Progress in Colloid Propulsion

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José Mariano López Urdiales
M.B.A., Collège des Ingénieurs, Paris, France, 2002
Ingeniero Aeronáutico, Universidad Politécnica de Madrid, Madrid, Spain, 2000

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Author ....
Department of Aeronautics and Astronautics
July 19, 2004

Certified by ....
Manuel Martínez Sánchez
Professor
Thesis Supervisor

Accepted by ....
Jaime Peraire
Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

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Abstract

In the early decades of the Space Age, a great deal of work was put into the development of the Colloid Thruster as an electric propulsion system for spacecraft. In spite of the effort by the end of the 70s the programs were stopped in the USA and Europe before any design had gotten to fly in space.

An exhaustive study of the literature has been performed to identify what were the reasons behind the disappearance of Colloid Thrusters. Apart from programmatic reasons related to the introduction of the Space Shuttle, some technical reasons where identified. The technical difficulties had to do with the use of arrays of needles.

Aiming at overcoming these difficulties, an alternative way to construct Colloid Thrusters has been proposed. Instead of needles, holes in Teflon where used. This has been tested both numerically and experimentally with positive results.

This development may be useful not only for colloid propulsion but also for other technologies that require electrospray emission.

Thesis Supervisor: Manuel Martínez Sánchez
Title: Professor

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Chapter 1

Introduction

1.1 Rocket propulsion

A rocket is device that contains matter and a means to provide some part of this matter with kinetic energy and then eject it in a desired direction and in a controlled rate. The remaining mass of the rocket undergoes a time rate of change of momentum which constitutes a useful thrust.

An electric rocket is a type of rocket which transforms electric energy into kinetic energy for the ejected matter. This concept is illustrated in figure 1-1

A good review of the technologies and state of the art in electric propulsion of spacecraft can be found in reference [47].

1.2 Colloid propulsion

Colloid propulsion is a type of electric space propulsion . As such its aim is, using electrical energy, to expel at great speed a jet of matter that is globally electrically neutral.

In its operation particles with a high electric charge per unit mass are produced. These highly charged particles are accelerated through an electrostatic potential. This same phenomenon is called electro-spray.

A colloid is a fine dispersion of particles. The matter in the jet that is produced

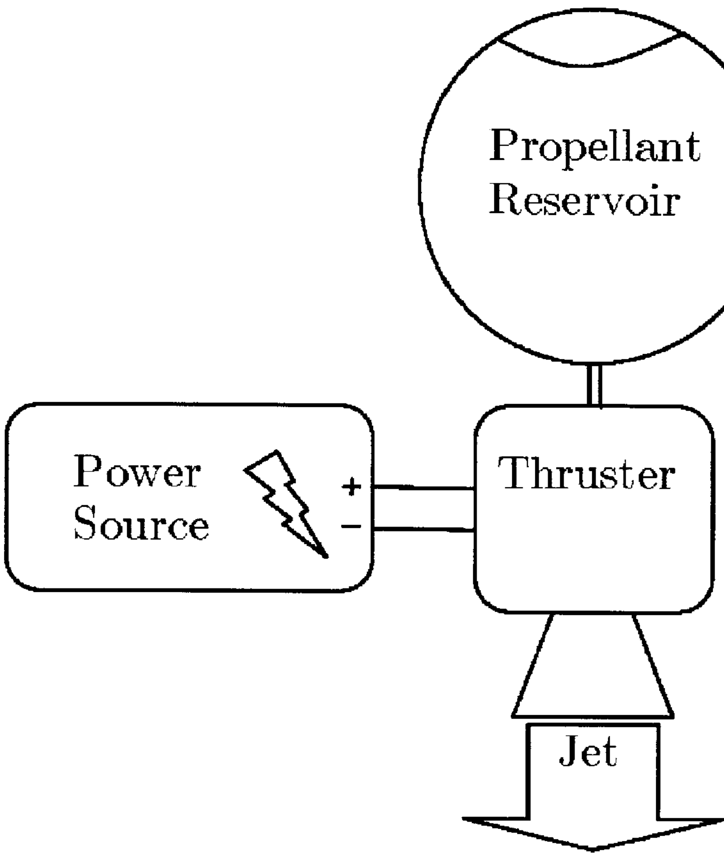

Figure 1-1: Functional diagram of an electric rocket

from a colloid thruster is finely dispersed and hence the denomination of "colloid propulsion". In most rocket propulsion systems the exhaust resembles a gas and therefore its behavior, notably its expansion, is different to that of a colloid thruster.

In order to assure the electrical neutrality it is necessary to expel the same quantity of charge that is being accelerated but of an opposite sign. This can be achieved either with many jets, some positively charged and others negatively, or by alternating the charge emission or finally by emitting a single positive jet and using an auxiliary cathode to emit electrons.

Of the many ways to produce charged particles that have been studied for this application it is electro-spray that seems to offer the best efficiency and uniformity.[18]

Electro-spray is a physical phenomenon that is used for many applications aside from electric propulsion. For instance, electro-spray is used to paint cars, or in the detection, by mass spectroscopy, of molecules in a sample. The idea is to subject a mass of electrically conductive liquid to a strong electric field. The field will draw charges to the surface of the liquid. If the field is strong enough, then the self repulsion due to the surface charge density overcomes the surface tension that holds the liquid together and, in this way, small charged drops will be ejected from the mass of liquid. The liquid should contain both negative and positive free charges.

Two types of liquids have been exploited as propellants. On the one hand, solutions of salts, such as salt water that has Na^+ and Cl^- dissolved in water and, on the other hand, molten salts. The solutions that are often used are based on formamide or glycerol. Liquid water, although an excellent solvent, is troublesome when used in a vacuum environment.

There exist salts that remain liquid at room temperature in a large window of pressures, they are known as ionic liquids. An example that is often used in colloid thruster studies is 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF4).

1.2.1 Electrospray, principle of operation

The following diagram shows an scheme of how an electro-spray works. In an axially symmetric configuration, an orifice full of liquid is in front of an extracting ring.

- In figure 1-2 the circuit is open and the liquid has its positive and negative charges evenly distributed. There are no external forces applied on the liquid and therefore the surface tension minimizes the surface of the liquid.

- In figure 1-3 the circuit is closed and a potential of about 1500 V is applied between the extractor ring and the liquid. Negative charges are attracted towards the liquid surface. Electric forces acting on the charges on the surface deform its shape into a cone, known as the Taylor cone.

- In figure 1-4 the surface charge density is large enough for negative charges to leave the bulk of the liquid towards the extractor. The electrospray has started.

1.3 Theoretical considerations

Some concepts that will be used later on this work will be introduced in this section. An extensive review of the magnitudes and physics involved in colloid thrusters can be found in reference [12].

1.3.1 Starting voltage

In order to start the emission of charged matter from an electrospray a certain electric field must be induced on the surface of the liquid.

Using an order of magnitude analysis and assuming the pressure in the liquid is small, one can equate the electrostatic pull felt on the surface with the surface tension. The following expression for the field can be thus obtained.

$$\frac{\varepsilon_o E_{tip}^2}{2} = \frac{2\gamma}{R_c} \tag{1.1}$$

In equation 1.1 ε_o is the vacuum permittivity, E_{tip} is the electric field at the tip, γ is the surface tension and R_c is a principal radius of curvature of the surface at the tip.

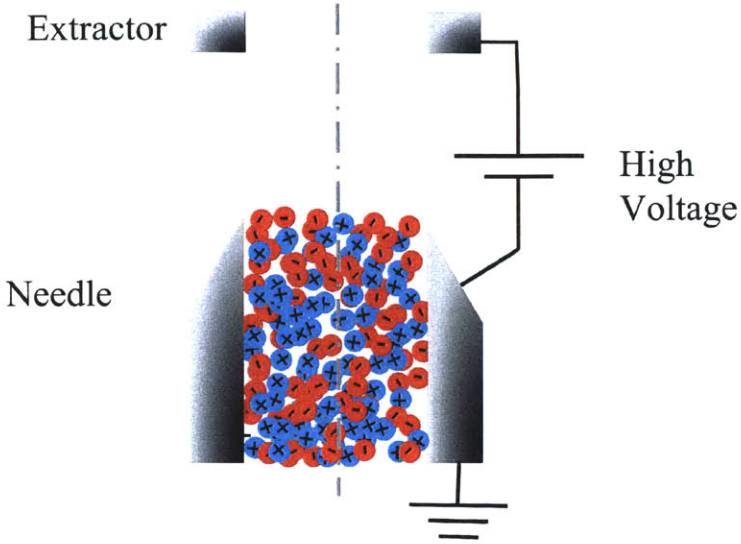

Figure 1-2: Electrospray off.

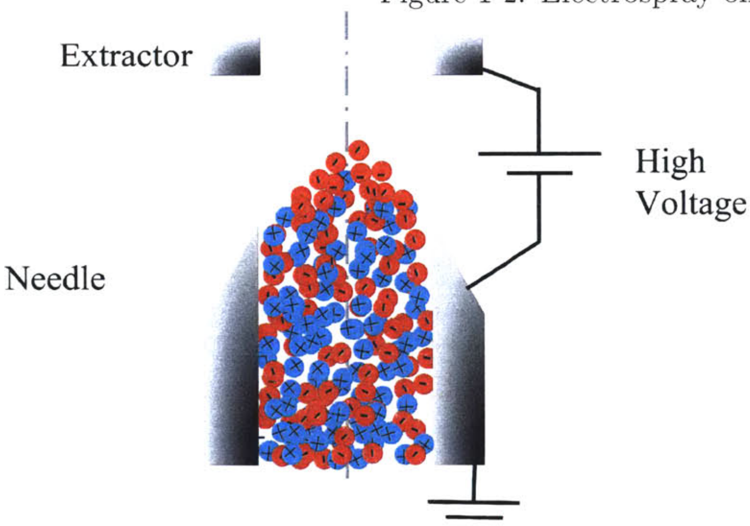

Figure 1-3: Electrospray starting.

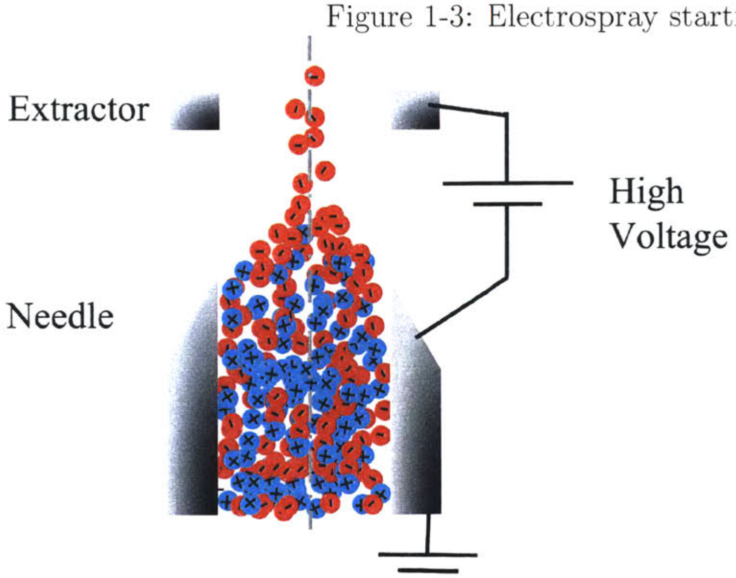

Figure 1-4: Electrospray on.

Assuming the shape of the tip constitutes an equipotential hyperboloid of revolution and the extractor is a plane the value of the electric field at the tip can be related to the voltage between the tip and the plane. Equation 1.2 was derived originally in the study of the field around solid metal tips [16]. This expression does not take into account the fluid dynamic nature of the phenomenon and it is therefore an approximation.

$$V_{start} = \sqrt{\frac{d_c \gamma}{2\varepsilon_o} ln(\frac{4D}{d_c})} \tag{1.2}$$

In equation 1.2, d_c is the diameter of the meniscus and D is the distance from the extractor to the meniscus.

1.3.2 Hydraulic impedance

One of the most important aspects of colloid thruster development is how to integrate a large number of emitters so that the total thrust approaches the values of interest for application of the technology. Arrays of emitters are needed to achieve this.

There are two ways an array of emitters can be fed with propellant. On the one hand each emitter could have its own propellant reservoir. This is an approach that has not been yet explored and holds promise because of the advances in microfluidics and microfabrication. On the other hand emitters may share a common reservoir and be fed from a manifold. This second approach is the most common one and the one that will be followed in this study.

