POLITECNICO DI MILANO

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Influence of Molecular Complexity on Nozzle Design for an Organic Vapor Wind Tunnel

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Motivation & Current Activities

Motivation of the proposed work:

Improvement of the performances of Organic Rankine Cycles (ORC) via better turbine design calls for experimental studies on ORC turbine flows

TROVA@PoliMI

- is designed to provide experimental data for flows typical of ORC turbine blade passages
- is a blow-down facily; expansion occurs through a **test section**: straight axis, planar, convergent-divergent nozzle
- Working fluid: siloxane MDM

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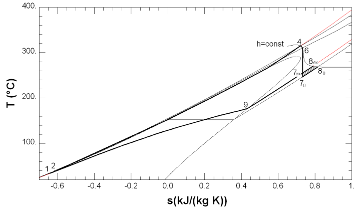

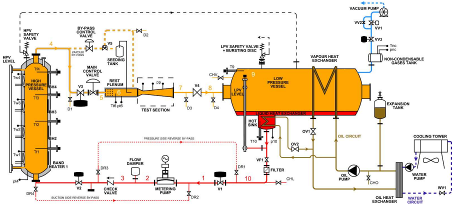

Presentation at 11.20 Senaatszaal…

TMD Cycle

4 - High Pressure Vessel

6 - Nozzle Inlet

7 - Nozzle Outlet

8 - Low Pressure Vessel

Design issue

The understanding of the gasdynamics of supercritical and close-to-critical flows is incomplete!

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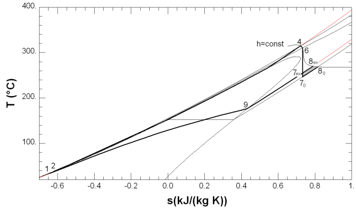

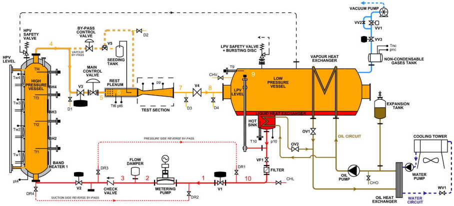

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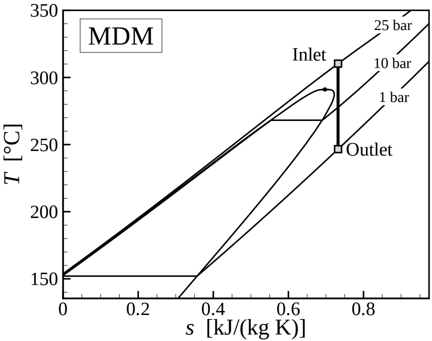
Nozzle design for ORC applications

Expansion occurs in highly non-ideal gas conditions

- Real-gas thermodynamic models
- High compressibility
- Non-ideal dependence of the speed of sound c on specific volume v at constant T

Dense gas dynamics



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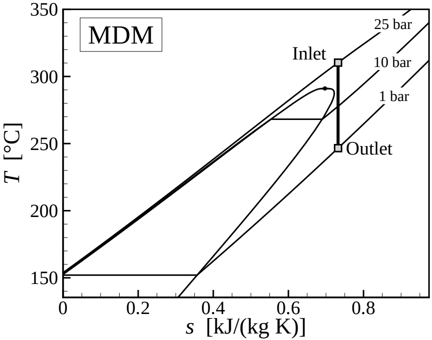


Dense gas dynamics

Fundamental derivative of gasdynamics

Phil Thompson, J. Fluids Mech. 1971

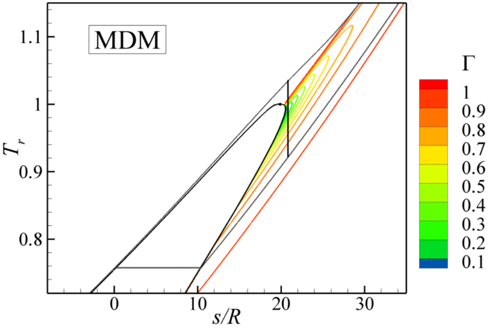
Fundamental derivative Γ

$$\Gamma = 1 + \frac{\rho}{c}\left(\frac{\partial c}{\partial \rho}\right)_s$$

c sound speed

ρ density

s entropy p.u.m.



