# A Particle Approach for the Simulation of High Density Nozzle Flow Expansions

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**ABSTRACT**

*We apply a particle code (Direct Simulation Monte Carlo, DSMC) to a nozzle flow expansion set-up. We obtain good results with respect to Pitot pressure measurements based Mach number estimations at different axial distances from the nozzle exit plane. The relative deviation from the measured references is mostly about 10 %.*

**KEYWORDS:** DSMC, Particle Simulation, Vacuum Spraying, Arcjet Facility, Nozzle Expansion Flow

## 1. INTRODUCTION

A variety of plasma-driven facilities is in use in order to reproduce the thermo-chemical loads experienced by a heat shield material during the atmospheric entry of a spacecraft [1]. Here, we present a successful attempt to kinetically simulate the expansion of an oxygen / argon flow expansion into vacuum. The gas mixture was heated in an arcjet of the University of Tokyo, details on plasma source and related measurement techniques are described in e.g. [2]. Basic quantities are the bulk enthalpy of 3.9 MJ/kg, a plenum pressure of 417 hPa, an argon mass flow rate of 0.12 g/s, and an oxygen mass flow rate of 2.39 mg/s.

## 2. NUMERICAL METHOD

A two-dimensional DSMC particle code named LasVegas (see e.g. [3, 4]) has been applied. The computational domain is a rectangle with a width of 75 mm and a length of 250 mm. For the limits of this area five boundary conditions have been implemented. The upper line and on the right side of the rectangle are open with the ambient pressure impressed while the lower line is the symmetric axis of the flow. On the left side of the area an adiabatic wall is implemented. The left side lower corner is the center of the nozzle exit plane. Tank state can easily be estimated making use of the ideal gas equation: T = 300 K, v = 0 m/s, n = $4.83 \cdot 10^{21}$ $m^{-3}$ [2].

Inflow conditions were derived from experimental data. Initial mole fractions were estimated on basis of equilibrium assumptions in the discharge chamber. An equilibrium code [5] yielded mole fractions of 95.10 % (argon) and 4.85 % (atomic oxygen). Assuming a chemically frozen flow inside the nozzle we applied these mole fractions at the nozzle exit plane. Using the Rayleigh-Pitot equation [6] the measured total pressure $p_{0e}(r)$ at the nozzle plane leads to a Mach number distribution $Ma_e(r)$, see **Fig. 1**. Given these data we derived further quantities like the enthalpy distribution as well as temperature, particle

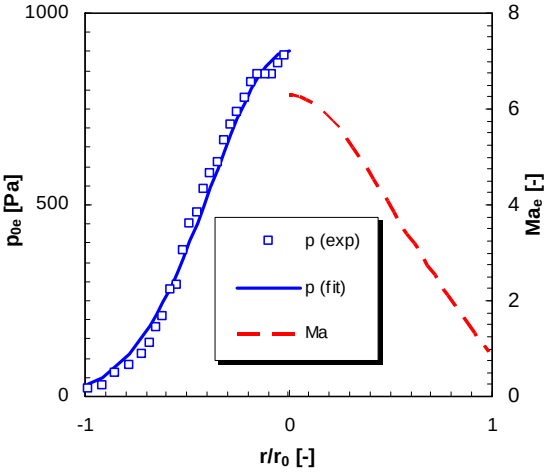


**Fig. 1** Derived profiles for inflow condition at nozzle exit plane

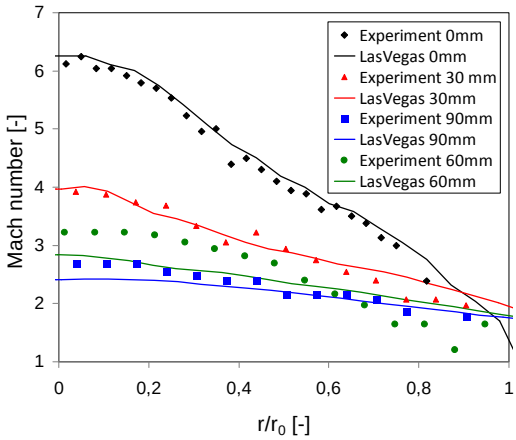


**Fig. 2** Measured and simulated Mach number profiles

density, and velocity profiles at the nozzle exit plane [2]. For the discussed flow we chose a time step size $\Delta t = 5 \cdot 10^{-9}$ s. Each simulated particle represents $5 \cdot 10^{12}$ real particles. Total iteration number is $1.4 \cdot 10^{5}$. In total, we made $4 \cdot 10^{4}$ averages over time for each cell once steady state was reached.

Certain code extensions with respect to earlier versions [7] allowed a successful simulation: A limitation with respect to a minimum particle number in each cell as well as an algorithm which searches for the closest collision partner in given cell.

## 3. RESULT AND DISCUSSION

**Figure 2** depicts the comparison of the radial Mach number profiles at different axial distances from the nozzle exit plane (x = 0 mm). The x-axis in fig. 2 is limited to the radius of the nozzle exit plane ($r_0$) since with increasing axial distance from the nozzle the radial velocity component increases which makes the of Rayleigh-Pitot equation less applicable.

Not surprisingly, the reproduction of the Mach number profile at x = 0 mm is good. At x = 30 mm the comparison between simulation and measurement is still good. With increasing distance from the center line measured Mach numbers seem to decrease faster than in the simulation. For x = 60 mm we observe a strong deviation between simulation and experiment. For small radii, the measured values are underestimated, for large radii, Mach numbers are numerically overestimated. The match appears to be at $r/r_0 = 0.6$. With increasing axial distance (x = 90 mm) the agreement gets better again. In fact, at larger radii the matching appears to be better than at smaller radii. In total, we qualitatively reproduce the radial Mach number profiles at different axial distances from the nozzle exit plane. A closer look at the relative deviations shows the following: The good agreement at x = 0 mm and low radii results from the inflow condition. For x = 30 mm the relative deviation is at most measurement positions quite low, especially near the center line. This we refer to the close distance to the inflow boundary. In case of x = 90 mm the relative deviation is also small, <= 10%. For larger radii the match regarding the relative deviation appears to be even better than for smaller radii which is contradictory to what we see at all other positions. The largest relative deviation is observed at x = 60 mm. At most radial positions at which measurements where taken the relative deviation is > 10%.

## 4. CONCLUSION

The newly implemented code extensions enable LasVegas to be applied to certain low Knudsen number flows. The relative deviation of about 10 % at the majority of measurement points in the discussed arcjet case suggests that simplifications like neglecting chemistry may have a low impact on the simulation results.

## ACKNOWLEDGEMENTS

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