It is useful to introduce the concept of hydraulic impedance, Z_h, across a duct. It is defined in equation 1.3 as the pressure difference across the duct (ΔP) between the mass flow flowing through it ($\dot{m}$).

$$Z_h = \frac{\Delta P}{\dot{m}} \tag{1.3}$$

It is generally accepted that in order to obtain stable emission from each emitter the hydraulic impedance from the common manifold to the tip of the emitter has to be large for each emitter. Otherwise only the emitters with low hydraulic impedance would emit. This implies that designs will typically have large ratios of the length of the channel divided by its cross sectional dimension.

Chapter 2

Literature review

The literature concerning colloid thruster development has been reviewed. It was found that while, a great deal of work was devoted to this subject in the 60s and 70s, there is a blackout in the 80s and early 90s. In addition, it has been noted that the work done from the mid-90s on is not a continuous development of what was left in the late 70s. This review has been done with the aim in mind of finding out why the development of this technology suddenly stopped. Shedding light on the reasons that lead to that interruption is a useful step in the process of directing innovation to improve the system.

2.1 Introduction of the concept and first efforts

The concept of electrostatic acceleration of colloids started to be seen as a viable and attractive means of propulsion in the early sixties. [64] Mission designers saw this technology, in synergy with nuclear reactors, as an enabling technology for human exploration of the Solar System.[34]

Different concepts to create the charged colloid were presented and studied. They produced a stream of charged particles by different means. These methods will be exposed in section 2.1.1.

2.1.1 Colloid propulsion systems not using electrospray

A great deal of the effort was devoted on the generation of the charged colloid itself. And it was not taken for granted that it had to be done using electrospray.

Some of the efforts to produce the charged colloid involved using small preformed solid carbon particles. In 1965 the results of an experiment were presented. Carbon particles were injected inside an Argon cold cathode ion source. The system applied an anode voltage of 1350 V and -1000 V at the cathode. The thrust was deemed too small to be practical.[23]

A different way to charge the carbon particles was tested with a new design. It used a hot filament to bombard with electrons a metal anode. This produced soft X-rays that by X-ray photoelectric effect and Compton scattering charged positively the particles. Two ring electrodes axially mounted provided the axial electric field that accelerated the charged particles. The specific charge was measured and a distribution between 1000 C/Kg and 10000 C/Kg was obtained. It was seen as a potential attractive alternative to cesium ion engines.[24].

At NASA Lewis the charging of preformed submicron carbon powder was studied. The particles were charged by contact between two metallic electrode plates at high voltage. Particles oscillated when they are charged between both electrodes. One of the electrodes had a hole through which some charged material eventually escaped. The powder was of about 1.5 μm average size. The specific charge was detected with a quadrupole mass filter. This device consists basically in four cylindrical rods in the corners of a square. Alternating current is applied to the rods to destabilize all particles trajectories except those with a particular q/m which is collected at the end. The specific charge measured was much lower than the one that would correspond to a sphere charging in contact with a plane. The reason for the poor charging is presumably that the once the particles charged a bit they left the contact with the electrode due to electrostatic repulsion, before acquiring that maximum charge.[21]

At Stanford, some efforts were dedicated to improve the mechanism of charging of the solid particles with hot cathodes. A solenoid was added to trap the electrons and enhance the charge transfer to the particles. In this new design, particles became charged because of secondary electron emission. Aluminum Oxide particles of 1 μm of diameter where used. The specific charge obtained was in the range 100-200 C/kg. The device operated with voltages of 700V and -1000V. [28].

Thiokol, the leader in Solid Rocket Propulsion in the United States of America (currently ATK) expressed interest in the concept of colloid propulsion. Thiokol proposed to generate a charged colloid beam by chemical reactions. A diffusion flame of Mg vapor with O_2 produced nanoparticles of MgO. Then a hot filament was used to charge them. This was enclosed in a tube of 3 inches of diameter. The nominal massflow of the thruster was 0.6 g/min .[13]

At NASA, experiments were done on the production of liquid particles from condensation of a homogeneous vapor. Vaporized propellant was expanded and rapidly cooled in a supersonic nozzle and thus homogeneously condensed into particles of 5-10 nm. The problem that approach faced was that the particle formation efficiency was too low.[21]

All these efforts to generate highly charged and monodisperse powders failed to reach the ranges of q/m that would make them attractive for colloid propulsion. However it should be noted that in recent years significant progress has been made on the capabilities to produce very small monodisperse solid particles. The growing field of nanotechnology may provide ways to overcome the limitations faced by researchers in the 60s and render the concept attractive again.

2.1.2 Initial US electrospray-based colloid thruster development

The idea of building a colloid thruster based on electrospray of a liquid was already discussed in the early 60s. Three patents protecting three particular embodiments of the technology, were issued in 1964. These works only provided general advice on the properties that the liquid propellant should have, such as low vapor pressure. It was yet unclear then what liquid and with what dopants would be most appropriate.[61][60][20]

The United States Air Force started a systematic effort to identify a propellant that would work well in the negative mode, that is when the jet is negatively charged. A concern was to avoid negative emission of electrons since that would greatly decrease the efficiency. They identified a set of electrochemical criteria that the metallic electrode must have with respect to the ions in solution in the propellant. A series of time of flight experiments was carried out. One propellant combination that performed well was $ZnCl_2$ dissolved in glycerol, resulting in a specific charge of over 3000 C/kg. [72].

Also interested in the negative mode operation, TRW went on to do a parametric study using a singel needle as an emitter. They looked for working fluids that performed well on the negative mode. An extensive campaign of propellant testing on negative mode was performed. The propellants were all glycerol based and the dopants included H_2SO_4, $MgCl_2$ $FeCl_3$ and $SnCl_4$. The most promising results came from solutions of glycerol doped with Stannic Chloride ($SnCl_4$) and glycerol doped with Ferric Chloride $FeCl_3$. Apparently the chloride plays a role in avoiding the formation of bubbles in the negative mode. $SnCl_4$ was chosen to be used for the negative mode in a bipolar design. Using time of flight, a specific charge of up to 3000 C/kg was measured. The typical massflow was 1.3 10^{-9}kg/s [30]. On all negative modes erosion was seen after more than 200 hours. [29] TRW presented a working prototype of a 16 needle bipolar module. In order to test the new colloid thrusters, TRW built a vacuum thrust test-stand able to measure in the range 1-8 μlb.[76] The device had an overall specific impulse of 800 s at an efficiency higher than 70%. The neutrality was measured as the voltage on the collector. This voltage remained always in a range of $\pm$100 V. The thruster used different propellants for each mode of operation, for the positive one it used 19.3 % by weight solution of NaI in glycerol, whereas for the negative mode it used $SnCl_4$. The propellant feeding mechanism consisted on a spring loaded tank. The thruster was capable of electrostatic thrust vectoring and the transversal thrust was measured. The engine compared favorably to cesium contact ion engines and was proposed for North-South station keeping of geostationary satellites.[7]

In a joint effort of the Air Force Aero Propulsion Laboratory in the Wright-Patterson Air Force Base in Ohio and TRW, a bipolar thruster prototype was built. It sprayed simultaneously with eight negative emitters and six positive ones. Time of flight techniques were used to measure a thrust of 51 μlb at an specific impulse of 760 s. NaI/glycerol was used for positive emission while $SnCl_4$/glycerol was chosen as the propellant for the negative emission. This negative mode propellant was developed to mitigate the bubble formation problems of NaI/Glycerol when used in the negative mode. The gas in the bubbles was identified to be Hydrogen. Stannic Chloride was chosen because the stannic ion reduced itself to stannous thus oxidizing the hydrogen which this way stayed in solution. Among other compounds that had this property SnCl4 was preferred for the higher conductivity solutions that could be prepared with it. Another problem that was encountered was arcing. Positive changes in the design were: to reduce capacity of the needle-emitter by reducing the mass of the extractor, and to place a $10^5\Omega$ resistor between each emitter and the high voltage circuit. Three life tests of about 50 hours were performed. To check the neutrality of the beam, the current impinged on a floating collector that stayed always at $\pm$ 100V.[1]

The Air Force of the United States of America along with Electro-Optical systems, a subsidiary of Xerox Corporation, worked on another exploratory program of colloid propulsion. The study mapped the specific charge distribution efficiency with average specific charge for a large group of propellants. A general trend followed by most propellants tested was that increasing the average specific charge of the beam had a detrimental effect on the charge distribution efficiency. The best propellant identified was tetraethylammonium chloride oleic acid (TEAC). TEAC performed equally well for negative and positive voltages, it also exhibited good feed control and reproducibility. An attempt at a bipolar thruster was made. Tapered needles with a sharp rim of 0.001 inches were chosen for the injector geometry. The needles were made with platinum to prevent corrosion. The needles' capillaries were stuffed with a wire to increase the flow impedance. The spacing between similar polarity emitters was 0.2 inches and 0.141 inches between opposite polarities. The propellants used were

20 g of NaI in 100 ml of glycerol for positive operation and 2 ml H_2SO_4 in 100 ml glycerol for negative. The emitter section was designed to operate at a mean negative voltage to shield it against electrons. The voltages of operation were 4.4 kV and -5.8 kV. The average currents in the experiments were 150 μA plus and -154 μA negative. The final output was a bipolar thruster of 70 μlb of thrust what worked for over 50 hours. Using time of flight experiments the power over thrust ratio was measured to be 20 W/mlb.[50] In parallel, at the United States Air Force Base of Wright-Paterson work on a 80 μlb bipolar thruster was initiated. The typical specific charges achieved were 1.3 10^5 C/kg in the positive mode and 1.3 10^4 C/kg in the negative mode. The voltages used were also +4.4 kV and -5.8 kV. It was claimed that the system yielded better efficiency than ion engines up to an specific impulse of 3000 s. The inherent scalability of the device promised a large array of potential uses. Another advantage that was pointed out was that it could operate in pulsed mode without power penalties. The main problems that were encountered were erosion of the emitters due to arcing as well as deposition on the negative emitters and erosion on positive ones. The system used 73 needles as emitters. The positive mode propellant was a solution of 20g of NaI in 100ml of glycerol, whereas the negative mode propellant was 2ml of H_2SO_4 dissolved in 100 ml of glycerol. [15] As part of this effort, models and analytical derivations of performance curves for these thrusters were developed.[53]

From experimental observations it was understood that the satisfactory operation of the thruster greatly depended on the needle electrochemical properties and geometry. NASA at Goddard started a project aiming for a better understanding of what should drive the needle design. In an extensive test program, forty-eight single needles with various materials and geometries were tested. Pointing out the analogy of electrospray and an electrochemical process in an electrolytic cell, needles where tested as electrodes on an electrolytic cell. To accelerate the corrosion process the current applied was of several mA instead of the μA encountered in electrospray operation. Experiments on a electrochemical cells were performed at 20 V DC. The fluid in the cell was a typical glycerol NaI colloid thruster propellant. The experiments showed that heavy deposits of iodine appeared on gold plated stainless steel needles while, on the platinum plated ones, the iodine washed off easily. Recognizing the difficulty of maintaining aligned an array of hundreds of needles permanently attached to a common feed system, all equidistant from each other and each surrounded by an extractor, considerable thought was given to finding an alternative and simpler geometry. An annular slit thruster was then proposed, built and tested. The propellant was made to flow out of the gap between two concentric surfaces. It was tested only in the positive mode. The propellant was 25 g of NaI in 117 ml of glycerol. The propellant was fed at a pressure of 55 mmHg. The total voltage was 20 kV and it extracted a current of 175 μA. The specific charge achieved was 2852 C/Kg, yielding a thrust 6.2 μlb at an specific impulse of 1085 s. [68]

The design of the annular thruster was further improved in NASA Goddard. The annular gap between the concentric cylinders was brought down to 0.001 inch or less.[74]

A series of tests on a 36 needle thruster were performed. The device was capable of thrust vectoring. Normal conditions of operation where the following: total voltage of 9.35 kV, current of 240 μA, feed pressure of 1.1 inches of Hg, massflow of 12 μgram/s. In that conditions an specific impulse of 1650 s at an efficiency of 70% where attained. The performance was measured both by thrust stand measurements and time of flight. The agreement between both methods was up to a 10%. [31]

Aiming for high thrust controllability, TRW presented a three needle thruster. It consumed 5 W of power to provide 8 μlb of thrust at 990 s of specific impulse. It had a very smooth steady state and transients. The total system weight was 7 lb. The device operated for 1750 hours with a current of 36 μA. It was noticed that operating at higher voltages a more collimated beam was produced.

