Diagnoses of Micro Fluidic System by Particle Image Velocimetry

Executive Summary

An experimental program on the micro attitude control thruster is under investigation. Tasks include nozzle design and particle image velocimetry (PIV) development for optimizing the thruster performance.

Achievements made in the first year

Jet nozzle design and fabrication

The micro-nozzle design is important so that the shock associated losses and viscous dissipation can be minimized. Based on the linear momentum conservation principle, the thrust developed by a jet can be represented as the produce of the jet mass flow rate and the jet velocity (for simplicity, the pressure difference between the nozzle exit and the surroundings is neglected). In space applications the resource of propellant is limited and its conservation is a primary issue in developing an efficient space propulsion device. Consequently, to produce a specified amount of thrust the jet exhaust velocity has to be maximized in order to preserve the propellant. However, higher velocity means significant higher viscous dissipation and pressure loss. Moreover, if the exit jet velocity exceeds the speed of sound, strong shock waves can emerge and generate more pressure losses. Therefore, a detailed characterization of the micro-nozzle configuration and its optimization are important for the project. The followings are our first-year efforts in terms of the micro-nozzle design, fabrication and testing:

Nozzle Fabrication

The micro nozzles were fabricated on a 500-µm thick silicon wafer using the Deep Silicon Reactive Ion Etching (Deep Si RIE) processing. All nozzles and their corresponding settling chambers were patterned using photoresist as an etch mask and the unwanted parts were etching out using reactive ion beams with almost vertical (90°-95°) sidewalls. In order to allow the jet to become supersonic, the nozzle has to be designed with a converging profile followed by a diverging section. The Convergent-Divergent (C-D) profiles of the micro jet nozzles were computed based on a two-dimensional method of characteristics calculation without using boundary layer correction. It is expected that significant viscous effects will modify the nozzle flow and the correction process will be considered for the design of the next generation nozzle. Two types of nozzles were fabricated. The first kind of nozzle design has a throat (the minimum opening area of the C-D profile) that is 100 µm width and 83 mm depth. Covering the processed wafer with a slice of Pyrex glass and cemented them together using anodic bonding technique completed the jet package. A second kind of nozzle design has a throat that is 100 µm and a depth of 500 µm by etching the wafer all the way through. This type of nozzle was finished by sandwiched and anodic bonded the nozzle piece between two slices of Pyrex glasses (figure 1). The second kind of nozzle was used primarily for the flow visualization tests. For all jet packages, each chamber was also equipped with two holes; one for inlet pressure line and the other for chamber total pressure monitoring.

Thrust test results

The experimental setup of the micro jet is shown in figure 2. It includes compressed gas supply with filtration system, pressure gage, mass flow rate meter, and associated data acquisition system. High-pressure gas cylinder, going through a two-stage pressure regulator unit with a working pressure range between 0 to 400 psi, is used to provide the desired gas flow. In order to remove impurities from the system, two 5-micron filters are connected upstream of the nozzle. The nozzle chamber pressure is measured by a micromachined pressure sensor (Novasensor NPC-1210, 0-200 psi). The mass flow rate is monitored by a mass flow meter (Hastings instruments HFM-200 series, 0-30 slpm). All data are digitized using an ADC board interfaced to a personal computer.

To measure the jet thrust, a force balance system (Denver instrument DI-400) is used. The jet is directly impinging on the top plate of the balance as shown in figure 3. If one assumes that the pressure is uniform around the jet (as should be the case for a subsonic jet but required correction for transonic and supersonic jets). The jet thrust should be equal to the force measured by the balance as required from the principle of linear momentum conservation. The range of the balance is from 0-400 g and the resolution is 1 mg. Because the range of the thrust measurements is around 1 mN (around 102 mg), the resolution is enough for our purpose. A micro translational stage is used to adjust the position of the nozzle so that the measured force is not a function of the separation between the nozzle exit and balance plate.

The mass flow rate and the thrust measurements are presented in figures 4 and 5, respectively. Both data show a linear variation with respect to the pressure inside the nozzle chamber. The mass flow is increasing as the pressure is increased, indicating that the jet is not choked yet. Therefore, it has not reached sonic speed at the throat. Similar linear trend can be found in the thrust data in the range between 0.4 and 1.4 mN. There is no distinguishable discontinuity in the data, also suggesting that there is probably no shock-associated loss within this range. The estimated jet velocity based on the thrust and the mass flow rate is of the order of 280 m/s, which is significantly lower than the sonic speed of the Helium gas (about 1,007 m/s in room temperature).

Micro PIV

A micro PIV system has been developed for the diagnosis of the micro fluidic system. The system consists of a microscope, a double-pulse laser system with associated optics, and a cooled CCD camera (figure 6). A doubly pulsed laser light sheet, with pre-determined pulse separation Δt, is used to illuminate the flow field of interest. A highly sensitive CCD video camera is used to record the reflected doubly exposed images of seeded particles. The displacement between successive image pairs of a particle, Δx, can be analyzed using an auto-correlation scheme. The local particle velocity, u, can therefore be determined easily as $u=\Delta x/\Delta t$ (figure 7). Shown in figure 8(a) is a representative micro PIV image field of flow past a backward facing step. The processed PIV velocity vector field is presented in figure 8(b). There is no data immediately behind the step because the flow velocity is very low in this region and the image displacements are too close to be measured by the autocorrelation scheme. This can be resolved either by introducing an artificial shift to the recorded image field or use a double exposure CCD camera to take two successive images and apply cross correlation scheme. It is to be noted that PIV can provide instantaneous, whole-field velocity information. This allows the capture of transient flow behavior of the pulsing micro jet to be studied in the current project.

The micro PIV system experiences additional difficulties different from the traditional PIV arrangement. First, the signal intensity is low since the high-magnification microscope usually has a very low light throughput. Second, the reflection of illuminating light from the neighboring surfaces can severely contaminate the signal quality. Third, it is difficult, if possible, to project a focussed laser sheet into a micro device. Fourth, due to its extremely low thermal inertia, micro flow device can experience strong interference when laser or other high-intensity light sources be introduced. Finally, seeding particles have to be very small (sub micron range) in order to not interfere with the micro flow.

