates the degree of ionization within the flame to several orders of magnitude above what is predicted by the Saha equation for air at that temperature. There are more recent examples of dusty plasmas. These are ion thrusters used for propagation of satellites, processing plasmas used in device fabrication (e.g. amorphous silicon solar cells, microchips for computers), dusty plasmas created in laboratories for studying collective processes, plasma crystals, etc. In thermonuclear fusion plasmas dust formation takes place in the cool edge layers in contact with material walls. The dust has become a safety issue for future fusion reactors (ITER). The dust particles may retain a large fraction of hydrogen which will lead to considerable tritium inventories [1]. Furthermore, these fine dispersed dust particles may be chemically reactive and may spontaneously react with oxygen or water vapor in the case of a vacuum or coolant leak. Another
aspect is the migration of dust particles. Due to thermophoretic forces and due to repetitive evaporation and condensation they may accumulate at cold areas of the device and they may block spacings and fill gaps which were introduced for engineering reasons.

1.2 Complex plasmas

In the previous paragraph some examples of dusty plasmas have been given. In the case of a processing plasma, e.g. for the fabrication of amorphous silicon solar cells, a mixture of silane and hydrogen gas is injected in a reactor. These gases are decomposed by making a plasma. A plasma with a low degree of ionization (typically $10^{-5}$) is usually made in a reactor containing two electrodes driven by a radio-frequency (RF) power source in the megahertz regime. In that case a RF plasma is made in which a lot of species (ions, radicals, neutrals and electrons) are formed. Under the right circumstances the radicals, neutrals and ions can react further to produce nanometer sized dust particles. These particles can stick to the surface and thereby contribute to a higher deposition rate (increase with 100 %) which is often seen when the plasma enters the so-called $\gamma'$-regime. Still no definitive explanation has been found for this large increase in deposition rate. Another possibility is that these nanometer sized particles coagulate and form larger micron sized particles. These particles obtain a high negative charge, due to their large radius and are usually trapped in a radio-frequency plasma, because of there interaction with the electric field present in the discharge sheaths which is directed towards the electrodes (fig. 1.1)

When the interaction of the dust particles with the plasma changes considerably the plasma quantities as e.g. electric potential, electron density and temperature, ion densities and gas temperature, the plasma is called a dusty or complex plasma. Others [2] have studied complex plasmas by injection of spherical micron sized particles in noble gas plasmas. On earth usually a two-dimensional dust crystal is formed containing several lattices. In these crystals the dust particles hold each other at regular distances due to the Coulomb force. Electrons, ions and neutrals can still move freely through the lattices. In some of these dust crystals a dust free region (void) has been observed [3] which is usually surrounded by a crystalline region. Similar experiments have been carried out on the MIR, International Space Station (ISS) and TEXUS rocket experiments to observe dust crystals under microgravity. These microgravity experiments show three-dimensional crystals with a void in the middle. The appearance of this void was a mystery for quite some time. Modelling efforts from our side have shed some light on this issue.
1.3 Previous work, Contribution of this thesis

Prior to the work in this thesis, modelling has already addressed the behavior of dust in radio frequency plasmas [4, 5, 6]. However these models can not be used to model discharges which contain a large amount of dust (million of dust particles) as in the experiments carried out under microgravity. Usually important processes like, e.g. recombination on the surface of the dust, dust transport, accounting for the dust charge in the Poisson equation and heating of a dust particle are neglected. The main contribution of this thesis is the self-consistent modelling of complex plasmas including the important processes mentioned above. For this two previously developed fluid models (silane and argon) [7, 8] have been extended with a dust fluid to model a complex plasma. The one-dimensional silane fluid model has been extended with dust as an additional species to find a possible mechanism which could explain the large increase in deposition rate seen in the experiments when the plasma enters the dusty regime. To model the experiments performed at the ISS, a two dimensional argon fluid model has been extended with dust. Both extended models are special in the sense, that these where the first models which could deal with the transport of large quantities of dust. The main problem behind modelling the transport of dust is the large difference in time scales between the highly mobile electrons ($10^{-9}$ s) and the slow, heavy dust particles ($10^{-2}$ – 1 s)
1.4 Outline thesis

This thesis deals with numerical fluid models which have been extended to model complex radio-frequency discharges. In the models dust is also treated as a fluid. The models are based on a combination of particle and energy balance equations for the plasma and neutral species, the Boltzmann equation to solve the electron energy distribution function and important processes which are triggered by the dust species. In chapter 2, the relevant basic theory of complex plasmas is reviewed. In chapter 3, the one-dimensional silane model extended with a dust fluid is described. Also results, e.g., for the electric potential, densities and deposition rates obtained for silane plasmas containing different amounts of dust are discussed. In chapter 4, the two-dimensional argon-dust fluid model has been used to give some insight in the formation of the void seen in the dust crystal experiments carried under microgravity. In chapter 5, the two-dimensional argon model extended with a dust fluid is described. Results obtained for situations where the dust fluid has a significant influence on the plasma properties are shown. In chapter 6, the two-dimensional argon-dust fluid model has been extended with a particle tracking module to take the inertia of the dust particle into account. The particle tracking module is described. Results obtained with this extended model show vortices which usually appear in dusty plasma experiments carried out under microgravity. In Chapter 7, the two-dimensional particle tracking model in which the forces are taken from the argon-dust fluid model is compared with a three-dimensional particle tracking model where the forces are modelled via a harmonic potential. Chapter 8, deals with the extension of the model described in chapter 5 to a multi dust fluid model. In this model different sized dust species can be followed. Results are shown for situations where the different sized species interact with each other. In chapter 9, the argon-dust fluid model described in chapter 5 is extended to a model that can deal with discharges containing positive ions, negative ions and dust. Comparisons are made for dusty electropositive and dusty electronegative discharges. The chapters 3 through 9 are approximately one to one copies of the papers listed below.

1.5 Publications related to this thesis

1.5.1 Publications related to chapters of this thesis


1.5. Publications related to this thesis


1.5.2 Contributions to work of others


1.5.3 Contributions to various international workshops and conferences

References