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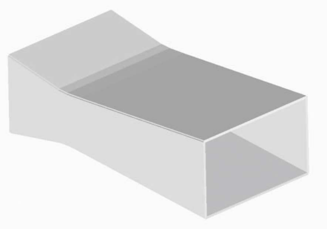

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To design the divergent section of subsonic-supersonic nozzles operating in the dense gas regime

Assumptions

Flow is two-dimensional, flow is expanding from uniform reservoir conditions into uniform ambient conditions, high-Reynolds number flow, no flow separation, no shock waves, adiabatic walls

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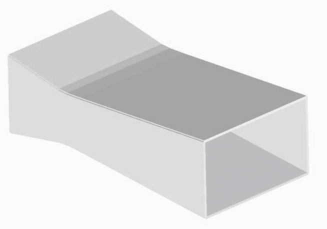

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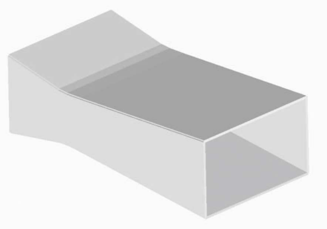

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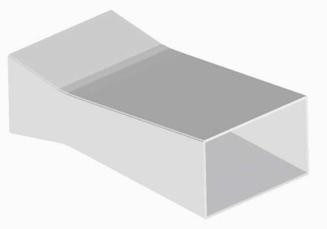

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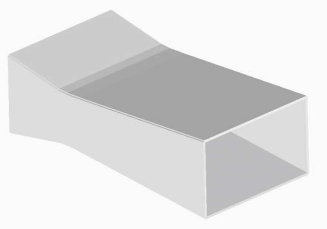

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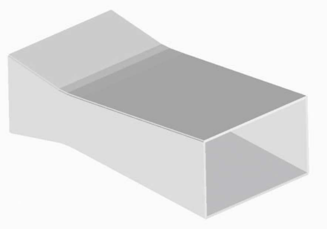

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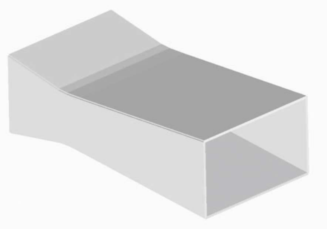

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Mathematical model

Full potential equation

Compressible non-viscous isentropic irrotational flow

$$\left(\Phi_x^2 - c^2\right)\Phi_{xx} + 2\,\Phi_x\Phi_y\Phi_{xy} + \left(\Phi_y^2 - c^2\right)\Phi_{yy} = 0$$

with $\Phi \in \mathbb{R}$, $u = \Phi_x$ and $v = \Phi$ flow velocities, $w^2 = u^2 + v^2$.

Thermodynamic closure

$c = c(s, h) = c(s_\mathrm{r}, h_\mathrm{r} - w^2/2)$?

StanMix and RefProp libraries in FluidProp:
- Stryjek-Vera Peng-Robinson cubic EOS (PRSV)
- Span Wagner multiparameter EOS (SW)

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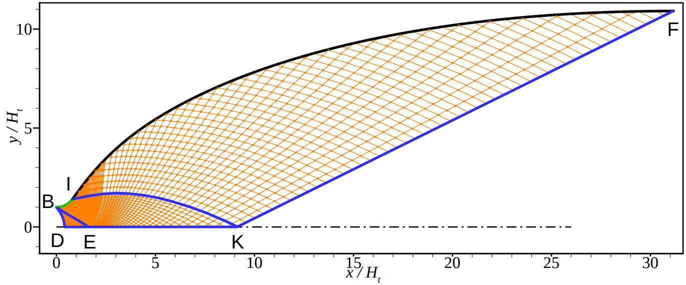
Design procedure

Method Of Characteristics (MOC) (Zucrow & Hoffman, 1977)



Initial data (BD)