In light of these considerations, a different micro PIV arrangement is chosen. The new system uses an epifluorescent microscope unit as shown in figure 9. The inverted microscope setup allows only the reflected or emitted light to get into the camera, reducing the background illumination. The use of fluorescent particles in combination with color filters not only increases the imaging quality due to the fluorescence but also removes the reflection from the surfaces. Moreover, use high magnification/numerical aperture objectives significantly reduces the depth of focus to a few microns or shorter. This eliminates the need to focus the laser into a sheet and minimizes the number of out-of-focus particles. Finally, a motorized attenuator is added to the laser system to provide a precise control of the laser intensity, important for a micro PIV system as discussed before. Preliminary results from the new system show much-improved PIV data and will be fully implemented in the second year.

Schlieren Flow Visualization

In addition, a qualitative flow visualization test using a traditional schlieren system is made. The technique is based on the principle of visualizing the light contrast due to the refraction of light rays going through a medium with density variation. Helium gas is used to increase the density variation for better-visualized results. The nozzle has a 100 μm by 500 μm nozzle diameter. A Xenon-lamp stroboscope unit is used to provide the illumination light source and the image is recorded using a Kodak Megaplus CCD camera. The nozzle is pressurized to a maximum absolute chamber pressure of 380 psi. Several interesting observations can be made on the visualization picture (figure 10). First, there is no apparent shock structure inside the jet although the nozzle exit pressure ratio is well above the threshold of achieving supersonic flow. It is possible that there are shocks but either they are too thin and too close to the nozzle exit to be visualized. Also it is likely that there are no shock because the strong viscous effects generated by the narrow nozzle can dissipate the discontinuities. Further experiments will be undertaken to explore these possibilities. On the other hand, there appears to have large scale flow structures embedded inside the shear layers. It is surprising since it is generally believed that these large-scale structures should not exist at high convective Mach number flow such as the present one. It is speculated that because the Reynolds number in a micro jet is much smaller (two order magnitude or more smaller) than a macro jet, therefore the conventional scaling such as the convective Mach number does not apply here. This observation is interesting since it suggests that it is possible to enhance supersonic mixing by the use multiple micro jets, taking advantage of the emergence of these large-scale structures.

Pressure Measurements

In order to obtain information about the pressure loss through the micro nozzle, a pitot tube connected to a pressure transducer is placed at the exit of the nozzle. The total pressure of the jet as a function of the settling chamber pressure is measured (figure 11). It is to be noted that the pitot tube has a 0.5-mm diameter and is large than the jet nozzle. Therefore, the measured pitot pressure should underestimate the true exit total pressure of the jet. Moreover, the possible existence of a normal shock in front of the tube can further reduce the total pressure measured by the pitot tube as relative to the jet total pressure. Despite all considerations, the maximum value of 92.7 psia suggests that the exit jet flow is indeed supersonic since theoretically the isentropic total pressure for the Helium gas to expand to sonic speed is only 30.2 psia. Based on the underestimated pitot pressure value of 92.7 psia, the isentropic Mach number can reach 1.8. Another important observation is that although the pressure loss is very high but there is no discontinuity in the exit total pressure data as the settling chamber pressure is increased. This seems to suggest that shock associated losses do not play an important role in determining the pressure drop through the micro nozzle.

Proposed short-term works for the second year

Thrust measurement and CFD comparison

Continued efforts will be made to measure the micro jet thrust by improving the present setup. Additional micro nozzles with different configurations (different C-D profiles and nozzle dimensions) have been designed and will be tested to compare the present system. Their differences will be analyzed to characterize the micro jet behavior for optimization purpose. In order to expedite the optimization process, numerical solutions of the nozzle flows using a Computational Fluid Mechanics (CFD) code (developed by CFDRC, Inc.) have also been undertaken. This software comprises of three modules: CFD-GEOM for grid generation; CFD-ACE for the actual numerical computation, and CFD-VIEW to post processing visualization and data presentation. A sample calculation is presented in figure 12. This commercial package solves full compressible, Navier-Stokes equations and has been validated for many complicated flow field computations. The field of interest is subdivided into 18,000 grids with 60 by 30 by 10 grid points along the x, y, and z directions, respectively. The flow accelerates rapidly inside the contraction and reaches a Mach number of 0.7 at the exit. The CFD results will be used to compare to the experimental measurements. If the numerical solutions are found to be consistent with the experimental data, the CFD package can be used as an efficient optimization tool since it can be easily modified to accommodate different operating parameters.

CFD Inverse design of the nozzle

In order to design a nozzle geometry that is optimized for low-pressure loss, an inverse nozzle design scheme will be investigated. As described earlier, we would like to fabricate micro nozzles with minimal viscous dissipation and shock loss in order to reduce the mass consumption of the propellant. With this design target in mind, we will be able to establish an optimization scheme taking advantage of the availability of the CDF flow solver. First, a baseline design of the nozzle profile is obtained based on the isentropic flow solution. The CFD numerical solutions of this baseline configuration will be used to compare to the experimental data. By comparing their differences, an algorithm will be developed to predict how the nozzle contour should be modified in order to match the design target. Once the new contour is defined, the entire procedure can be repeated until all desired criteria are met and the optimization process is complete. It is believed that a combination of the experimental results and the CFD solver can provide an efficient scheme for the nozzle optimization process.

Micro PIV

In addition to the adaptation of the inverted, epifluorescent microscope configuration, the micro PIV system is under continuous development and several improvements are planned: First, a high numerical aperture oil-immersion objective lens is being tested on the microscope system. It has a much shorter depth of focus (< 1 μm) that allows the microscope be focussed better on the image plane, reducing out-of-focus particle images. Second, a post-processing digital filtering program will be developed to remove unwanted out-of-focus particles from the recorded imaging field. Finally, a seeding system will be designed to provide uniform particle flow to the micro nozzle. Currently, the micro PIV system has only been applied to liquid micro systems because they are easier to set up and uniform seeding is usually not a problem. Micro PIV tests on gas flow micro systems are planned for the second and third years in order to provide measurements of the micro jet flow configuration. Another concern to be considered is the possible of the emergence of shocks when the jet reaches supersonic speed since under this circumstance seeding particles might not be able to follow the flow. To solve this problem we suggest combining PIV processing with the particle-tracking scheme in order to increase the spatial resolution of the technique. Therefore, it is possible to resolve velocity data of a single particle, allowing the accurate measurement in a supersonic flow field.