A study of the beam divergence was performed. It was found out that the specific charge emitted from the needles was anisotropic. Therefore the time of flight values measured using one single collector provide only the average value of the charge distribution but not the value at each angle of divergence. [19]

TRW also explored AC and pulsed operation of colloid thrusters. It was hypothesized that the hydrogen bubble generation problem present when operating in the negative mode is neutralized by the free iodine produced by the positive half of the cycle. The minimum pulse periods measured where of 50 ms. It was observed that to operate in pulsed mode, it is better to reduce the extraction voltage by about 25 %, just below the voltage at which the emission stops, instead of turning it off. Interesting observations of the AC transient jet dynamics where made: the jet collapses in 1 ms however to completely reform the jet the time needed was about 3 ms. Results were taken using both square and sinusoidal waves. In spite of having an inferior duty cycle, sinusoidal AC was preferred over square waves because of simpler and less heavy electronics. The results indicated a lower specific impulse for the negative half period. For instance, at 50 Hz the specific impulse in the negative mode was about 500 s and in the positive about 700 s. Using stroboscopic imaging it was seen that, if switching was done at less than 100 Hz, the jets appeared and disappeared during switching. For higher frequencies the jets remained stationary through the cycle. Different frequencies up to 50 kHz were studied. The idea behind going to very high frequencies was that, at some very high frequency, the thruster would not be space charge limited. The mechanism proposed was that the ions and particles would make a quasineutral plasma and, as such, it would not build up potentials high enough to spread the beam or stall it. [62]

In another series of tests, a single capillary needle in AC was used. An audio oscillator fed a sine wave signal to a 200 W amplifier which was connected to a high voltage transformer with 4 kV rms. Again, while recognizing that square wave is more attractive because of its fuller duty cycle, sinusoidal waves are preferred because the simplicity of the analog electronics required outweighs the loss in efficiency. In the study different propellants were used, including NaI with glycerol, tetraethyl ammonium chloride and H_2SO_4 with glycerol. The range of frequencies studied was from 100 Hz to 2.7 kHz. It was noticed that in the continuous negative dc mode NaI performed "hashily". On the other hand at AC the operation was very smooth at both half cycles. Both the positive and negative beams have particles of an specific charge of the order of 10000 C/kg at 1000 s of specific impulse. Using time of flight it was determined that the efficiency was about 40%, which may seem low but since no neutralizer would be needed it is still considered attractive for thrusts below 100 μlb. [11]

The United States Air Force wanted to increase the thrust per emitter and decided to explore two new configurations of emitters. One was a tubular emitter that has a capillary for mass flow control ending on a tip that has a rim of relatively large diameter was constructed. A four emitter prototype was tested a 100 hour resulting in 75 % efficiency, a current of 265 μA and 123 μlb of thrust. The other new configuration consisted in annular feeds between two concentric cylinders. A three emitter prototype was been tested for 113 hours with average values of specific impulse and thrust of 1370 s and 400 μlb respectively. [58]

Further work was performed on the tubular concept. A prototype which provided 547 μN of thrust at 75 % efficiency was constructed. The specific impulse, as measured with time of flight, of the device was 1325 s. This device had extra electrodes for electrostatic thrust vectoring. [26]

The United States Air Force launched a flight qualifying program for a complete colloid thruster system. The design voltage was chosen to be substantially higher than originally thought in order to take into account manufacturing variability, build up of films on the emitters, the subsequent changes in the configuration of the propellant a the tip and the effect of all this in the electric field. [27]Under the Colloid Advanced Development Program, TRW designed a 432 needle colloid thruster for the US Air Force. It had 12 modules each with 36 needles. Aiming for 1 mlb of thrust, it used a solution of 3 g of NaI per 10 ml of glycerol. The motor operated only in positive mode and the potential in the needles was 12.3 kV needles, while the extractor was at -2 kV. It had a shield electrode around each needle to protect them from secondaries. The specific impulse targeted was 1500 s. At TRW a 36 needle module was tested 4350 hours and it showed a 15 % performance loss at end of life. The degradation was caused by needle tar buildup, material build up on the shield electrode and needle erosion. The three have a detrimental effect on the configuration and intensity of the electric field. [59].

TRW went on to carry out investigations on multi needle configurations but needle erosion or wax build ups were a recurring problem. The multi-needle arrangement was complicated to reproduce while making sure that each needle had the right shape for the field and also the same dynamic impedance for the flow.[9]

The following table 2.1.2 indicates some characteristics of the 432 needle prototype.

Table 2.1: Performance of a 432 needle prototype in 1974.

Thrust	Specific Impulse	Power	Efficiency
1 mlb	1365 s	70 W	58 %
Needle Voltage	Extractor Voltage	Specific Charge	Extractor Current
12.2 kV	-2.3	12500 C/kg	25 μA

There were concerns about the erosion and deposition on the needles.[75] From 1975 to 1978 work was done to understand these problems. An interim report already pointed out that that the jet contained ions and that these ions could collide with the drops and produce negative ions that were thus accelerate towards the emitter, causing erosion. [51]

In 1978 an extensive report from the AFOSR was issued to try to identify the mechanisms that caused the performance degradation of colloid thrusters that was observed after 1000 hours of operation. The thrusters emitted only positively charged drops and ions. The explanation put forward was that the fast ions hit drops and produced some negative iodine ions that hit back the emitter. This, through erosion and sputtering, changed the shape of the emitter, changing the electric field at the tip of the emitters. The model seemed to account for the damage observed. [43] Erosion and deposition problems where technical issues that, while serious, could be tackled by better designs. Issues of a different nature proved harder to overcome. The following paragraph extracted from reference [75] sheds light on the type of concerns of the program at the time:

> *"11.1 APPLICATION TO NEAR-TERM MISSIONS Hard targets for advanced performance systems such as colloid propulsion are clouded by*

two considerations that dominate current advanced space mission planning. First, is ***extreme dominance of budgetary considerations*** *and elimination of new "high risk" equipment wherever possible. Potential advanced capabilities are not used in the most preliminary mission feasibility studies. This is especially true for housekeeping subsystems. The second dominant consideration is the introduction of the Space Transportation System, or Space Shuttle. This has two effects. One is that the cost of the Shuttle itself will dominate the available space budget for the next several years. This is specially true for the NASA, but also true for DoD's committed development of the Interim upper Sate. In an era of fixed budgets for space, the payload funds will have to shrink to meet any growth of Shuttle funding requirements. The payloads directly tied to Shuttle, such as Spacelab and its derivatives, will likely fare better than the free flyers. Second, the* ***announced payload mass capabilities of the shuttle*** *are greater than current booster's. Many mission planners assume that this extra capability will be used to extend the use of current technology and relieve the dominant need for mass efficiency."*

In other words, the colloid thruster was another casualty of Shuttle. Now it is well known that Shuttle failed miserably to deliver on its promised economic efficiency and that is another reason colloid thrusters, and electric propulsion in general, may receive more attention.

2.1.3 Initial European electrospray-based colloid thruster development

The European Space Research Organization (ESRO), precursor to the current European Space Agency (ESA) started to work on colloid thrusters in 1969 and concentrated in developing a linear emitter of about 19 μm separation but first efforts obtained still very low charge over mass (10 C/kg). [14]

A linear slit thruster using a pair of commercial razor blades was developed at the University of Southampton. The device yielded a specific charge of 40000 C/kg, a thrust of 100-150 μN at an efficiency of 60%. The performance was measured using time of flight. The divergence of the jet was deemed too large. Another problem identified was that the NaI glycerol propellant had undesirable electrochemical side effects. The liquid was fed into the slit by capillarity between the razor blades. The two most typical gaps tested were 150 μm and 200 μm. [41] Due to the large divergence of the beam, of about 60°, a new design was made. It introduced a single raised edge sandwiched inside a slit and made from a commercial razor blade. This central blade was externally wetted and the emission took place at its rim. The propellant wetted both sides of the blade and the beam divergence was reduced to 30°.[6] The thickness of the blade was 100 μm and the central edge protruded 400 μm from the edge of the exterior blades. The specific impulse was about 1530 s at an operating voltage of 10.5 kV. The slit provided a thrust of 80 μN. The problem with this design was the evaporation of propellant from the large exposed area.[42]

In Europe various slit colloid thrusters were tried both in linear and annular configurations. A typical value of thrust per unit length was 70 μN/cm.[9] At the European Space Research and Technology Center (ESTEC) an annular thruster was tested and characterized. The propellant used was a mixture of sodium iodide and glycerol of 20% by weight. Successful operation at both positive and negative polarity was achieved. At high current levels in the negative mode hydrogen was liberated. [5] In addition to the linear emitters, an annular emitter of 15 μm annular gap was designed. The voltages of operation where 12.5 kV and -2.6 kV. Using time of flight a thrust of 0.5 mN at an specific impulse of 1223 s was measured. It was life tested for 500 hours.[10]

As a result of an strategic study on the European propulsive needs, ESRO decided that colloid thrusters was the most promising technology for secondary propulsion, like station keeping. It chose to develop at a lesser level the field emission thruster (FEEP) for missions requiring very high specific impulse. However there were concerns about the actual life colloid thrusters could to endure.[8]

Recognizing the interest of possible bipolar or AC operation, ESRO started a program with the University of Southampton to find a propellant that would be suitable for both polarities. A series of experiments using cyclic voltametry were made to study the oxidation and reduction reactions that take place in the propellant of choice at the time, NaI dissolved in glycerol. The results indicated that the said propellant lacks an ability to accept electrons, making it unsuitable for continuous negative mode operation. Then the efforts concentrated in trying to find a molecule that would have the ability to take an electron or a hole, with equal ease. A candidate material that is identified as a promising is 9:10 diphenyl-anthracene.[44].

Apart form the basic research on propellants, ESRO sponsored theoretical and experimental studies of the energy losses from surface creation and viscous dissipation of a single Taylor cone were performed.[2]

The University of Southampton tested a 3 cm linear slit thruster with a separation between blades of 16 μm. A mixture of glycerol and NaI was used as propellant. The current versus voltage plot exhibited quantum like jumps, probably due to bifurcations of the points of emission. Typical values of the operation of the were an specific charge of 6000 C/Kg, a current of 100 μA, a thrust of 150 μN at an efficiency of 65%. [3] This result, in 1975, was the last reported. It is unclear why no more publications or reports on colloid propulsion where issued in Europe. A possible explanation could be have to do with the reorganization of the Space supranational institutions in Europe that took place precisely in 1975. ESRO was incorporated in ESA and funding and priorities shifted towards the development of the Ariane launcher.

2.1.4 Soviet electrospray-based colloid thruster development

In the Moscow Aviation Institute work on colloid thrusters went on for 35 years until 1995. Some of this work became public that year. A unit of 0.5-1mN thrust and 10Ns total impulse consuming 30W was developed but, as far as it is known, never flown. The thruster operated in DC and had an Isp of 10^4Ns/kg, an average specific charge of 3330 C/kg, weighting 5kg and had a life of 2800 hours. The propellant was glycerol-based.[63]

One of the applications that was looked at was small satellites. The propulsive requirements of 35kg mass satellites ejected from the airlock of the the space station MIR were studied. These satellites could be useful for conducting experiments that require periods of astronaut interaction and also periods in a very clean acceleration environment. The requirements were estimated to be a mass less than 7 kg, a total power consumption of less than 30W, a thrust range of $4*10^{-4}$ to 10^{-3} N, and total impulse 1400 Ns for an active flight time 30 days. The study pointed to colloid thrusters as the most efficient option for the mentioned requirements. [45]

2.1.5 Contemporary colloid thruster development

In 1997 in an article from JPL in which state of the art small propulsions systems such as small ion engines and FEEPS was published. This work pointed out that:

> of all micro-electric primary propulsion options [...] colloid thrusters are quite possibly the most suited for microspacecraft primary propulsion applications[...]

[48].