Sauer (1947) scheme
$2\Gamma^* \phi_x \phi_{xx} - \phi_{yy} = 0$

Kernel region (BIKD)

Direct MOC from initial data line BD

Turning region (IKF)

Inverse MOC from exit characteristic KF

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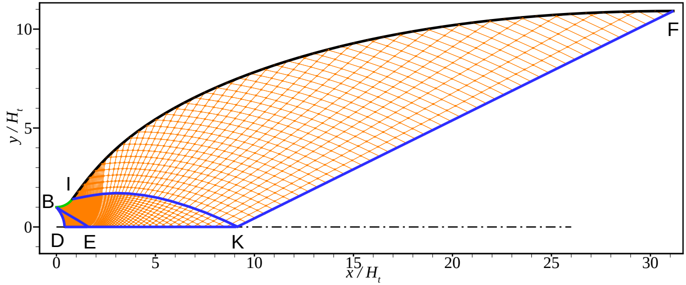

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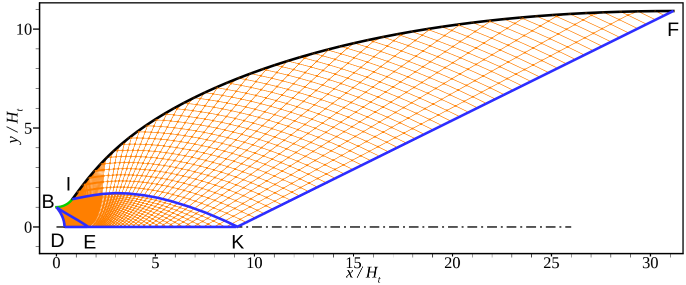

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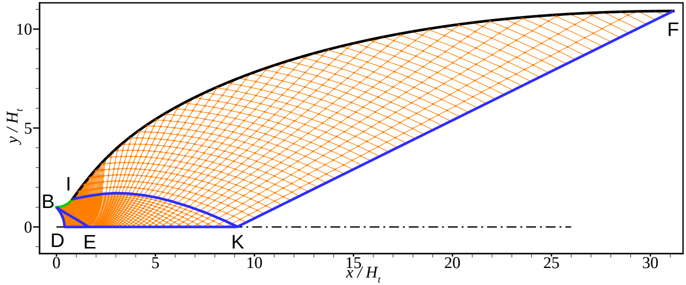

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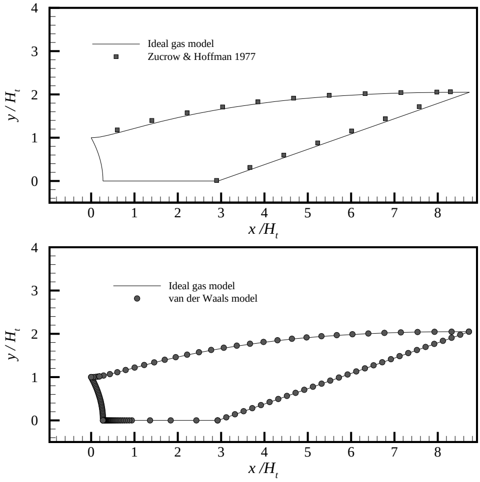
Recovery of perfect gas results



Perfect gas results

Diatomic nitrogen dilute conditions

Nozzle design for MDM

Reservoir conditions

$P_0 = 25$ bar
$T_0 = 310.3$ °C

Expansion ratio

$\beta = 25$

Design conditions

Exit Mach number
$M_d = 2.25$
Velocity vector parallel to x axis

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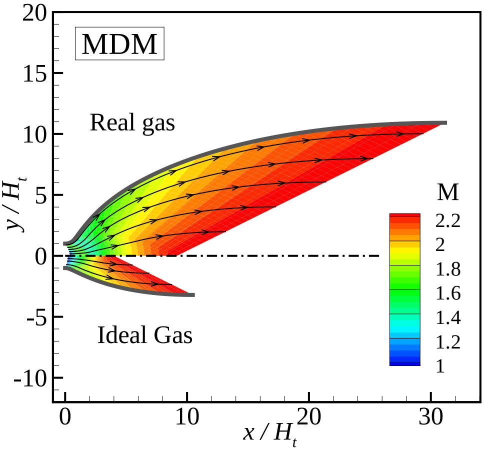

