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Design of a small-scaled de Laval nozzle for IGLIS experiment

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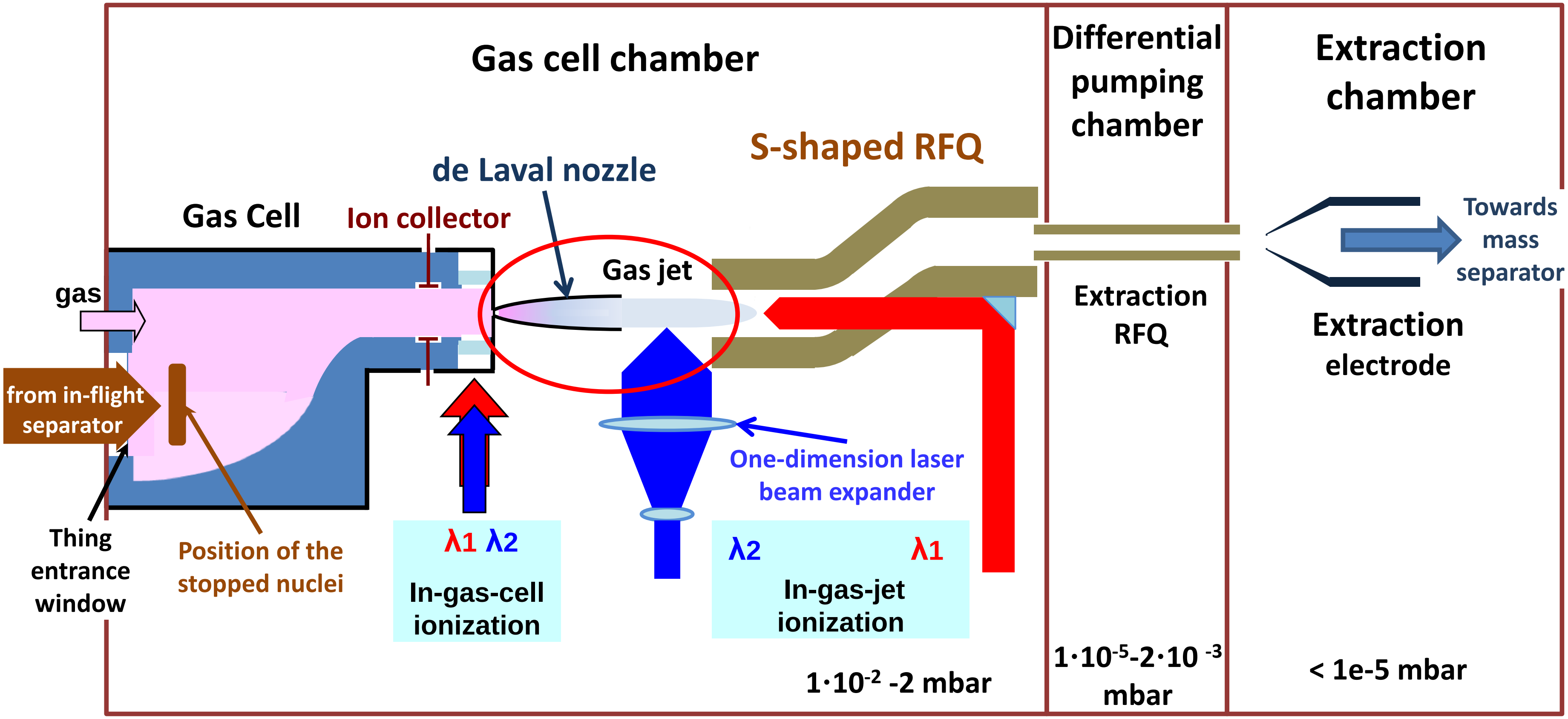
Outline

- IGLIS technique and requirements for a gas jet
- Classical way of a nozzle design
  - Method of characteristics
  - Boundary layer correction
- Iterative method based on CFD with COMSOL
- Conclusions and further steps

IGLIS= In Gas Laser Ionization Spectroscopy



- Products of a nuclear reaction get into the gas cell (Argon or Helium, 500 mbar)
- Atoms are neutralized and stopped in the cell, then transported towards the nozzle
- Two-step ionization is used for resonance ionization of the specified element

Requirements for the jet

- Cold enough with no pressure (high Mach number)
  - No Doppler and pressure broadening
- Long enough with no shocks (uniform)
  - Enough space and time to light up all the atoms
- Small enough flow rate
  - Pumping system capacity

