Gas expansion and nozzle shape

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BGC Collaboration Meeting, 27.11.2018

Outline

- Gas expansion in a nozzle
  - slightly underexpanded jet
  - highly underexpanded jet
  - overexpanded jet
  - supersonic gas jet expansion into the molecular vacuum

  (slightly underexpanded, highly underexpanded and overexpanded jet: medium vacuum conditions)

- Nozzle shapes
  - different possibilities
  - design methodology

- Conclusions

Gas jet

Theory

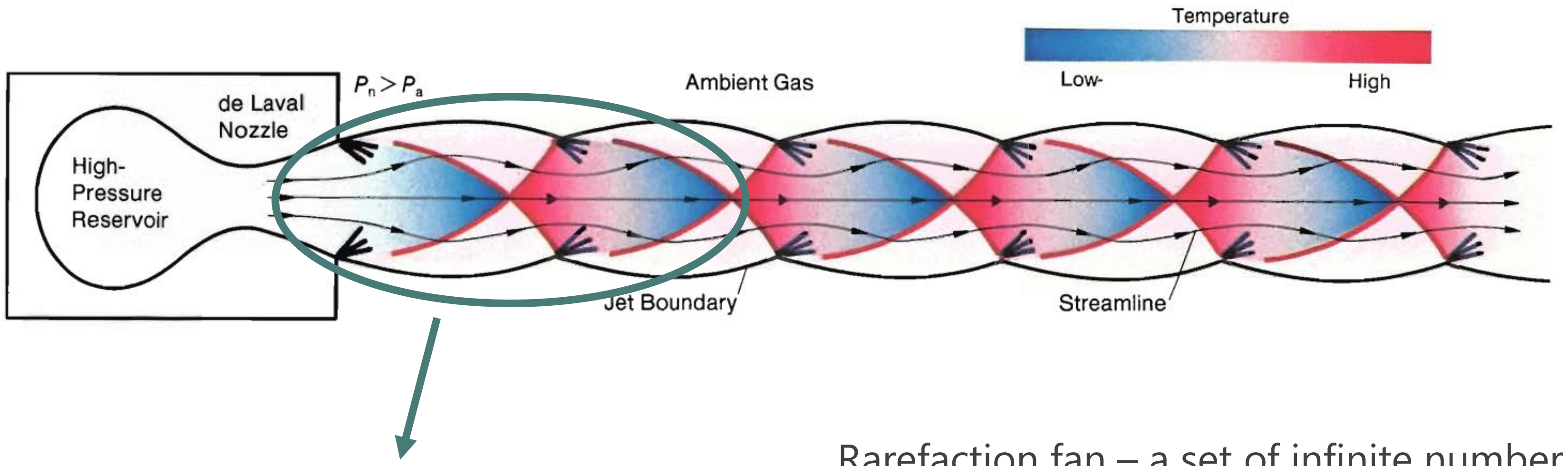
1) underexpanded gas jet – the gas leaves the nozzle at pressure higher than ambient (backpressure)

    1) slightly underexpanded
    2) highly underexpanded

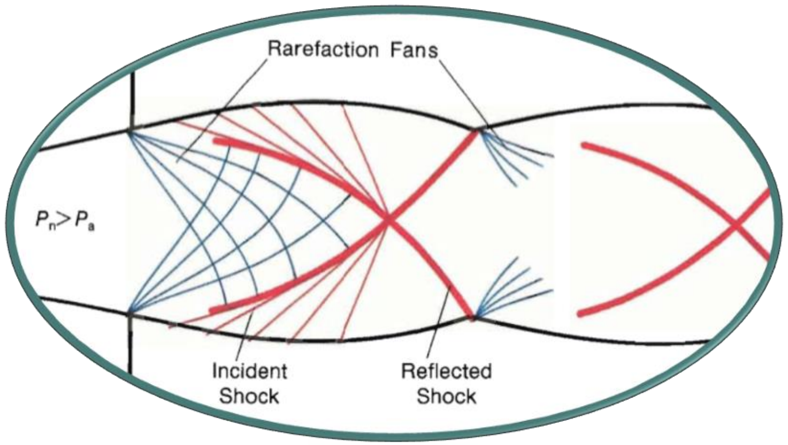
2) overexpanded gas jet – the gas leaves the nozzle at pressure lower than ambient (backpressure)

- Pressure in the container must be obviously always higher than backpressure.