Veterans of the technology of colloid thrusters, notably J. Perel, started a company named Phrasor in California. In 98 Phrasor proposed it again using an integrated MEMS design of "microvolcano emitter". They also proposed feeding the emitters with capillarity. The foreseen application was microspacecraft main propulsion systems.[52]

At about that time a team formed by MIT, Yale and Busek, a company based in Natick Massachusetts, published preliminary work on the topic.[46]

Development work was started in Stanford, where a prototype of 100 emitters stainless steel capillaries with 0.006" od and 0.002" id. was constructed.[55]. The prototype included the emitters, power processing unit and controls; it was tested for 100 hours. With a 4.4 kv acceleration potential it attained 200 s of Isp. The propellant was glycerol with 2 molar sodium iodide. In addition to needle emitters, Stanford also did experiments with a slit emitter provided by the company Phrasor.[56]

Applying modern results in electrospray applied to mass spectroscopy, electrospray in the cone jet mode was proposed as a source of particles for colloid propulsion. This allows for lower voltages of operation. An example: using a solution of Sodium Iodide in formamide with a conductivity of 1.5 S/m. Experiments have been reported in which at a massflow of 4 10^{-11} kg/s and an extraction voltage of 1547 V produces an specific charge of 4760 C/kg. The thrust thus obtained is 0.134 $/muN$ and the specific impulse is 341 s.[18]

Busek worked on a 57 needle thruster with an extractor grid and accelerator grid. A carbon nanotube neutralizer was included to emit electrons. The needles where made of stainless steel and had an internal diameter of 30 $/mu$ m and an external diameter of 180 $/mu$m. The thrust was measured to be from 20 to 189 μ N and the maximum Isp was 400 s. The propellant was a Formamide solution with 0.5 S/m of electrical conductivity.[25]

Interest in formation flying mission sand microspacecraft constellations revived research on colloid thrusters. Missions like LISA require accuracies of the order of 0.1 μN in a range up to 20 μN as well as high specific impulse (more than 500 s). Colloid thrusters are specially well suited to meet the new requirements these new missions have. According to an MIT study fine controllability and moderate to high delta V is a niche that colloids could fill, having the additional advantage over other competing technologies that they need substantially less power. [57]

With the aim of taking advantage of recent advances in miniaturization, MIT has worked on a 1-D array of microfabricated emitters. This effort resulted in a prototype using 240 emitters which, if operated at 4000V, would yield a performance 0.3 μN at an Isp of 500 s, using formamide with NaI as propellant. The prototype was microfabricated on silicon.[71] Further work performed at MIT involved the microfabrication of externally wetted 2D thrusters. Emission from the 2D emitter array was verified experimentally.[70][69] MIT has also advanced the understanding of what is called the mixed ion-droplet regime, that is when the plume consists in a mixture of drops and solvated ions. This is attractive because solvated ions have a charge/mass ratio too large and drops only has too low Isp, only acceptable to low Delta V missions. Time of flight and stopping potential experiments have been performed to determine the energy distribution of Formamide NaI plumes.[36] Experimental results show that drops have up to about 9000 C/kg. Solvated ions consist of Na^+ ions and seven molecules of formamide which results an specific charge of 280590 C/kg. While this averaging effect can be useful, too much polidispersity in the beam can can result in low overall efficiencies,[35][37]. Following the design of Liquid Metal Ion Souces, but using the ionic liquid EMI-BF4 instead of a liquid metal, externally wetted ion sources have been developed at MIT[38]. The life of these devices has been shown to increase dramatically if voltage is alternated instead of kept constant[39]. This remarkable electrochemical behavior opens the prospect for bipolar thrusters based in the technology of externally wetted ionic liquid ion sources.[40]

JPL has also worked to produce a 1 D array of 36 emitters on silicon. [49]

An article from the Edwards Air Force Base has proposed an AC colloid thruster concept multiple acceleration gates using frequencies of around 10 MHz.[32]

A group from Tsinghua University in China has developed an integrated microthruster comprising a MEMS based micropump and a thruster made with print circuit board technology (PCB) which has the advantage of being less costly than MEMS. The propellant used was formamide with 30% NaI. An array of 81 emitters of copper with an internal diameter of 0.3 mm and an external diameter of 0.5 mm. The distance between emitters was 1.5 mm. Cantilever beam measurements of the thrust indicated it was about 1.5 $/mu$ N. The device was tested in air and suffered from an unsteady burst-like mode of operation.[73] The design evolved into a MEMS based using ICP etching. An array of 192 emitters was built using this technique. An array of four emitters was tested on a vacuum chamber and measured 6.8 μ N with an extracting voltage of 2000 V in good agreement with theory. This thruster is mentioned to meet an urgent requirement for a microsatellite.[77]

In the UK, interest in colloid thrusters has recently renewed. The main effort has been the framework of a collaborative program between Queen Mary University of London and the Rutherford Appleton Laboratory. [65] The focus of this work is to produce emitters using microfabrication techniques. Single nozzles of 35 OD with 25

/*mu* m ID and 400 μ m length were manufactured. Using silicon microfrabrication techniques which are highly scalable an array of 20000 emitters on a 75 mm^2 area has been proposed. [67] The work is at the stage of testing individual emitters.[66].

Chapter 3

The needle-less thruster

An alternative design has been proposed to overcome two of the problems that colloid thrusters had. The first problem is the alignment of the needles has to be very precise, reproducible and durable [68] . The second and most important technical problem was that, by design, the successful operation of the emitters relied on a sharp geometry to operate. This geometry was often altered by erosion or deposition thus decreasing the performance of the thruster. [51]

We can decompose the functions of the needle in a conventional colloid thruster:

Fluidic To hold the fluid together.

Sharpness To provide a sharp equipotential tip that enhances the electric field.

Electrical To act as an electrode, that is to allow the transfer of electric charge to the fluid.

The three functions are implemented by the same form, the needle or capillary. Some benefit could come from decoupling these functions and assigning them to other forms.

In terms of the electrical function it is clear that since the fluid itself is conductive, the needle does not have to be. An electrode in contact with the fluid can provide the necessary charge.

A measure of the sharpness of an edge or axially symmetric tip is its radius of curvature R. Concerning the role of the sharpness of the needle it is worthwhile to mention two things. First when the device is operating, the sharpness attained by the Taylor cone is much more acute, a few nanometers, than any sharpening coming from the geometry of the needle. Second, when no electric field is applied, for any sharp internally wetted needle, the minimum radius of curvature is the radius of the hemispherical liquid meniscus. Then a liquid cylinder of constant radius ending on a hemispherical meniscus will be therefore more slender than any needle that surrounds it. Any needle material around it does not improve the sharpness of the equipotential. The ideal thing then would be to have the liquid held in place in vacuum in the shape of a cylinder capped with a hemisphere. The third function of the needle is to keep the fluid in place, it is desirable to hold it in a shape that is as slender as possible. Ideally it would be held in place without any material around it, just in a vacuum. This would be complicated to implement. The next best solution is to have a low dielectric constant isolator solid holding the liquid in place. From an electrostatic point of view its behavior is as close to vacuum as possible.

The author hypothesized that the function of holding the liquid in place may be better accomplished by a hole on a low dielectric constant material.

This presents the additional attractive feature that alignment of the needles is no longer an issue. Since arrays of holes can be made parallel to each other they remain robustly aligned.

After looking at various materials that were insulators and had a low dielectric constant, Teflon was selected because:

- It is electrically almost like vacuum, due to its low relative permittivity.
- It is extremely inert chemically.
- It has a very low surface energy, making it non-wetting.

Figure 3 shows a conceptual drawing of an array of holes in a block.

It is unclear to the moment why this constructive approach of using holes instead of needles has not been used before. A valid concern that could be raised was that

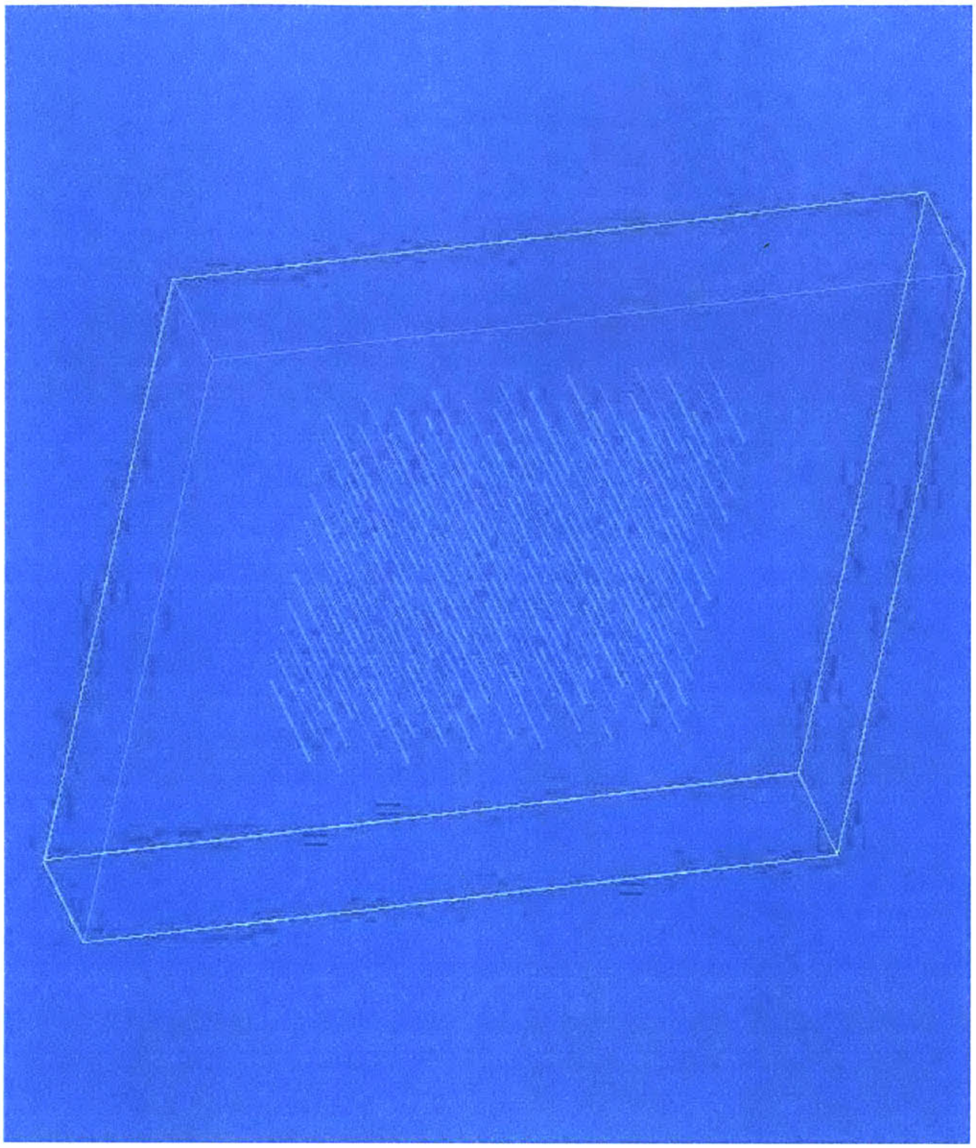

Figure 3-1: Array of holes in a solid block

the startup voltage may be too high for the device to be attractive. In order to verify if that was the case a series of computer simulations were run.

Chapter 4

Simulation

4.1 Statement of the problem

Of the many functions that needles have, as previously identified in chapter 3, enhancing the electric field at their tip is the one that is most often cited [4]. This enhancement is supposedly needed to start up the instability at the tip of the liquid meniscus. Therefore it was decided to perform a numerical simulation of the electrostatic potential for two cases:

Case I: Sharp Needle A sharp stainless steel needle caped by a hemispherical perfectly conductive meniscus. The dimensions are shown in figure 4-1. The stainless steel is assumed a perfect conductor.

Case II: Hole on Teflon A hole of the same diameter on a Teflon, assumed a perfect insulator and of relative permittivity of 2.08. The hole is capped by a hemispherical perfectly conductive meniscus. The dimensions are shown in figure 4-2.