Small scaled de Laval nozzle is required

De Laval Nozzle

Convergent-divergent nozzle:

$$\frac{dA}{A} = \frac{dV}{V}(M^2 - 1)$$

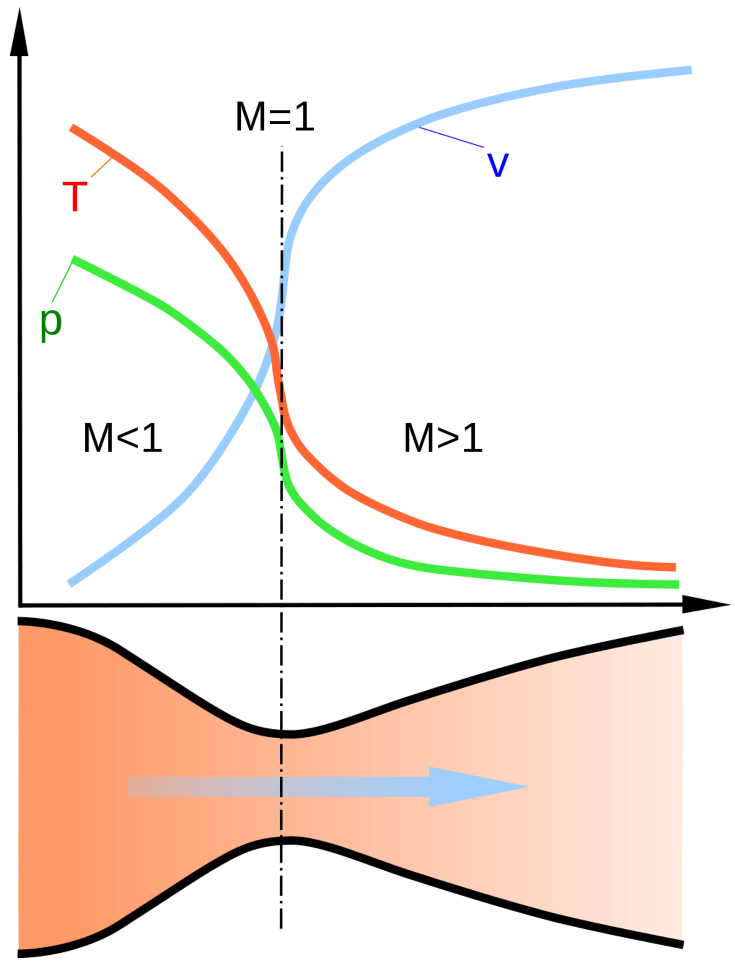
A – area of a cross-section, V – gas velocity,
M – Mach number

Pressure, temperature and density along the nozzle

$$\frac{p_0}{p} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{T_0}{T} = 1 + \frac{\gamma-1}{2}M^2$$

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{1}{\gamma-1}}$$



Quantitative characteristics

Parameter	Aeronautics [1]	Chemical study [2]	IGLIS[3]
Stagnation pressure	10^3 atm	10^(-5) atm	10^(-1) atm
Stagnation temperature	2000K	300K	300 K
Throat size	3 mm	25 mm	1 mm
Exit Mach number	6 to 15	4	8 to 12
Gas	Air	Helium	Argon
Reynolds number (in throat)	10^6	4000	3000

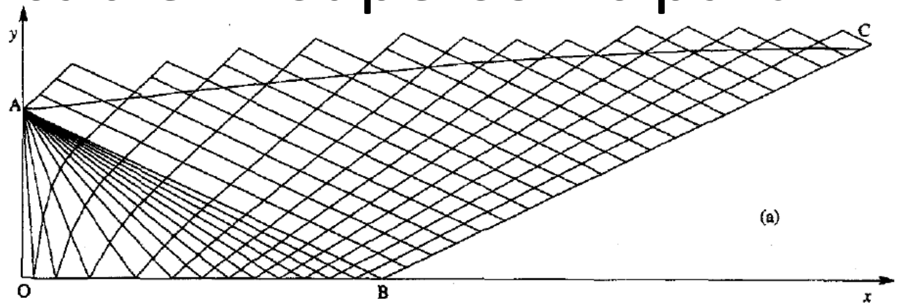
[1] J.J. KORTE et al, Least-squares/parabolized Navier-Stokes procedure for optimizing hypersonic wind-tunnel nozzles, J. of Propulsion and Power, **8**, No. 5 (1992), pp. 1057-1063