Long-term experimental Plan for the second and the third years

Second Year

- Detailed micro PIV measurements plus micro schlieren/shadowgraph flow visualization.
- Design and fabricate micro pressure transducers to measure pressure distribution inside a micro nozzle to determine the pressure loss through the nozzle.
- High thrust nozzle design: Emphasis on the nozzle optimization in order to minimize viscous and shock-associated losses.

- Design and fabricate a vacuum chamber to simulate the outer space operating condition.
- Preliminary design and testing of pulsating valve & nozzle assembly.

Third Year

- Micro PIV measurements and flow visualization inside the vacuum chamber.
- Detailed study of the pulsating valve/nozzle integrated system.
- Optimization of pulsating valve & nozzle system.

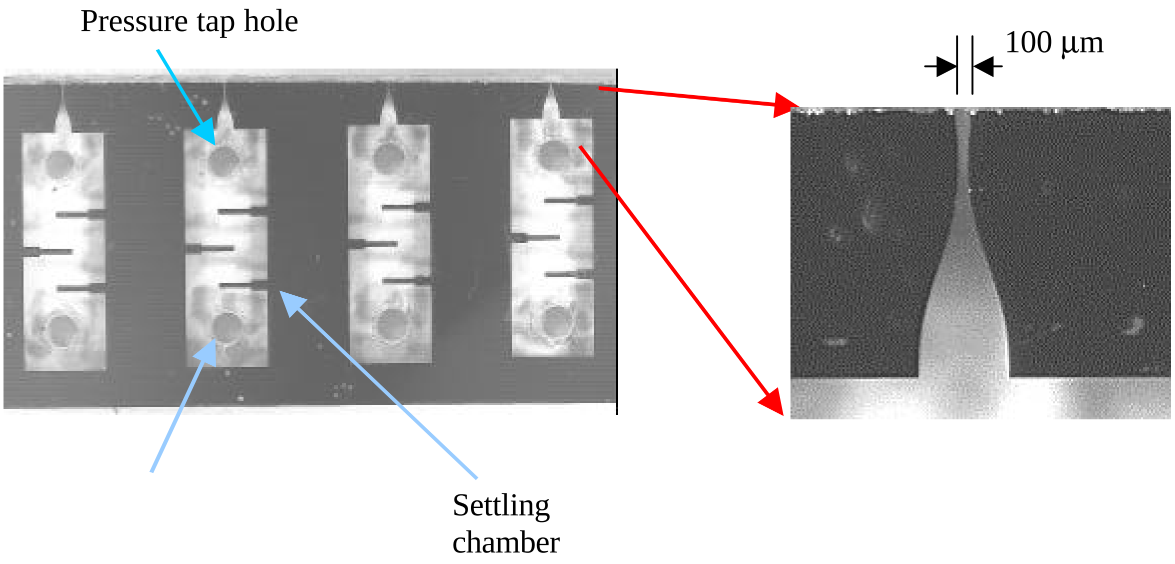


Figure 1 Supersonic jet systems fabricated using Deep RIE process, (a) a set of four jets packaged on a single chip, (b) magnified view of one jet, showing the converging-diverging nozzle contour with a throat height 100 µm.