The geometry is axially symmetric. 3500 V are applied between the extractor and the equipotential formed by: in Case I the needle and the hemispherical meniscus, in Case II the liquid column and the hemispherical meniscus. We are interested in comparing the intensity of the electric field at the tip for both cases. Note that due

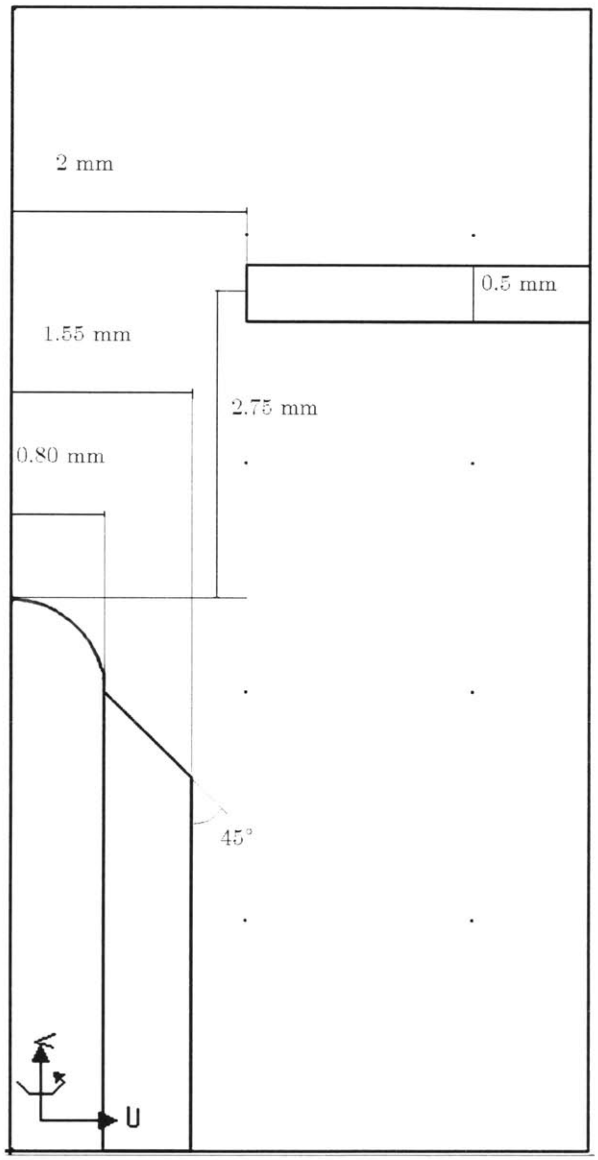

Figure 4-1: Case I dimensions

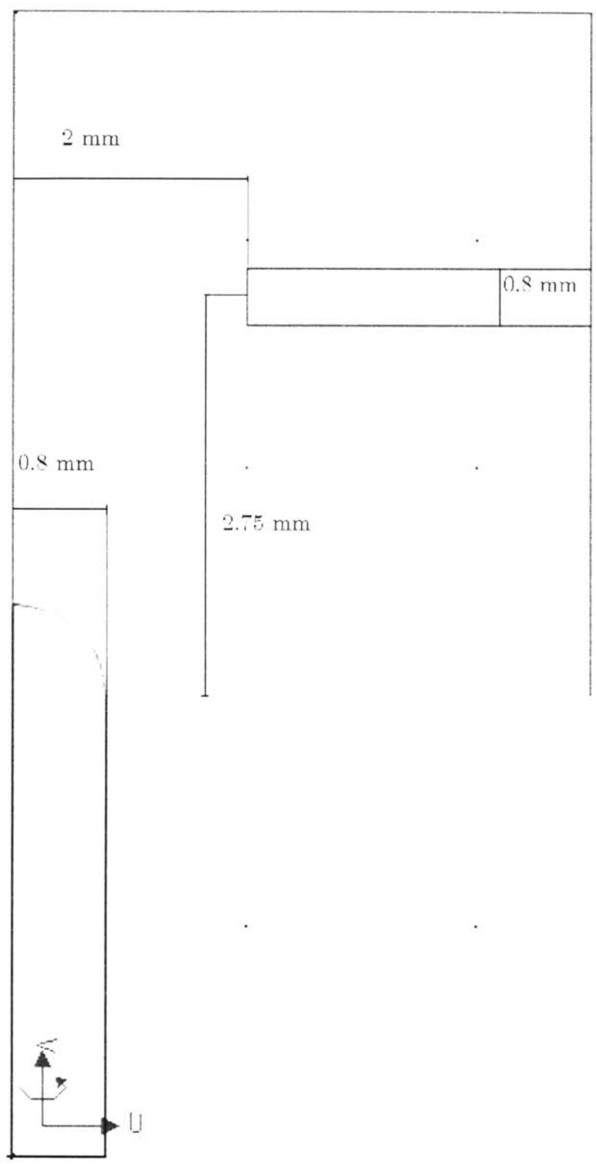

Figure 4-2: Case II dimensions

to the linearity of the problem any value can be used for this voltage, as long as the comparison between both cases is made with the same voltage.

4.2 Simulation method and accuracy

The electric potential and the modulus of the electric field were calculated using the Student Version of the software program Maxwell™. This program solves electrostatic problems using the finite element method coupled with an automatic adaptive meshing algorithm that can almost arbitrarily increase the accuracy of the solution.

The target error was 1%. For Case I 0.55% was achieved after 8 passes, the convergence data are summarized in figure 4-3. Case II, due to its much simpler geometry, converged to an error of 0.667% at the first pass. Further refinement is possible with this software, however it is unadvisable since, if forced to converge to a smaller error, spurious results appear in the solution. This is due to the piecewise linear approximation of the geometry of the hemispherical meniscus.

4.3 Simulation results

The main lesson that can be extracted from the results is that the electric field enhancement takes place, not only in the case of the needle (CaseI) but also in the case of a hole in Teflon (Case II). In fact the modulus of the electric field at the tip of the liquid meniscus is higher in Case II than in Case I, 3.9710^6 V/m compared to 3.5310^6 V/m.

Figures 4-4 and 4-5 show the electrostatic potential solution for cases I and II respectively.

Figures 4-6 and 4-7 show the electric field modulus solution for cases I and II respectively. The scale is the same for both figures and uses the maximum electric field of case II as a reference. As we would expect, in both cases the electric field is higher at the tip. What is more remarkable is that the value of the field near the tip is slightly higher in Case II than in Case I.