[2] G. Dupeyrat, J. B. Marquette and B. R. Rowe, Design and testing of axisymmetric nozzles for ion-molecule reaction studies between 20 °K and 160 °K, Phys. Fluids **28**, 1273 (1985)

[3] . Yu. Kudryavtsev et al. The in-gas-jet laser ion source: Resonance ionization spectroscopy of radioactive atoms in supersonic gas jets, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 297, pp. 7-22 (2013)

Classical way of designing a nozzle

- Step 1. Inviscid gas. The method of characteristic is applicable in supersonic part



- Step 2. The contour is corrected due to boundary layer.
- Step 3. The final contour is sum of inviscid contour and correction (the boundary layer is thin)

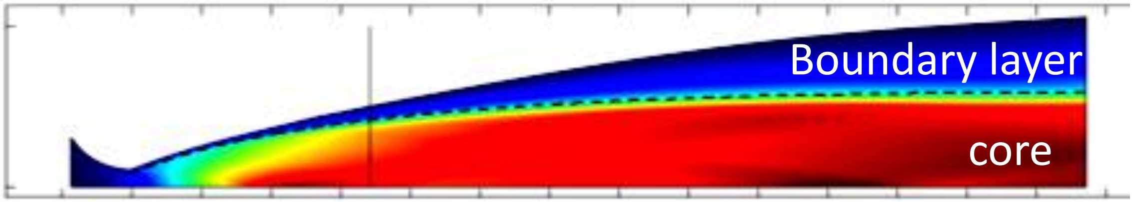
This procedure is not applicable, the boundary layer is thick

Iteration procedure

- Step 1. Inviscid gas
- Step 2. COMSOL simulation
  - 2d axisymmetric model
  - High Mach number flow module
  - 3 time-dependent studies with mesh refinement
  - Stationary study with the finest mesh
- Step 3. Boundary layer extraction
- Step 4. Producing of a new contour
- To step 2 until the procedure converges

Boundary layer correction

- Split the flow onto boundary layer and isentropic core: density, velocity, and entropy distributions are exported



- Boundary layer area and core factor are calculated

$$\alpha = \frac{\int_{core} \rho v r dr}{\int_{all} \rho v r dr}$$

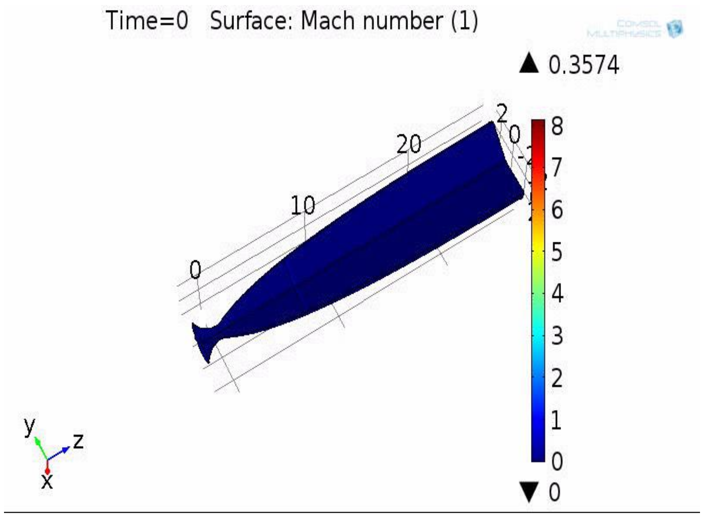
- New contour

$$S = \alpha S_{i.g.} + S_{b.l.}$$

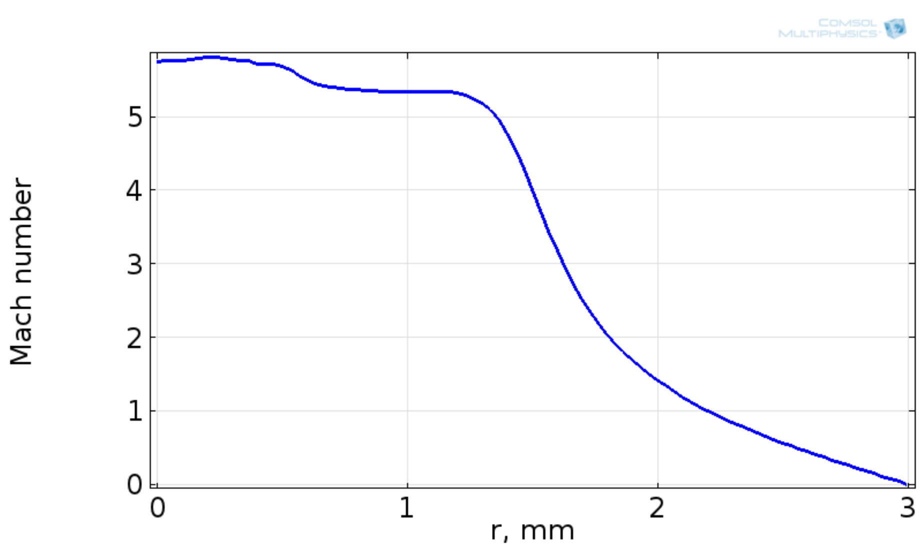
M=8. Initial attempt.