Slightly underexpanded jet



M.L. Norman, K.H.A.Winkler, *Supersonic Jets*, Los Alamos Science, 1985

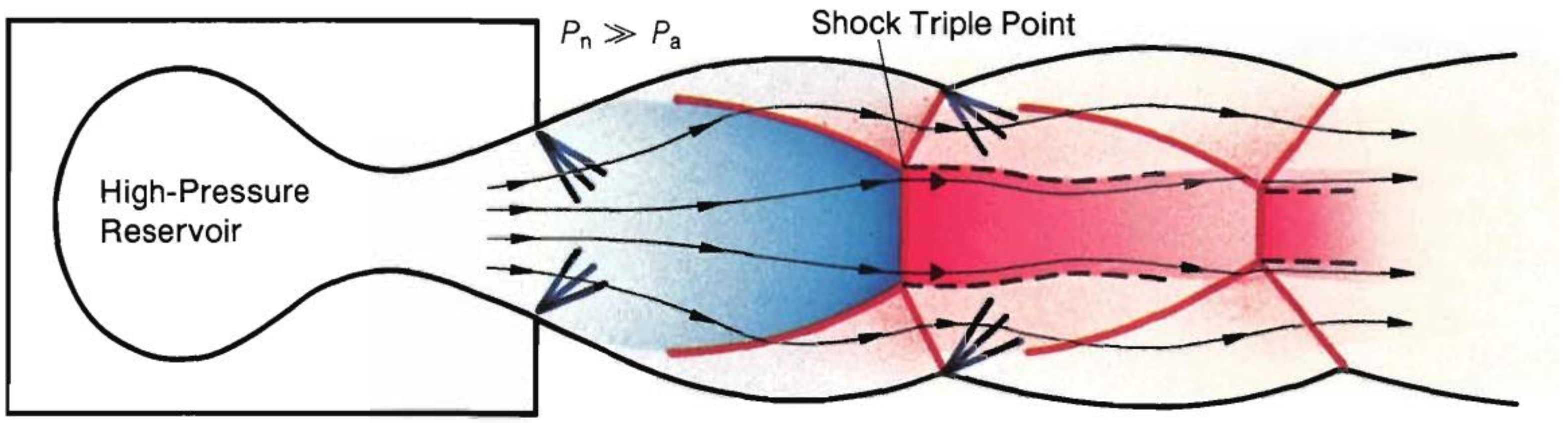


Rarefaction fan – a set of infinite number of Mach waves, each of them accelerating and turning slightly the gas flow