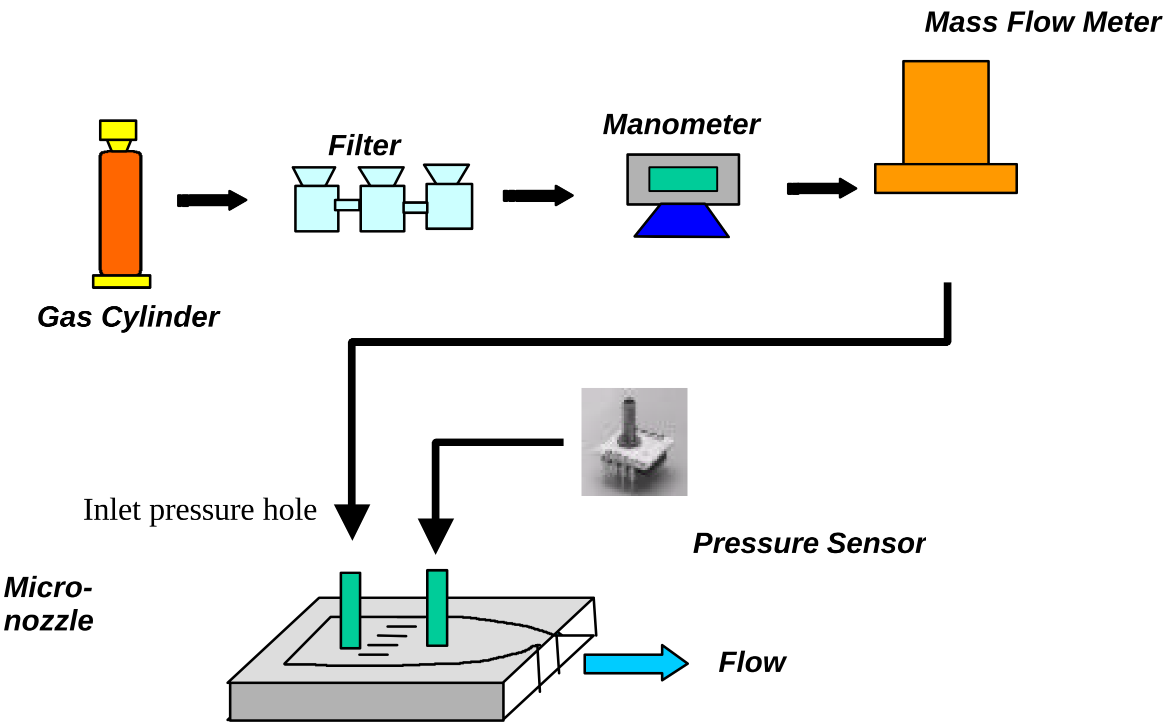


Figure 2 Micro nozzle arrangement

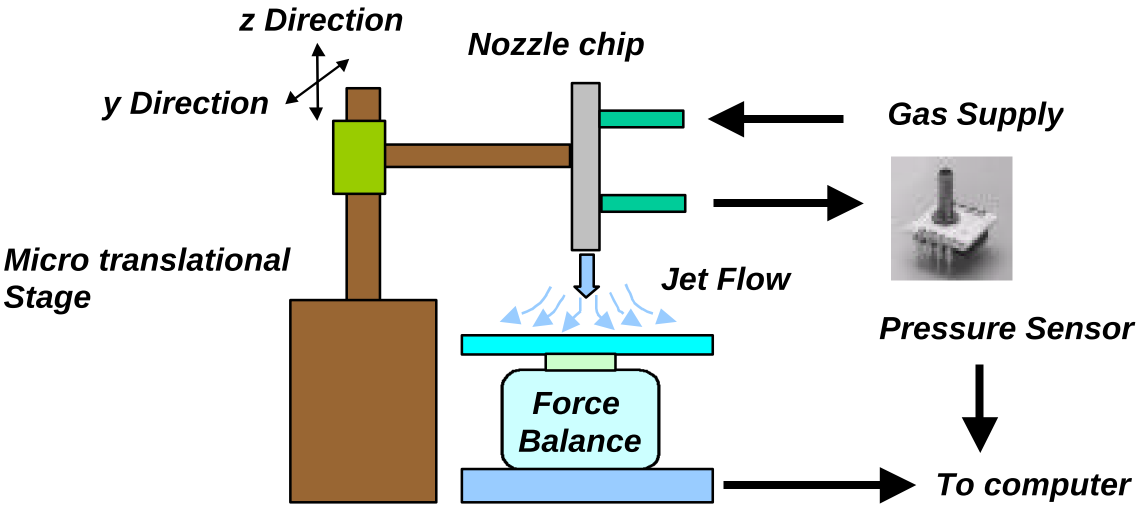


Figure 3 Experimental setup for the force balance thrust measurements

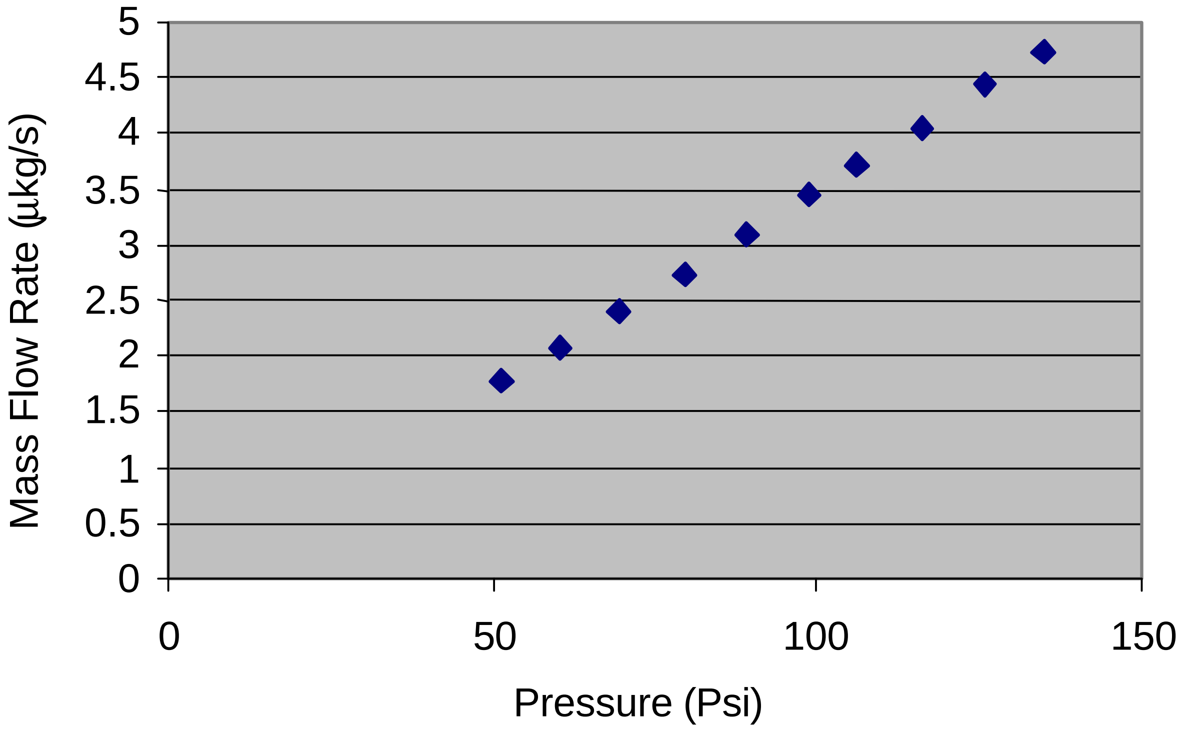


Figure 4 Micro jet mass flow rate as a function of the nozzle chamber pressure