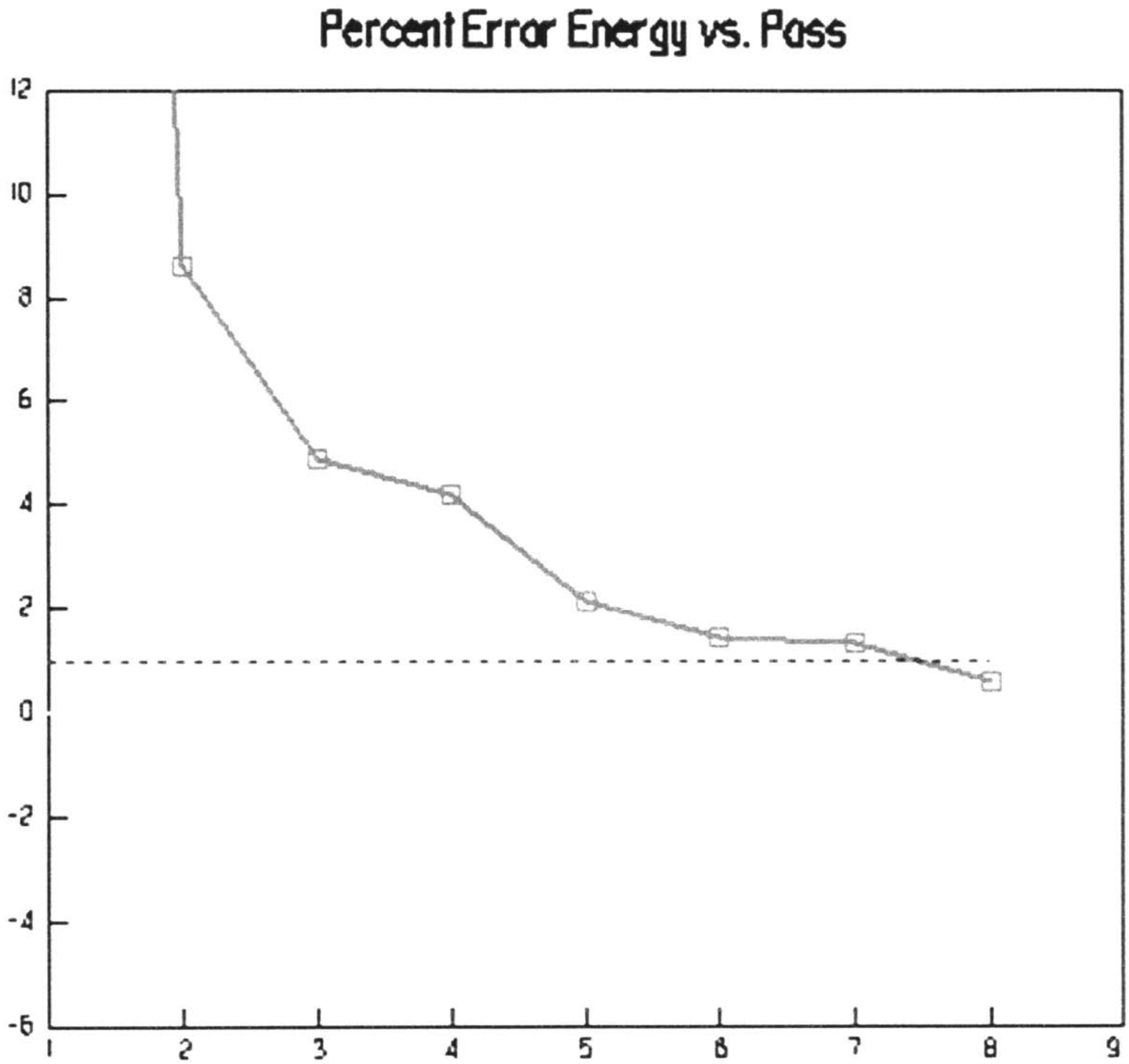

Figure 4-3: Case I: Convergence

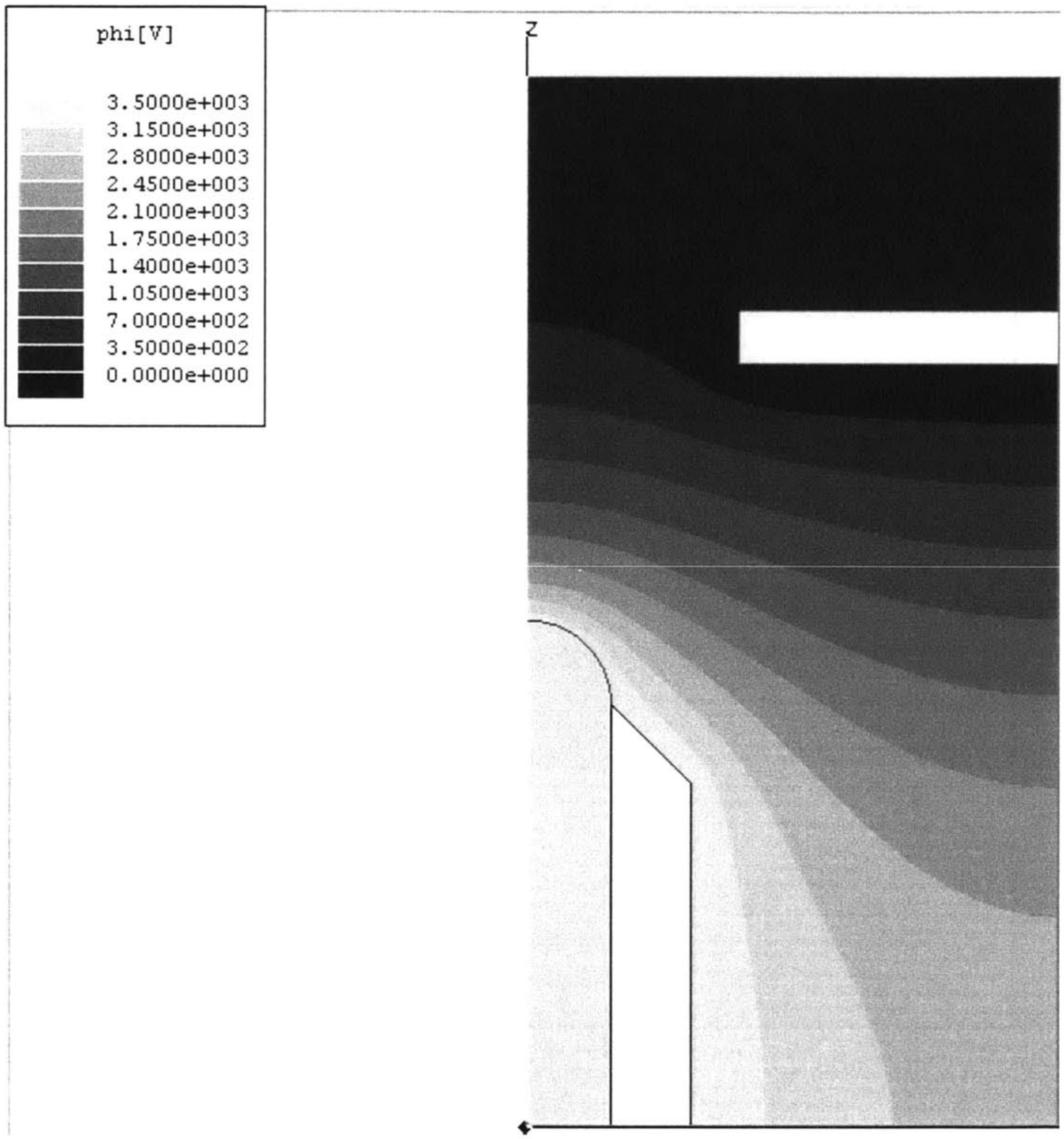

Figure 4-4: Case I: Electrostatic potential ϕ for a metallic needle

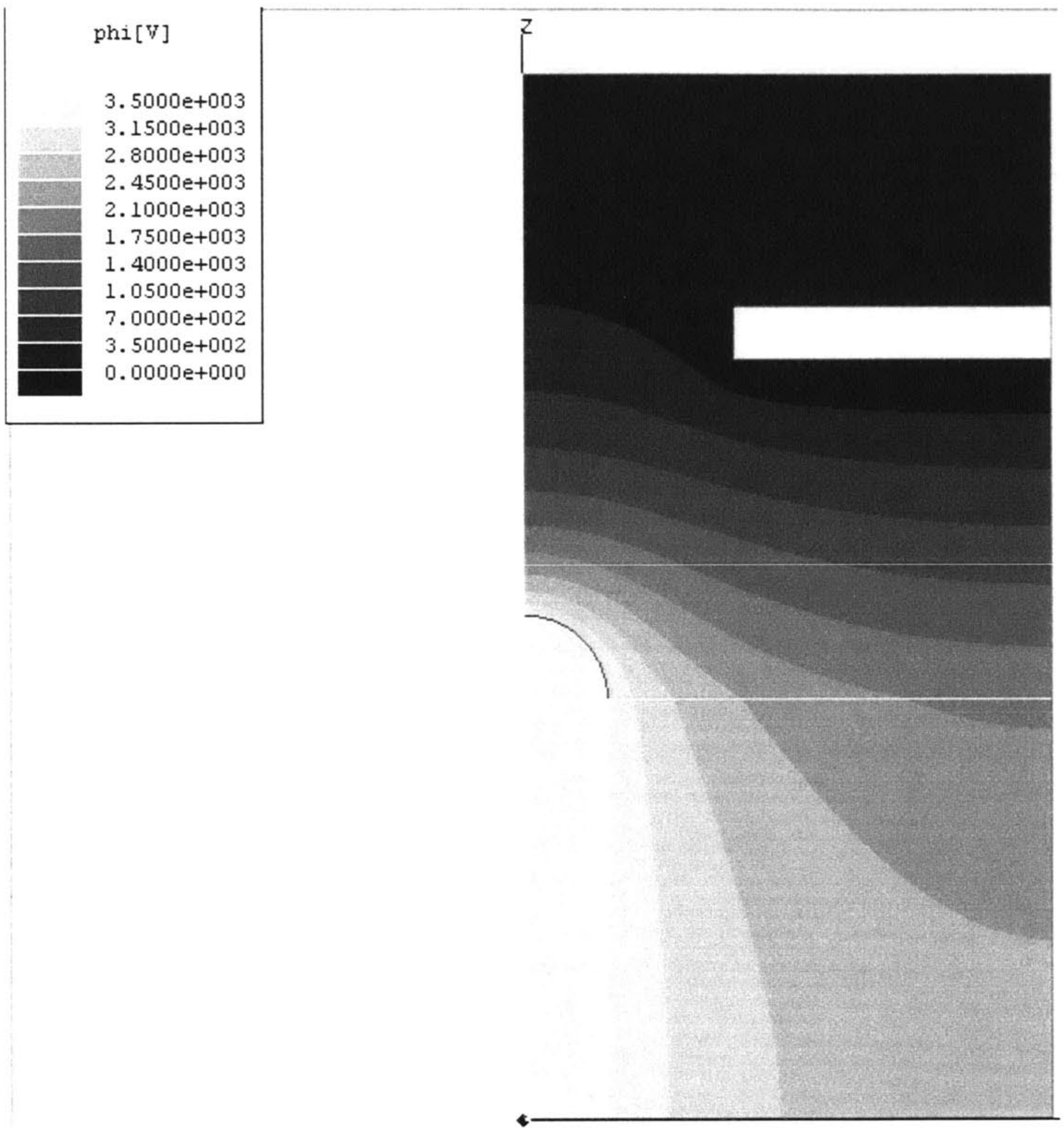

Figure 4-5: Case II: Electrostatic potential ϕ for a hole in Teflon

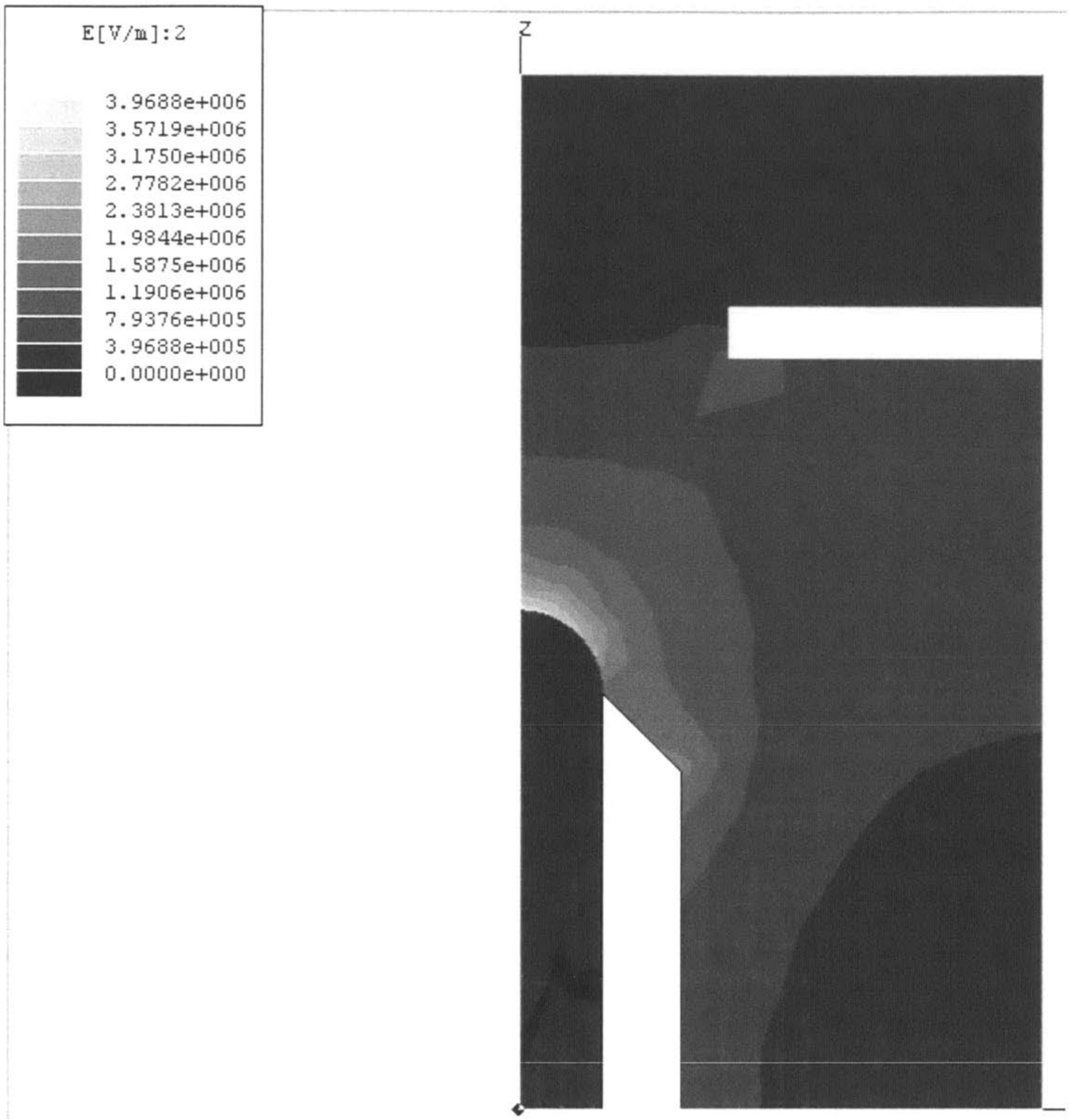

Figure 4-6: Electric field modulus for a needle, maximum electric field of 3.5310^6 V/m.

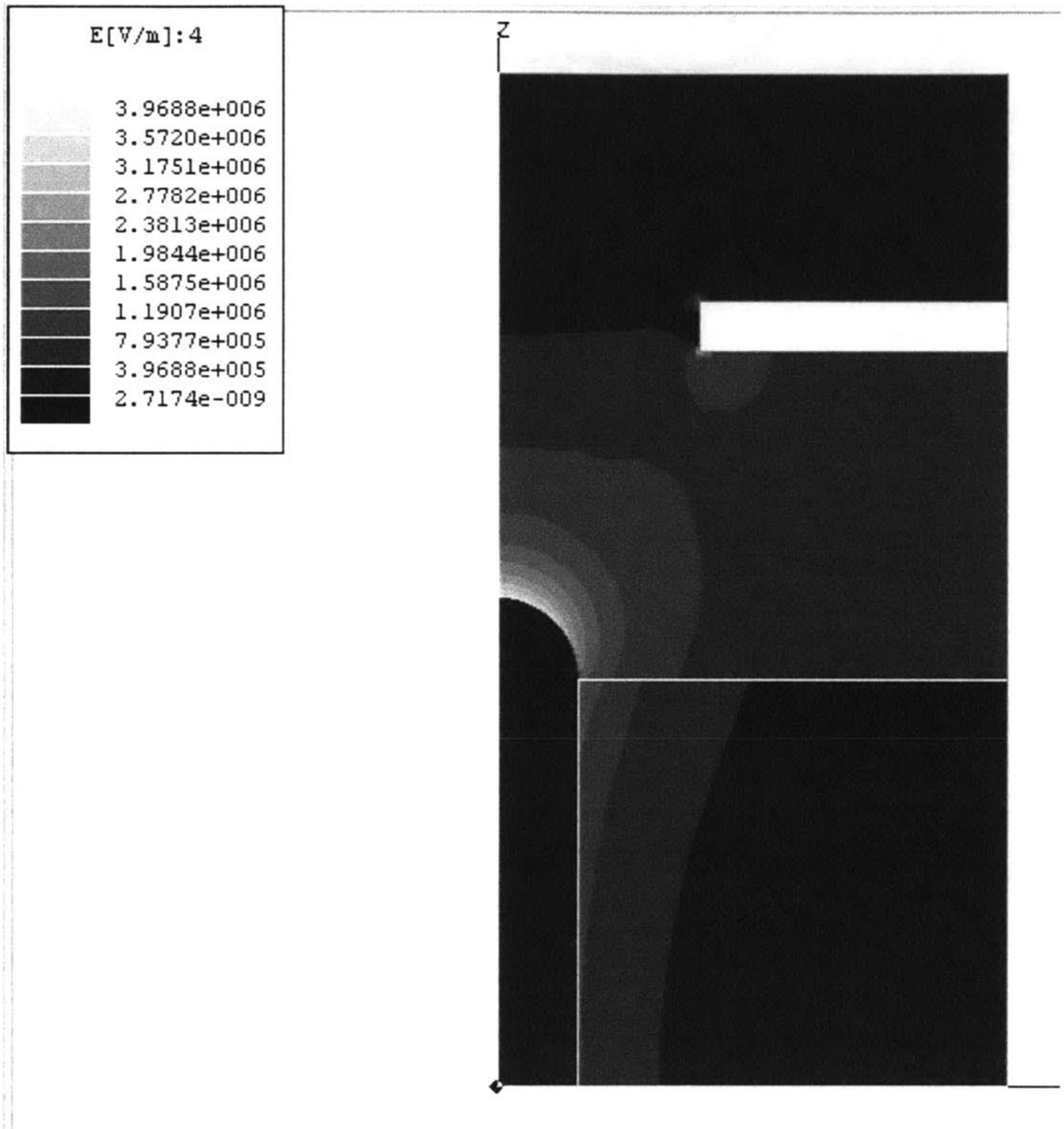

Figure 4-7: Electric field modulus for a teflon hole, maximum electric field of 3.9710^6 V/m.