$P_n - exit\ pressure$

$P_a - ambient\ pressure\ (backpressure)$

Highly underexpanded jet

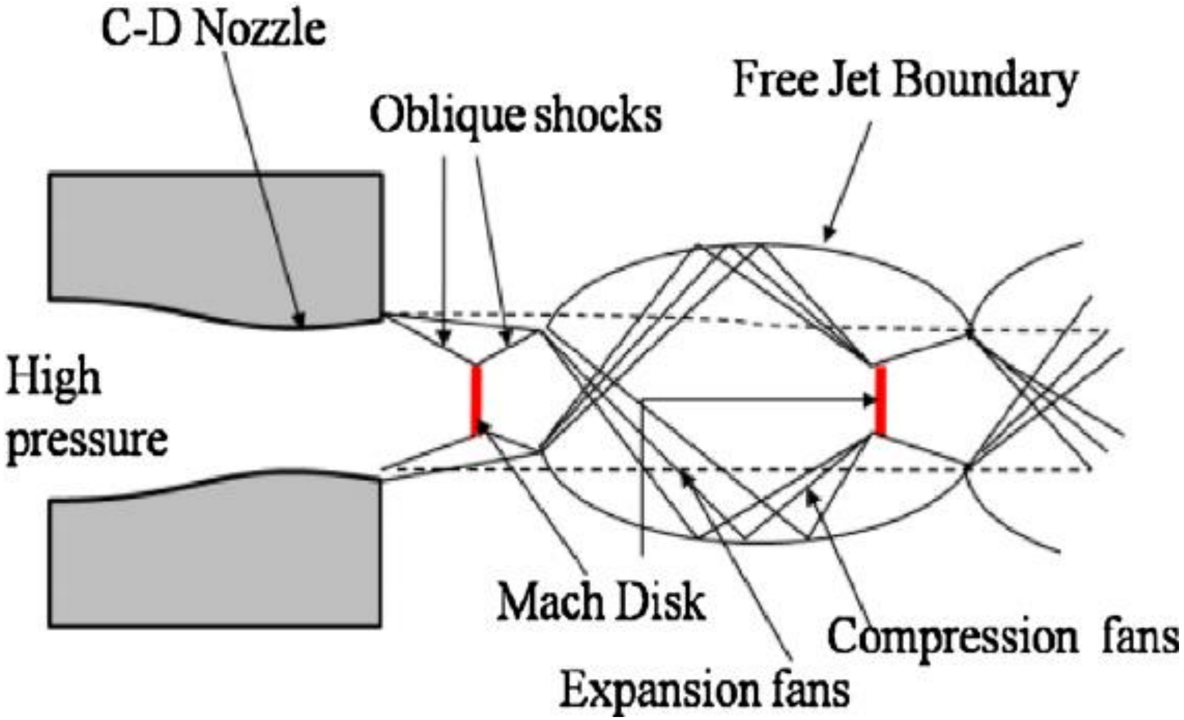


M.L. Norman, K.H.A.Winkler, *Supersonic Jets*, Los Alamos Science, 1985

$$\frac{L}{D} = 0{,}65 \cdot \left(\frac{p_0}{p_{inf}}\right)^2$$

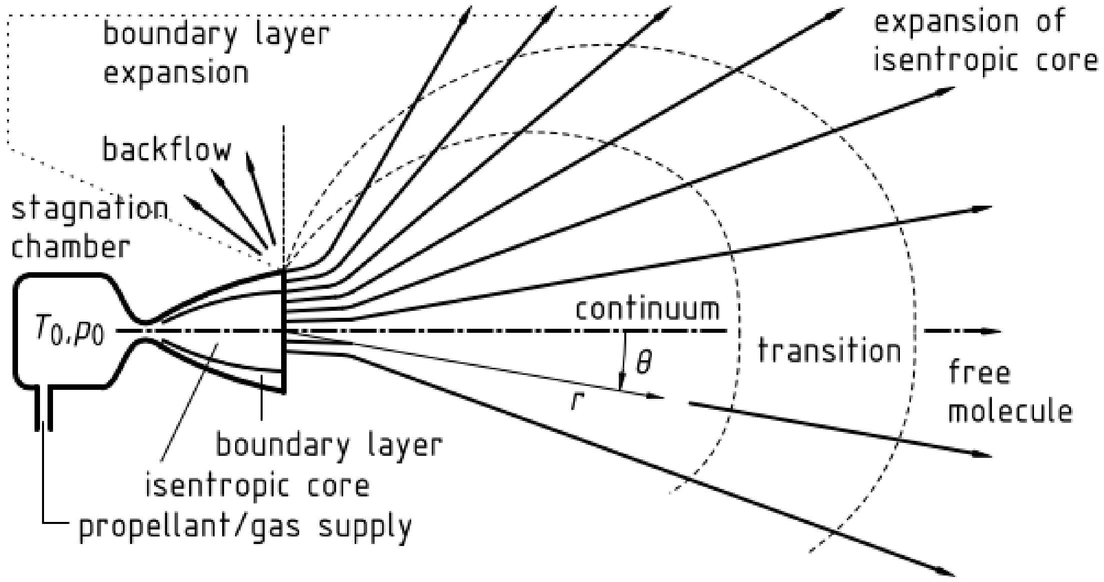
for $PR = \frac{p_0}{p_{inf}} = 20 \div 200$