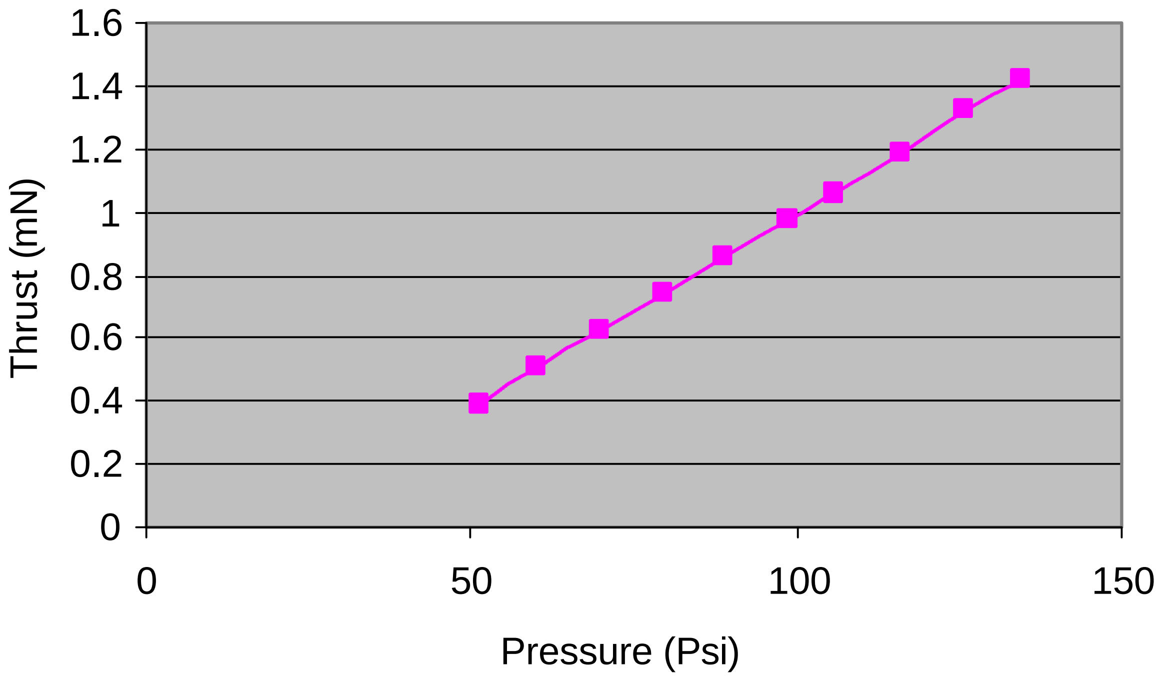


Figure 5 Micro jet thrust as a function of the nozzle chamber pressure

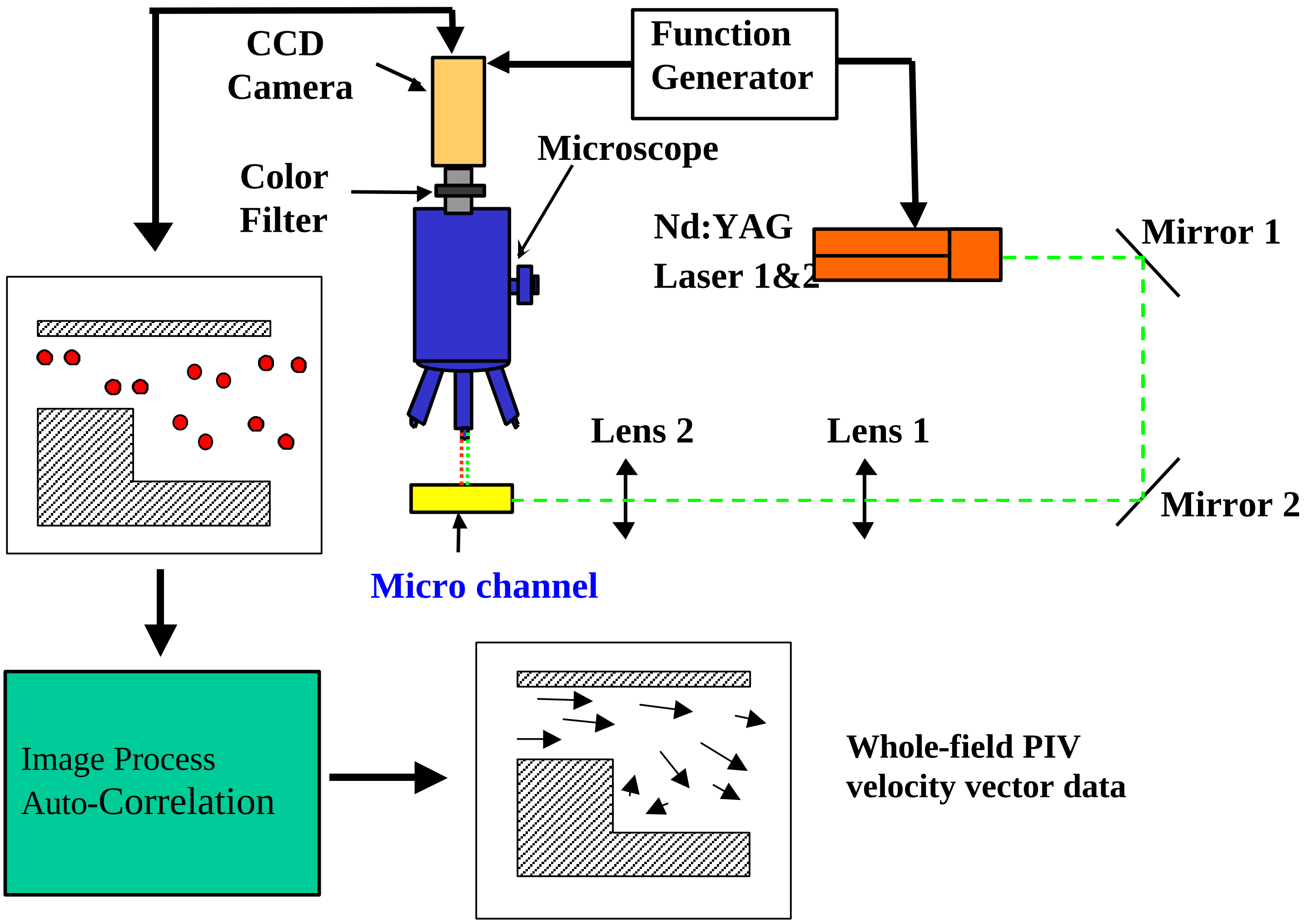


Figure 6 Micro PIV setup, non-inverted microscope arrangement

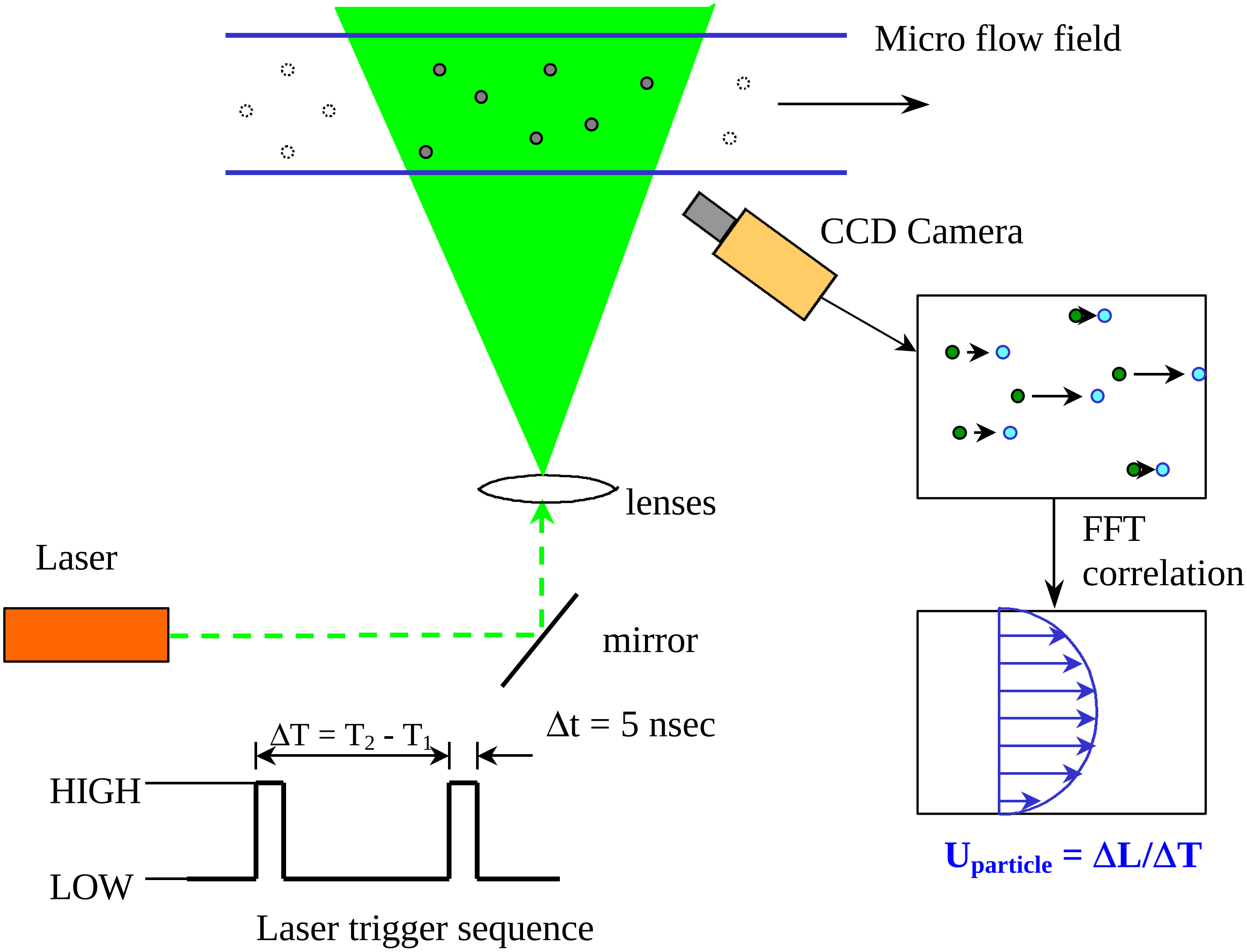
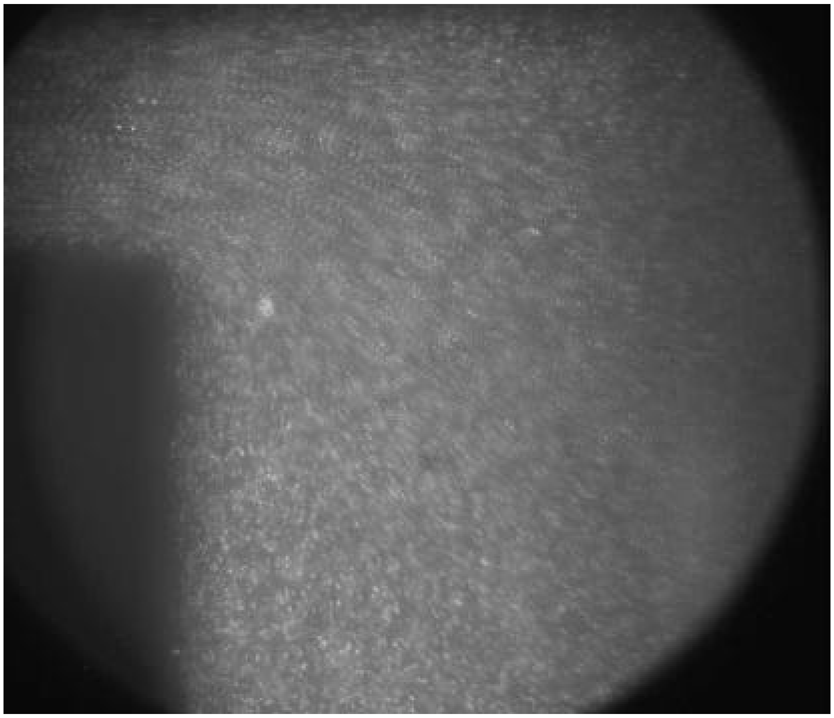