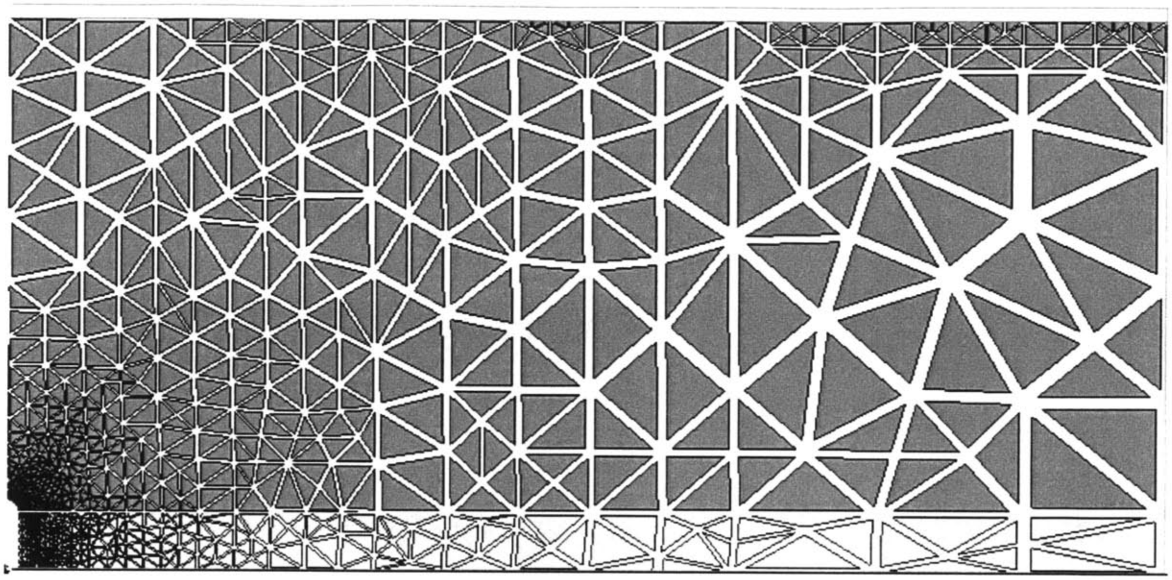

Figure 4-8: Model grid. For this particular run the dielectric material was teflon, the hole had 0.4 m of radius and was placed 17.25 mm from the extractor plate.

4.4 Effect of the dielectric constant on the field enhancement

The electric field at the tip of the meniscus is expected to decrease if materials with higher relative permittivity than Teflon are used. In order to gain a quantitative understanding of this phenomenon a series of models have been run. Figures 4-8 and 4-9 show a typical grid and close up of the electric field modulus near the tip.

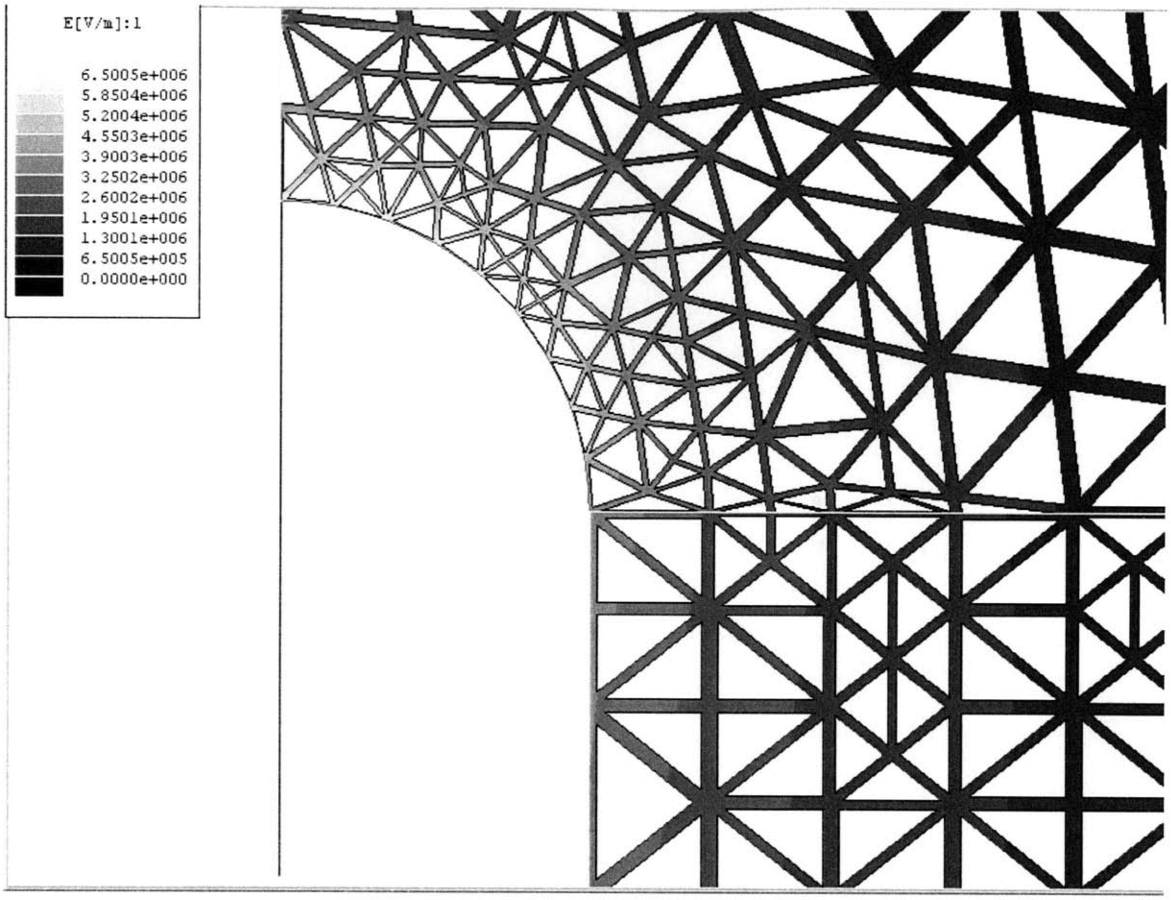

Figure 4-9: Close up of the electric field modulus near the tip. For this particular run the dielectric material was teflon, the hole had 0.4 m of radius and was placed 17.25 mm from the extractor plate.

Figure 4-10 shows the results of these simulations. For two values of the ratio between the distance to the extractor, D, divided by the radius of the meniscus, R, the inverse of the electric field at the tip normalized with the value for vacuum, has been plotted as a function of the relative permittivity. The ordinate thus represents, for a hole-based emitter, by how much the voltage has to be multiplied to obtain the electric field at the tip that would be obtained if the propellant were held by itself in vacuum. Figure 4-10 also illustrates the agreement with a previous analytical model that approximated the geometry of the liquid column and meniscus by an sphere and a cone[54]. It should be noted that the reduction in electric field enhancement at the tip becomes more pronounced as the ratio D/R increases. This result can be useful for the design of emitters from flat dielectric surfaces.

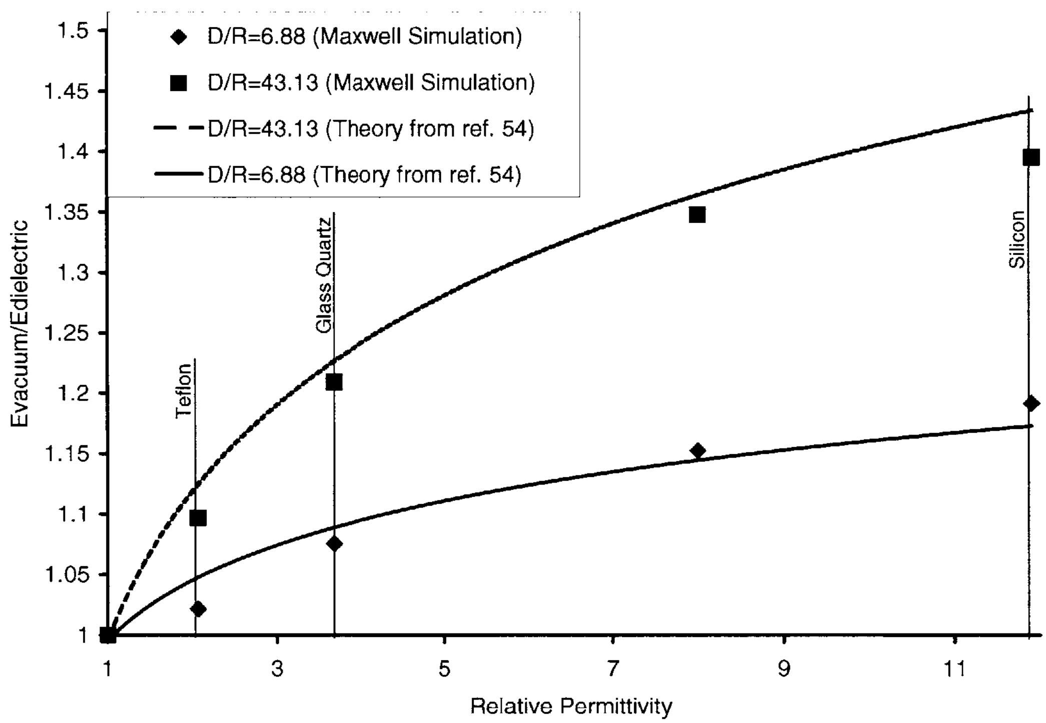

Figure 4-10: Effect of the relative permittivity on the Electric field at the tip.

Chapter 5

Experimental verification

An experiment was set up and operated by Dr. P. Lozano, Mr. P. Whitney and the author to verify the feasibility of emission from a hole in Teflon.

The working fluid was Ethylene Glycol doped with LiCl to raise its conductivity to 0.077 Si/m. The surface tension is 0.048 N/m and the dynamic viscosity 21 cP.

A digital syringe pump was used to provided a controlled volume flow to a tube that fed a hole of 0.36 mm of diameter in a teflon block. In front of the hole at a distance of 3 mm an extractor plate was placed. According to Equation 1.2 the starting voltage would have to bee close to 2.92 kV, however that equation assumes there is no Teflon around the liquid. An alternative way of deriving the startup voltage is to calculate the electric field modulus required at the tip by equation 1.1. The value of the electric field is $1.1\ 10^7$ V/m. Then a Maxwell model of the geometry can be run to identify the voltage that provides such an electric field at the tip. This process yields a value of the starting voltage of 2.61 kV.

A range of voltages and mass flows was explored. A Taylor cone formed on the hole and electrospray emission took place. Starting voltages were measured in the vicinity of 3 kV. The most stable condition corresponded to a volume flow of 0.01μl/min and 4.36 kV applied on the liquid, keeping the extractor grounded.

Figure 5-1 shows a stable Taylor cone at the mentioned conditions.

The emission was remarkably stable. When at some instances bubbles in the stream disrupted the emission, it recovered by itself shortly.

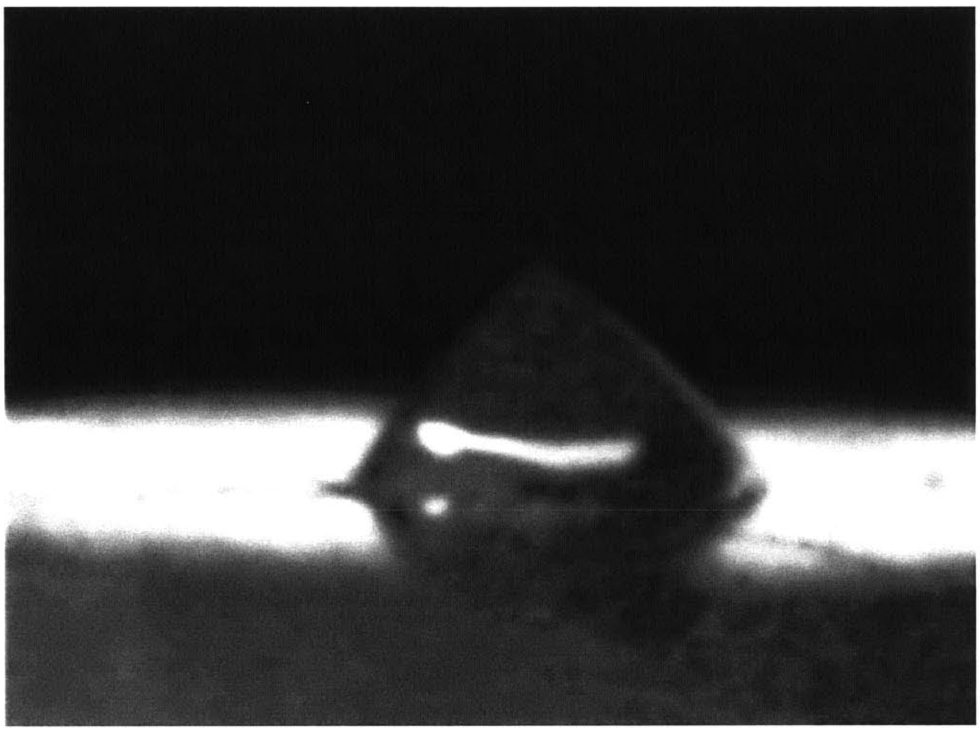

Figure 5-1: Taylor cone formed on a hole on Teflon.