Overexpanded jet

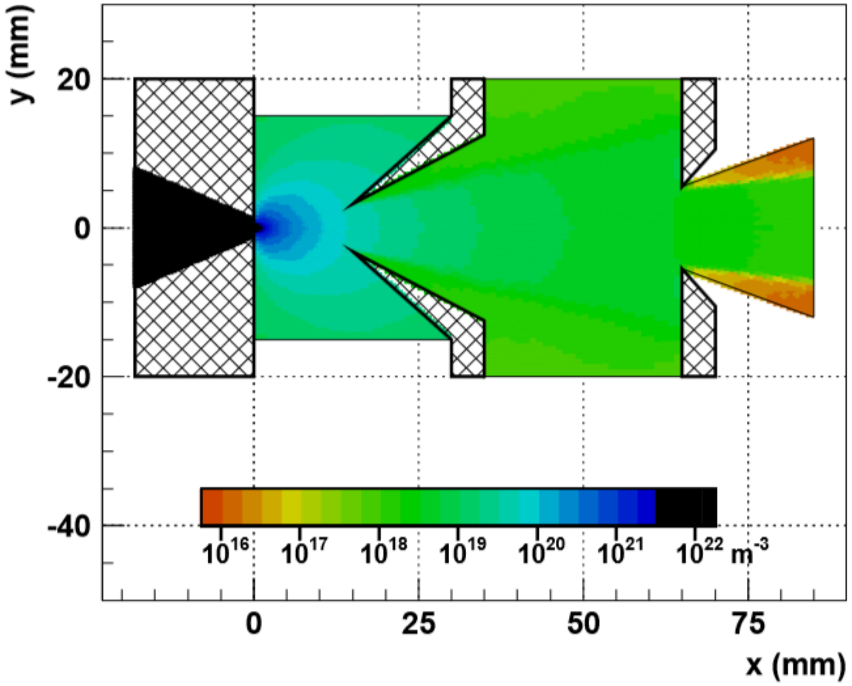


S.M.V. Rao, J. Gopalan, *Acetone planar laser-induced fluorescence for supersonic flow visualization in air and nitrogen gas,* https://www.researchgate.net/publication/270762073

Expansion into vacuum



M. Grabe, *Numerical simulation of nitrogen nozzle expansion using kinetic and continuum approaches*, conference paper, September 2008, https://www.researchgate.net/publication/224999345



A. Naβ, E. Steffens, *Direct Simulation of Low-Pressure Supersonic Gas Expansions and its Experimental Verification*, Preprint submitted to Elsevier Preprint, 28 May 2018

Conclusions for BGC

- We are in molecular flow regime. Backpressure is very low.
- There is no force which can push the gas back towards the centre.
- Normal shock wave cannot be formed.
- There are no Mach disks.