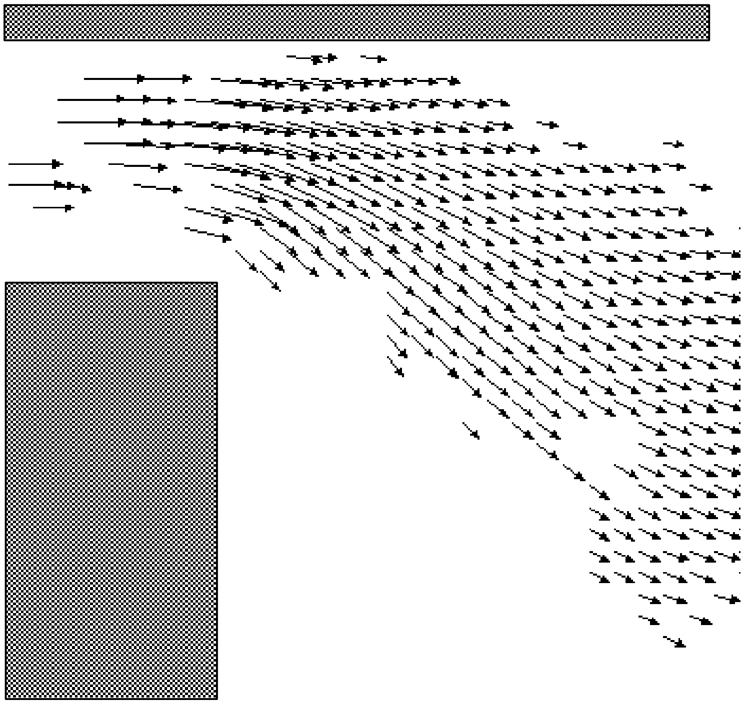


Figure 7 Basic principle for the micro PIV technique



(a) Micro PIV image field over a backward-facing step



(b) Corresponding PIV velocity vector field

Figure 8 Micro PIV image and velocity vector fields of flow over a backward-facing step