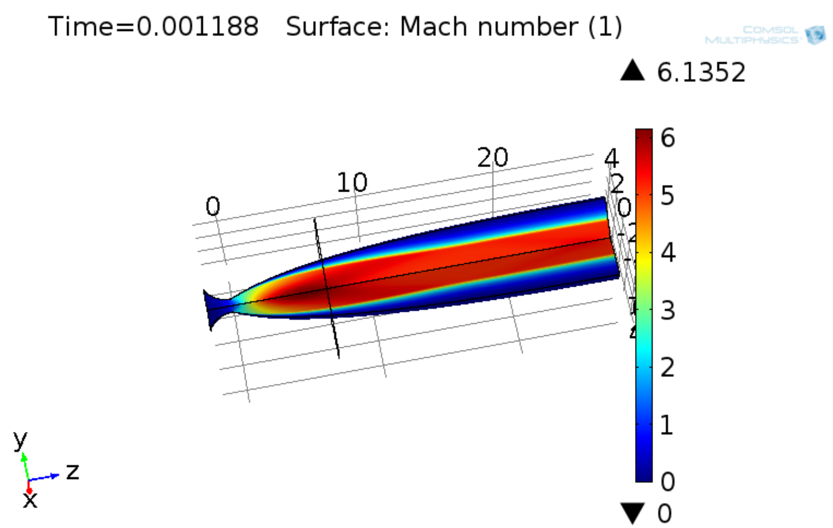
Start

Initial conditions: pressure in the left chamber is increasing from desired outlet pressure to the proper value and remains constant