Nozzle shape

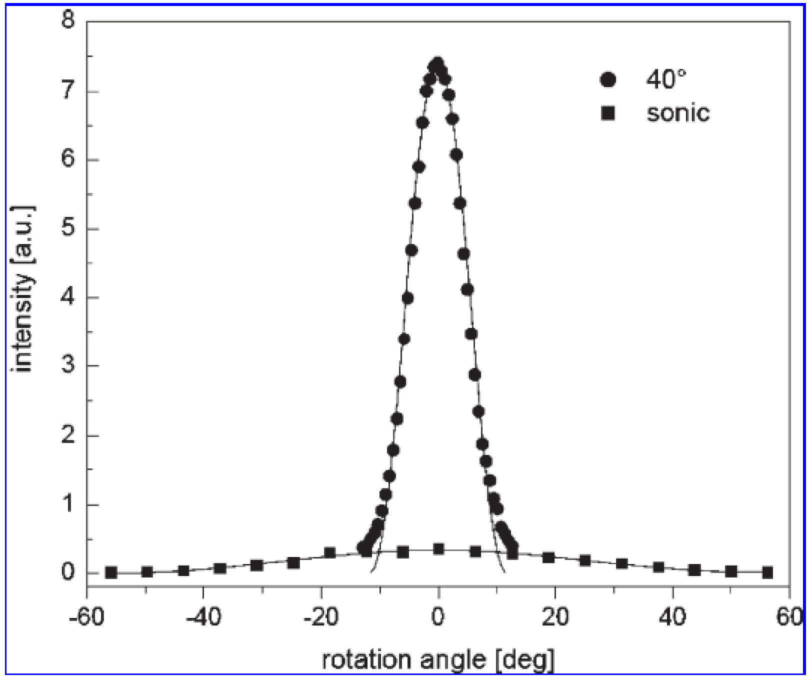
BGC nozzle design

- For BGC purposes we want to have high local gas density (through the third skimmer)
- We are dealing with vacuum conditions → satellites analogy was obvious
  - NASA reports on this issue are difficult to be found
  - reports from aerospace research centers have been studied
  - original Rao’s publications
  - Aerospace Testing Alliance

Possible designs (1) – simplest options

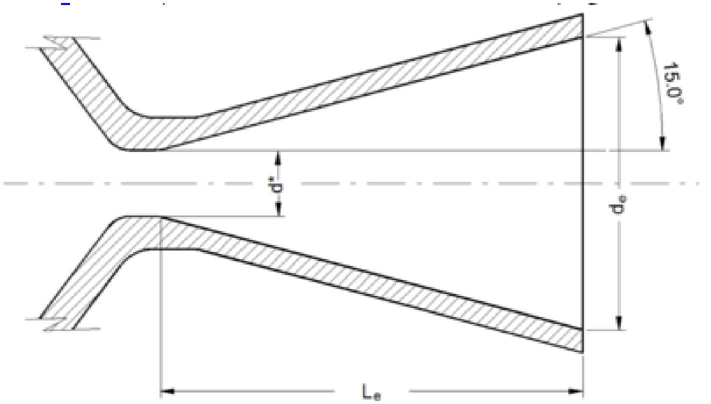
SIMPLE HOLE (SONIC NOZZLE)

- gives a subsonic flow



CONICAL NOZZLE

- gives supersonic flow
- much bigger density



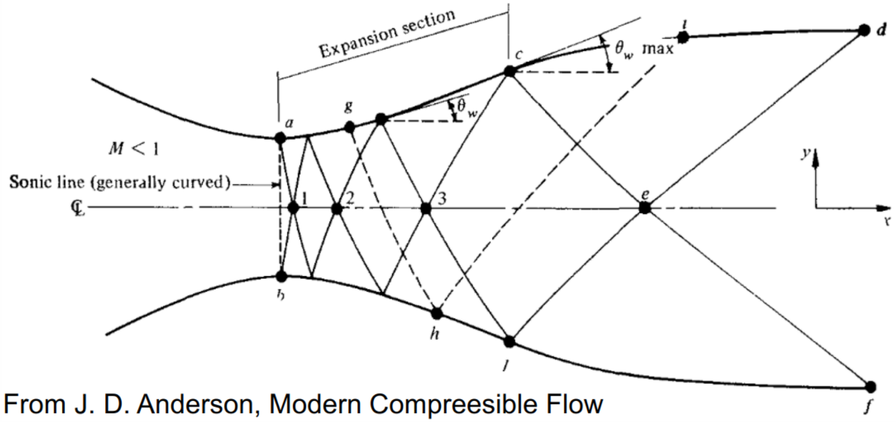
Helium density after 200 mm for 20-mm-nozzles at 50 bar

K. Luria, W. Christen, U. Even, *Generation and propagation of intense supersonic beams*, The Journal of Physical Chemistry, A 2011, 115, 7362-7367

Possible designs (2)

NOZZLE WITH EXPANSION SECTION

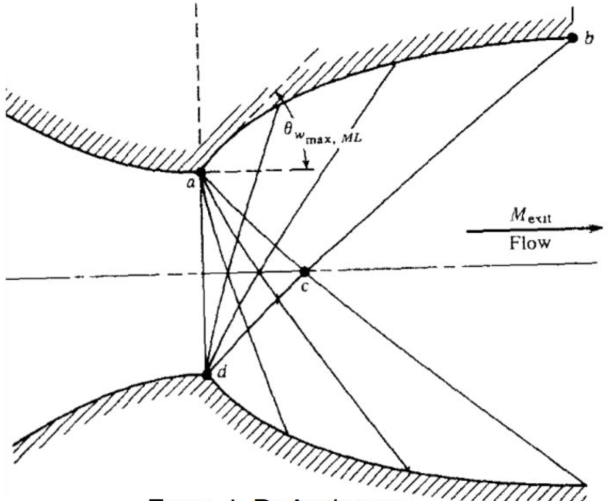
- better quality flow
- preferred for wind tunnels