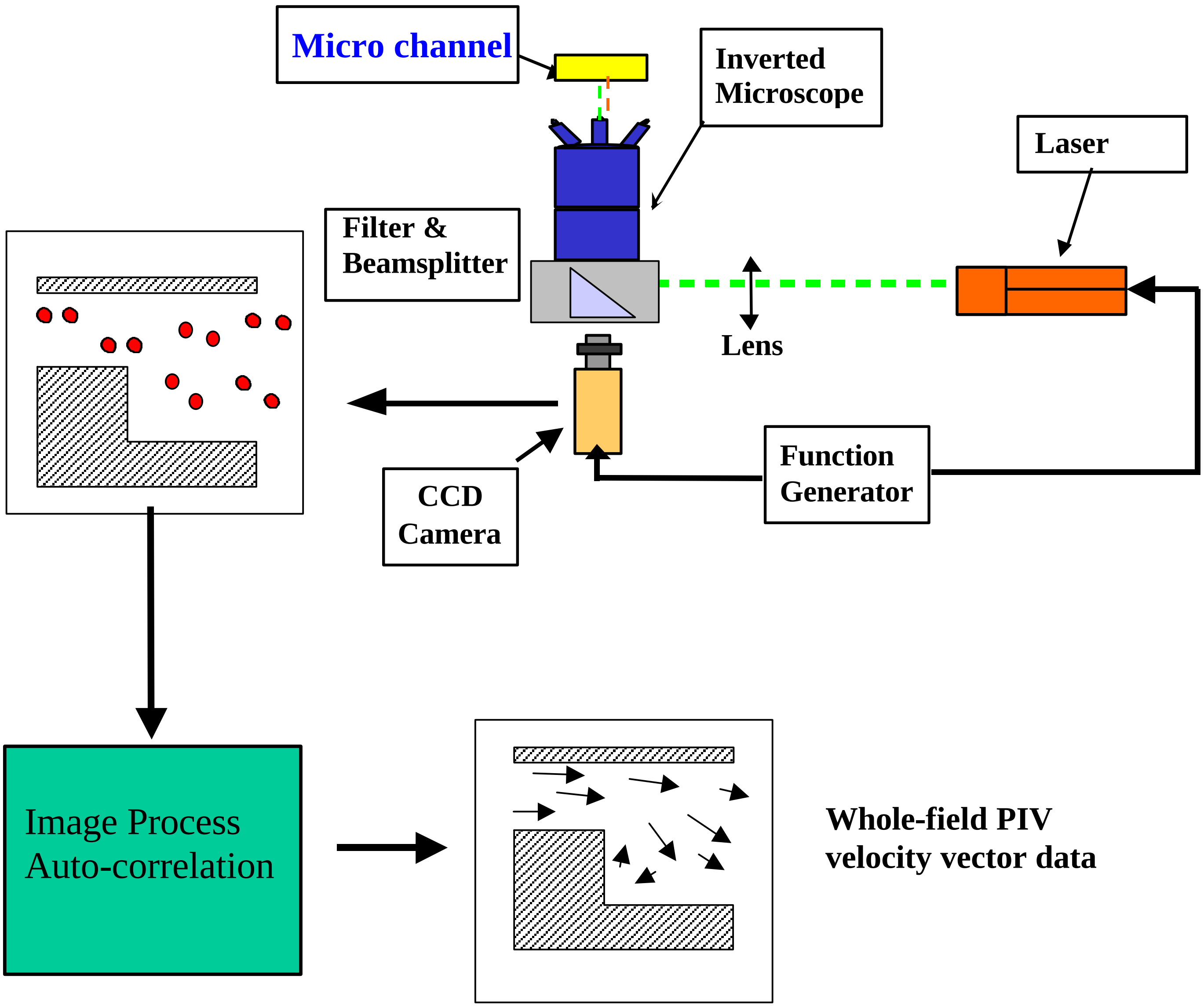


Figure 9 Newly improved micro PIV setup, inverted, epifluorecent microscope arrangement

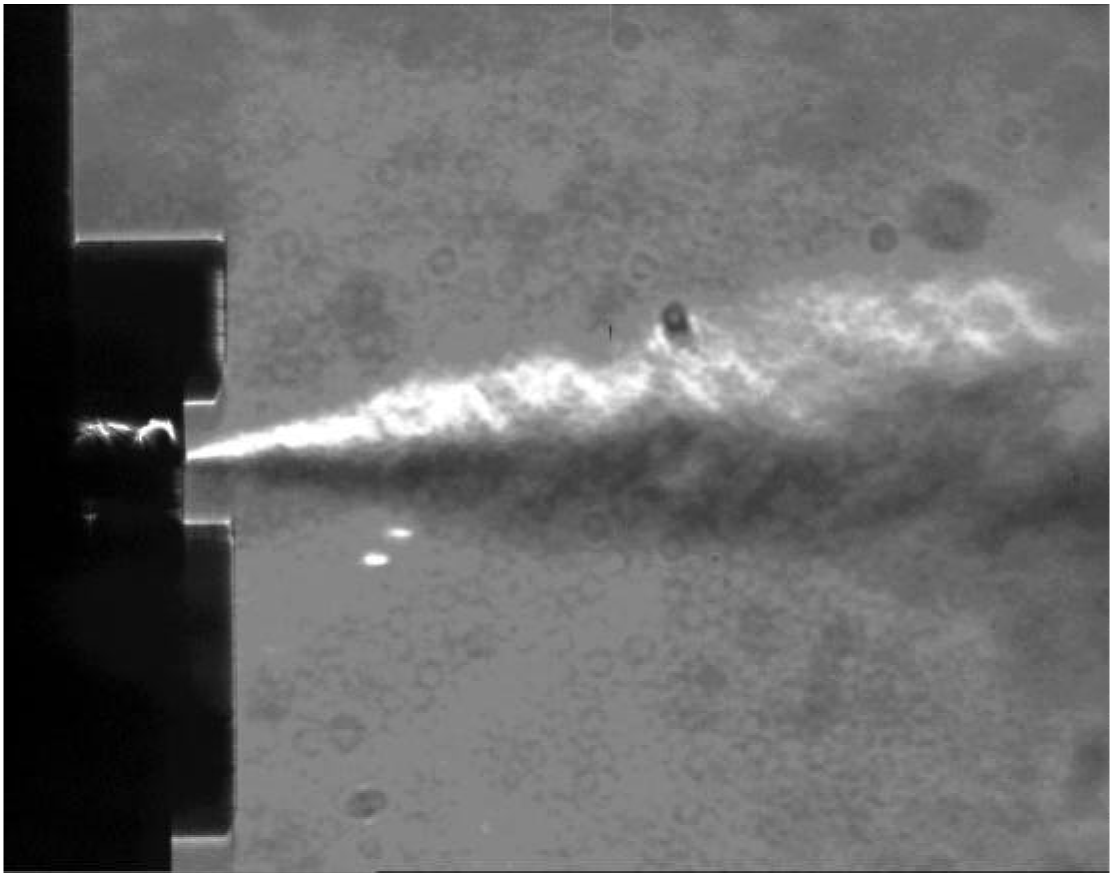


Figure 10 Schlieren flow visualization picture of a micro Helium jet (settling chamber pressure 380 Psia).

