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

A. Guardone, Aerospace Eng. Dept., PoliMI
A. Spinelli, V. Dossena, Energy Dept., PoliMI
V. Vandecauter, Aerospace Eng., TUDelft
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 facility; expansion occurs through a test section: straight axis, planar, convergent-divergent nozzle
- Working fluid: siloxane MDM
Motivation & Current Activities

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Chapter: Expanders for ORC Applications

TROVA@PoliMI

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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Nozzle design for ORC applications

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- 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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Fundamental derivative of gasdynamics

Phil Thompson, J. Fluids Mech. 1971

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

c sound speed
\( \rho \) density
s entropy p.u.m.
Goal of the research

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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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**

\[
c = c(s, h) = c(s_T, h_T - w^2/2)
\]

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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Recovery of perfect gas results

Ideal gas model

Zucrow & Hoffman 1977

Diatomic nitrogen dilute conditions
Chapter: Design of the test nozzle

Nozzle design for MDM

**Reservoir conditions**

\[ P_0 = 25 \text{ bar} \]
\[ T_0 = 310.3 \, ^\circ \text{C} \]

**Expansion ratio**

\[ \beta = 25 \]

**Design conditions**

Exit Mach number
\[ M_d = 2.25 \]
Velocity vector parallel to \( x \) axis
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The diagram shows a 2D plot with the following labels:

- **MDM**: A region labeled MDM with Mach numbers indicated.
- **Real gas**: A labeled region for real gas conditions.
- **Ideal Gas**: A labeled region for ideal gas conditions.

The plot includes a color gradient with Mach numbers ranging from 1 to 2.2, with corresponding colors for visual differentiation.
Chapter: Design of the test nozzle

Nozzle design for MDM

\[ \frac{dM}{dx} = \frac{1+(\Gamma-1)M^2}{M^2-1} \frac{M}{H} \frac{dH}{dx} \]

\[ \frac{dP}{dx} = \frac{\rho u^2}{P} \frac{1}{M^2-1} \frac{P}{H} \frac{dH}{dx} \]

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Nozzle design for different fluids

**Fluids**

D₄, D₅, D₆,
MM, MDM, MD₂M
R245fa, Toluene,
Ammonia
Chapter: Influence of molecular complexity

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**Warning**

Thermal decomposition!!!
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$D_4$, $D_5$, $D_6$, 
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**Design parameters**

\[ P_0 = 0.78P_c \]
\[ T_0 = 0.975T_c \]
\[ \beta = 25 \rightarrow P_d = 0.031P_c \]
Chapter: Influence of molecular complexity

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Conclusions

- A nozzle design tool for dense gases was developed and validated against ideal gas results using the cubic PRSV EoS and the multi-parameter Span-Wagner EoS in FluidProp.
- If the expansion process occurs in region where $\Gamma$ 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, $\Gamma$ decreases and the nozzle length increases.
- Caution: normalized mass flow varies dramatically for the diverse operating conditions.
Thank you!