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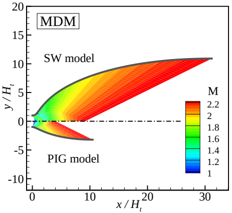

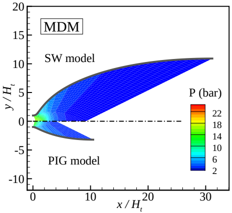

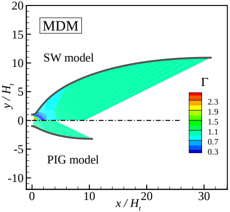

$$\frac{\mathrm{d}M}{\mathrm{d}x} = \frac{1+(\Gamma-1)M^2}{M^2-1}\,\frac{M}{H}\,\frac{\mathrm{d}H}{\mathrm{d}x}$$

$$\frac{\mathrm{d}P}{\mathrm{d}x} = \frac{\rho u^2}{P}\,\frac{1}{M^2-1}\,\frac{P}{H}\,\frac{\mathrm{d}H}{\mathrm{d}x}$$

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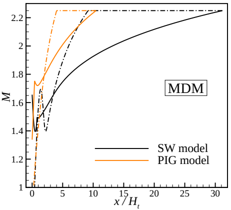

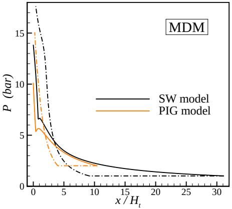

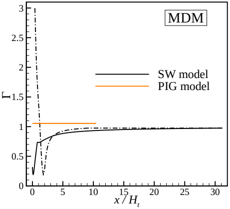

Nozzle design for different fluids

Fluids

D_4, D_5, D_6,
MM, MDM, MD_2M
R245fa, Toluene,
Ammonia

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Warning

Thermal decomposition!!!

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Design parameters

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$T_0 = 0.975 T_c$
$\beta = 25 \rightarrow P_d = 0.031 P_c$

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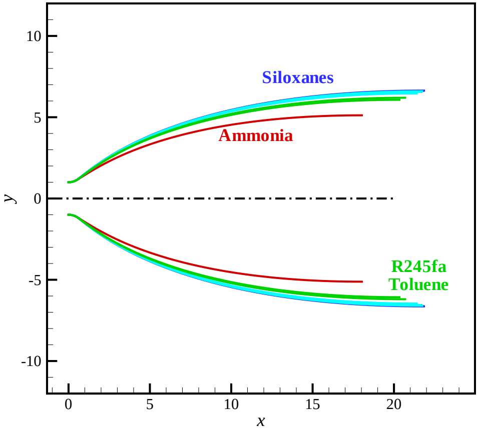

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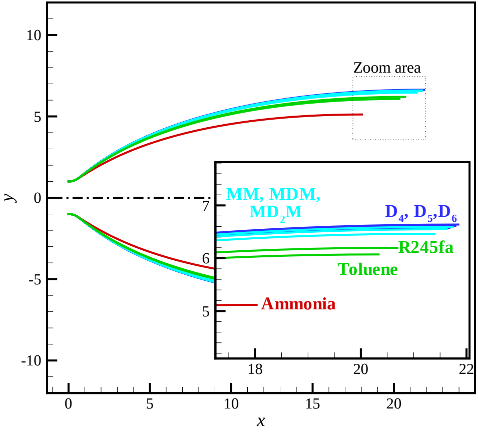

Conclusions

- A nozzle design tool for dense gases was developed and validated against ideal gas results using the the cubic PRSV EoS and the multi-parameter Span-Wagner EoS in FluidProp
- If the expansion process occurs in region where Γ is less than its dilute-gas value, then resulting nozzles are longer, in accordance with the one-dimensional theory.
- For increasing molecular complexity of the fluid, Γ decreases and the nozzle length increases.
- Caution: normalized mass flow varies dramatically for the diverse operating conditions

Thank you!