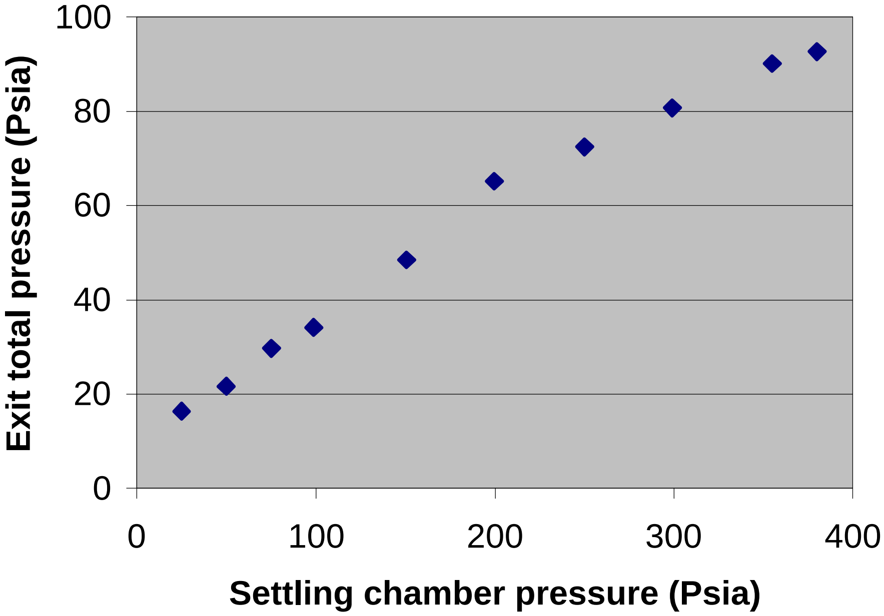


Figure 11 Exit total pressure as a function of the nozzle settling chamber pressure

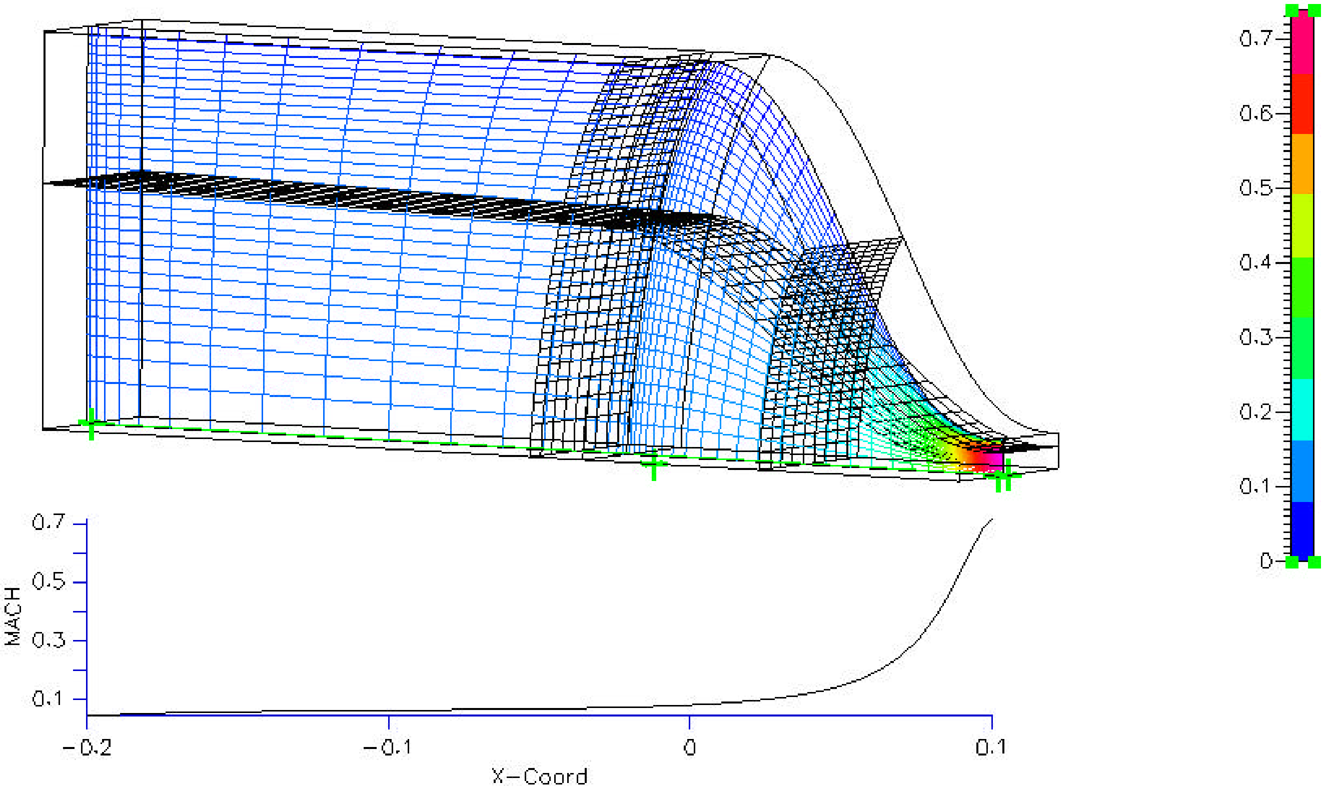


Figure 12 Sample CFD result: Mach number distribution inside a nozzle chamber