Chapter 6

Further work

Some potential issues that the needle colloid thruster could face, have been identified. This chapter will present those and propose tentative solutions.

6.1 Exposure to the space environment

Teflon was chosen as a material among other things because of its good non wetting surface properties. However, exposure to UV light or plasma can increase the surface energy of teflon and make it sticky. If the design relies on the low surface energy of the exposed teflon surface that could limit the life of the device.

Several studies have been made regarding the accelerated aging of Teflon due to the exposure to the space environment. This interest stems from the fact that Teflon is very often used as a coating in insulating materials for spacecraft. If thin layers of Teflon are good to protect other materials it is reasonable to think that it can protect itself to a certain extent.

The agents identified that contribute to the aging process are[17] [22]:

- Thermal cycling
- Atomic oxygen
- Ultraviolet radiation

- Contamination

Thermal cycling and UV radiation would be less of an issue for a colloid thruster because the extractor would shadow most of the Teflon. Since the properties of the propellants depend on the temperature, the thruster would probably have to be thermally controlled and therefore thermal cycles would be mild. Therefore the single most important factor that should be assessed experimentally is the effect of atomic oxygen. Of special interest would be to know if the relative permittivity of the surface is increased by the oxidation process. Also of concern is the possibility of contamination of the surface by a conductive layer. If this layer became in contact with the propellant it would adopt its potential and shield it from the electrode in a very short time. A stationary simulation of this configuration including a 13 μm conductive layer yields, as expected, an electric field that is lower at the tip and similar to the one in a parallel capacitor. Figure 6-1 shows a close up detail of the field around the meniscus.

6.2 Hydraulic impedance

As discussed in section 1.3.2 the hydraulic impedance of the path between each emitter tip and the common feed manifold should be high enough. For a cylindrical hole of diameter D and generatrix L, implies large L/D. This imposes a constructive constraint. Current laser drilling technology allows to drill arrays of holes of L/D of about 120 on Teflon[33].

An alternative construction that would increase the flow impedance is proposed and shown in figure 6-2. Instead of using one constant diameter for the tube, a flow restriction is in series with the flow. The flow restriction may not have a large L/D but it does increase the impedance. In the Figure 6-2 the restriction is placed at the exit of the hole, but it could be placed anywhere in series. This construction would be easier to manufacture on a single block by laser since the L/D is moderate for both the channel and the flow restriction.

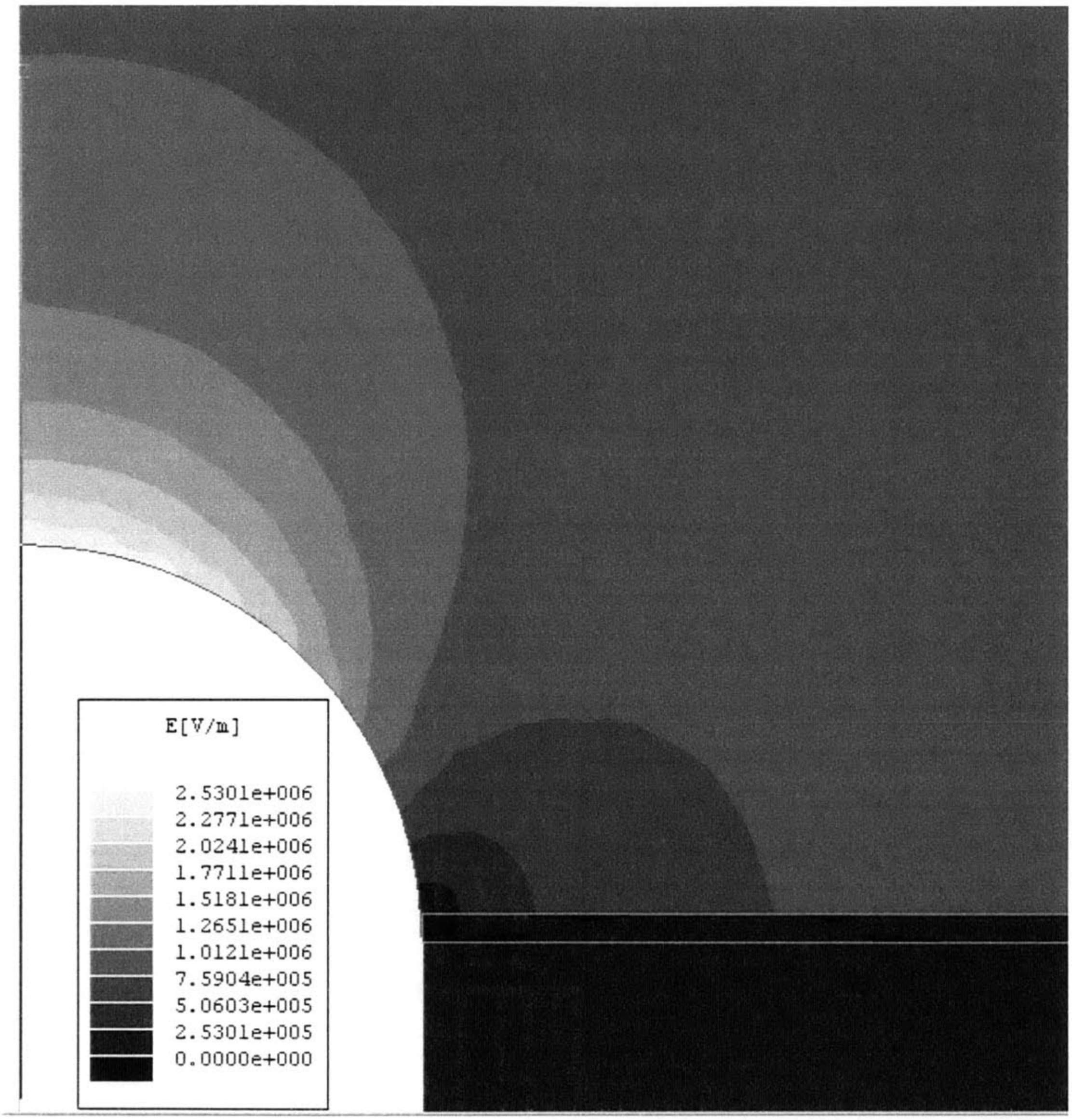

Figure 6-1: Close up of the electric field near the meniscus. The electric field intensity that would be attained in the absence of the conductive film is 1.1 10^7 V/m.

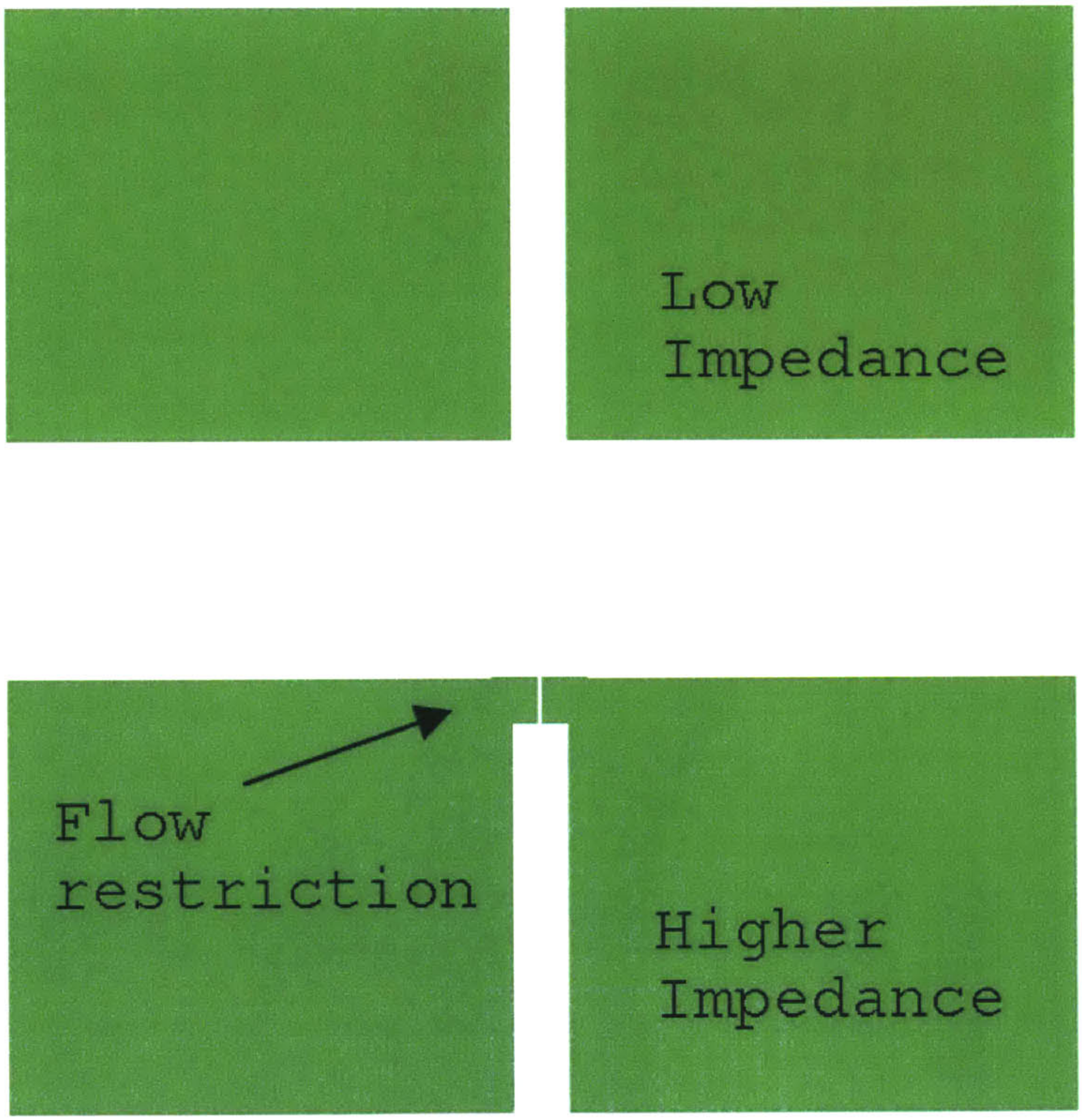

Figure 6-2: Top: Cylindrical emitter hole. Bottom: Flow restriction at the outward end of the cylindrical emitter hole to increase the flow impedance.

Chapter 7

Conclusions

The literature on colloid thruster development has been surveyed to identify the technical reasons why the program was stopped in the 70s. From this bibliographical research it has been understood that the performance was sensitive the sharpness of the needles used as emitters. In normal operation of the thrusters, erosion and deposition changed the shape of the needles and led to reduced performance.

An alternative way to construct an electrospray emitter for colloid thruster has been introduced. Instead of using a sharp needle, a hole in a dielectric nonconductive flat surface is used.

Numerical simulations have shown that the electric field can be higher using flat holes than needles of the same inner diameter. Via numerical simulations the effect of the relative permittivity of the dielectric material has been quantified.

Teflon, because of its low relative permittivity, has been identified as an apt material for such an emitter. Before holes on teflon can be applied for colloid thrusters in space, further work will be needed to characterize the effects of potential deposits and of the atomic oxygen on the electrical properties of Teflon. In any case, this type of emitter can already be useful in some of the many applications where electrospray is used.

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