From J. D. Anderson, Modern Compreesible Flow

MINIMUM LENGTH NOZZLE

- no expansion section
- preferred for rocket engines

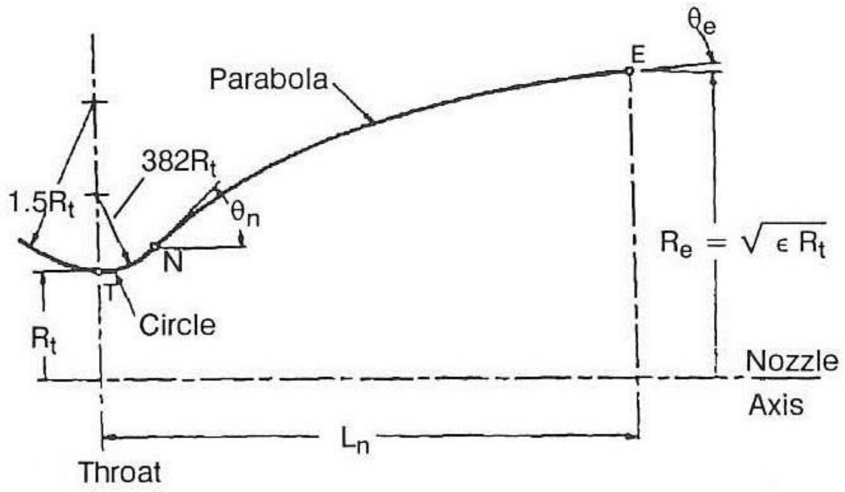


From J. D. Anderson,
Modern Compreesible Flow

Possible designs (3)

RAO DESIGN

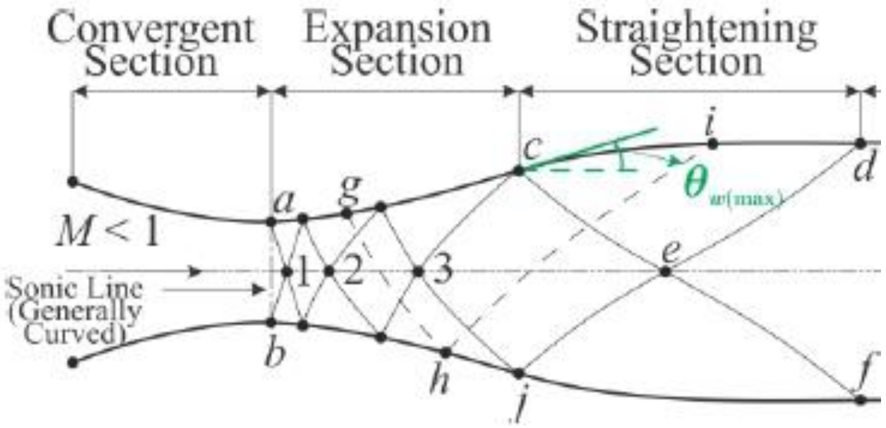
- simplified shape of Thrust Optimized Contour
- ready-made formula



G.V.R. Rao, "Approximation of Optimum Thrust Nozzle Contour," ARS Journal, Vol. 30, No. 6, June 1960, p. 561

IDEAL CONTOUR

- produces uniform axial flow
- expansion is slow



B. Vallabh, B.W. Skews, *Approximation of nozzle contours in the CSIR supersonic wind tunnel*, R&D Journal of the South African Institution of Mechanical Engineering 2017, 33, 32-41

Conclusions

- Simple hole (subsonic) nozzle gives the lowest density.
- Conical nozzle requires the smallest attachment angle and thus greater length is needed to expand to the same pressure.
- Optimized shapes can be used, further research will be conducted to choose the best one.

- Suggestions about sources for space nozzles?