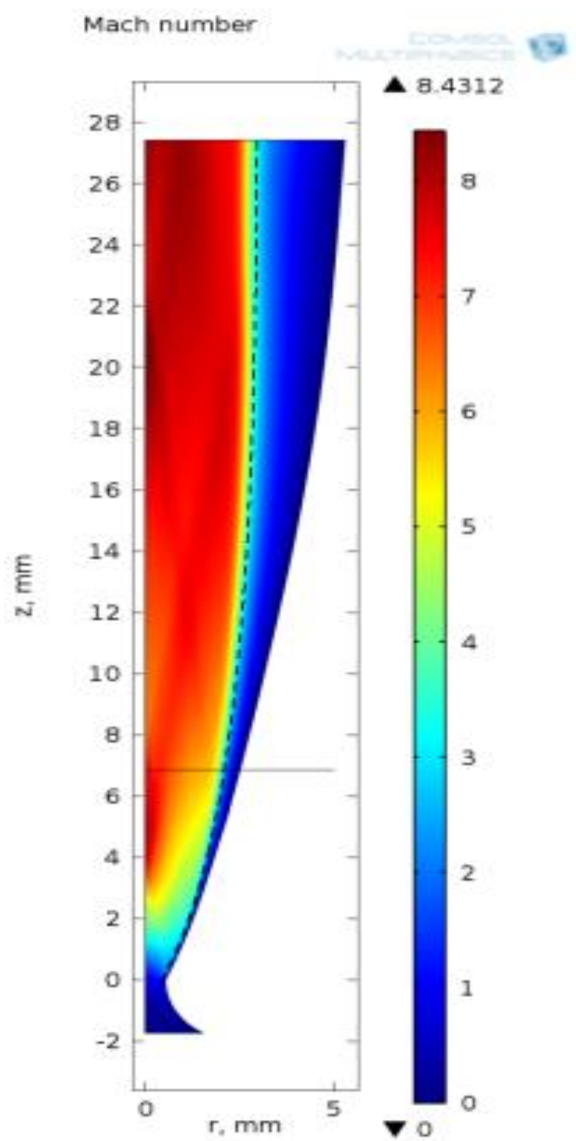


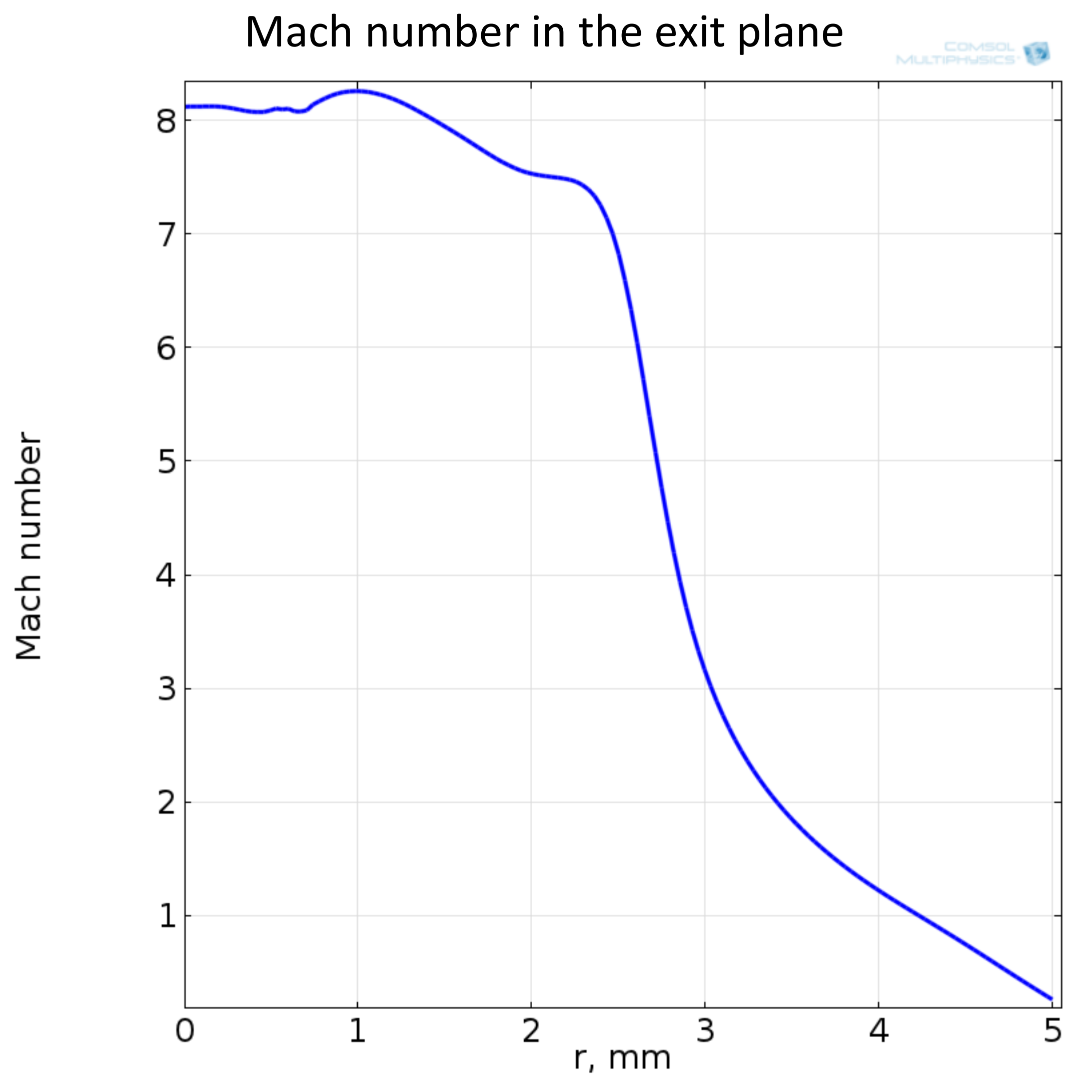
Refinement





M=8. Final design





Conclusions

- The iterative method for a de Laval nozzle design is proposed and tested
- Required nozzles for Mach number up to 8 are designed
- Mesh refinement leads to decreasing the viscous effects, but the process converges
- Designed nozzles are to be manufactured and tested

Thank you for your attention

Technical details of the simulation

- Step 1. 7 000 DOF. Nozzle is split onto 2 parts

  Outlet: hybrid conditions, pressure corresponds to desired Mach number (p_out)

  Inlet: Pressure rises from (10*p_out) to final value

  Border is located on 25% of the diverging part
- Step 2. Mesh refinement. Time dependent solver
- Step 3. 10^6 DOF. Stationary solver