Numerical and Experimental Investigations on Cylindrical Critical Flow Venturi Nozzles (CFVN)

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Numerical and Experimental Investigations on the Shape and Roughness of cylindrical CFVNs

Context

*Introduction - Overview:*
A way to calibrate flow meters is by using Critical Flow Venturi Nozzles CFVNs as a primary standard. International standard **ISO 9300** regulates the terms of use of CFVN in flow calibration.

**Problematics:**
- Improve range of applicability: Reynolds number range under $5 \times 10^5$ and over $1 \times 10^7$.
- Need less than 0.3% in terms of uncertainties.
- Understand flow phenomena: laminar turbulent transition? roughness effect?
- In terms of CFVN wall surface, roughness is difficult to characterise and to manufacture.

**Advantages:**
- Stable (reliable in time)
- Easy to transport
- Mono-bloc (no mechanism)
- Stainless steel (solid and replicable)
As the discharge coefficient is partially influenced by gas viscosity, it clearly depends on the Reynolds number in the nozzle.

\[
\text{Re}_D = \frac{4 \cdot Q_{\text{m theo}}}{\pi \cdot d \cdot \mu_0}
\]

\[
C_d = a - b \cdot \text{Re}_D^{-n}.
\]

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- Context
- Experimental characterisation of roughness effect
- Numerical investigation of flow structure
- Conclusion and perspectives
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Critical nozzles to be investigated (cylindrical shape as recommended by the ISO 9300 standard)

<table>
<thead>
<tr>
<th>d</th>
<th>Diameter of Venturi nozzle throat (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rc</td>
<td>Radius of curvature of nozzle inlet (m)</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of the upstream duct (m)</td>
</tr>
</tbody>
</table>

Critical diameters:

- \( D \geq 4 \cdot d \)
- \( r_c = d \)
- \( z = 0 \)
- \( z/d = 2 \)

Flow direction:

- Monobloc stainless steel

Symbols:

- \( \bullet \) = FLOW

Note: The image contains a diagram illustrating the critical nozzle dimensions and shapes, with specific ratios and geometric relationships highlighted.
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Dimensional characterisation

Critical nozzles to be investigated (cylindrical shape as recommended by the ISO 9300 standard)

Characterisation of roughness by different techniques:

Roughness characterisation by silicon moulding (nozzle diameter 5mm Poitiers university)

Diameter and cylindricity measurement (nozzle diameter 5mm IUT Angoulême – Poitiers University)
Critical nozzles to be investigated (cylindrical shape as recommended by the ISO 9300 standard)

<table>
<thead>
<tr>
<th>N°</th>
<th>Machined diameter d (mm)</th>
<th>Divergent length</th>
<th>Machined roughness range Ra (µm)</th>
<th>Corresponding non-dimensional roughness Range Ra/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>7d</td>
<td>0.4-0.6</td>
<td>8.00010^-5-1.20010^-4</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>7d</td>
<td>0.6-0.8</td>
<td>1.20010^-4-1.60010^-4</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>7d</td>
<td>0.8-1.2</td>
<td>1.60010^-4-2.40010^-4</td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td>7d</td>
<td>0.4-0.6</td>
<td>5.33310^-5-8.00010^-5</td>
</tr>
<tr>
<td>5</td>
<td>7.5</td>
<td>7d</td>
<td>0.6-0.8</td>
<td>8.00010^-5-1.06710^-4</td>
</tr>
<tr>
<td>6</td>
<td>7.5</td>
<td>7d</td>
<td>0.8-1.2</td>
<td>1.06710^-4-1.60010^-4</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>7d</td>
<td>0.4-0.6</td>
<td>4.00010^-5-6.00010^-5</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>7d</td>
<td>0.6-0.8</td>
<td>6.00010^-5-8.00010^-5</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>7d</td>
<td>0.8-1.2</td>
<td>8.00010^-5-1.20010^-4</td>
</tr>
<tr>
<td>10</td>
<td>7.5</td>
<td>16.4d</td>
<td>0.6-0.8</td>
<td>8.00010^-5-1.06710^-4</td>
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</table>
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Experimental Part

Experimental Part : Study of the dimensional sizes of 10 cylindrical nozzles:
Evaluation of the nozzle shape, examples of local measurements:

- Variations of the diameter in the cylindrical part due to roughness but also to shape defaults.
- Minimal diameter located mostly at the end of the cylindrical part.
- Dominance of the shape default over the roughness in the Cd evaluation with $\omega_1$ and $\omega_2$ as mentioned by MICKAN in 2018.
- The need for the equivalent measurements for comparison with the historical nozzle database.
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Experimental set-up: NMI Methods

Standard facilities used for the flow rate measurements

<table>
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<th>Gas used</th>
<th>Primary standard</th>
<th>Maximum pressure (Bar)</th>
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<tr>
<td>PTB</td>
<td>Air</td>
<td>Bell prover**</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Natural gas</td>
<td>piston prover***</td>
<td>56</td>
</tr>
<tr>
<td>CESAME-EXADEBIT</td>
<td>Air</td>
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** Working standards were used for the calibrations in all measurements with air above 100 kPa.
*** Working standards were used for the calibrations in all measurements with natural gas before 2015.

Maximum flow rate: 8 m³/h to 7200 m³/h
Pressure range: From 16 bar to 50 bar
Temperature range: From 8 °C to 20 °C (stability <0.1 K during test)
Measurement uncertainty: Max. 0.15% (double standard deviation $k=2$)
Working fluid: Natural gas with uncertainty of $C^*$ estimated at 0.065%, ($k = 2$) and molar mass uncertainty estimated at 0.1% ($k = 2$)

Maximum flow rate: 200 m³/h
Pressure range: From 6 bar to 60 bar
Diameter throat range: From 1.5 mm to 20 mm
Measurement uncertainty: 0.11% on $AC_D$ value for pressure up to 60 bar ($k=2$).
Working fluid: Dry air near ambient temperature with molecular weight of 28.966 g/mole and uncertainty of $C^*$ estimated at 0.05% ($k=2$).

Acknowledgement: This research was partially supported by Bodo Mickan and Ernst von Lavante. Thanks to our colleagues from PTB in Germany who provided insight and expertise.


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Experimental part

Experimental measurements with roughness of 5mm nozzles

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- Smoother level
- Rougher level
- laminar
- transitional
- turbulent

Reynolds number

VINCENT 1968
Nozzle n°1 pVT,t ; 2018
Nozzle n°2 pVT,t ; 2018
Nozzle n°1 PTB (NG) ; 2018
Nozzle n°2 PTB (air) ; 2019
Nozzle n°3 PTB (NG) ; 2018
Nozzle n°3 PTB (air) ; 2019
ISO 9300 (cylindrical equation)
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- **VINCENT 1968**
- ▲ Nozzle n°2 pVT,t ; 2018
- ▲ Nozzle n°2 M1 ; 2019
- ▢ Nozzle n°2 PTB (NG) ; 2018
- ▲ Nozzle n°2 PTB (air) ; 2019
- ISO 9300 (cylindrical equation)
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Numerical Part

Global Numerical strategy

- Compressible Navier-Stokes (RANS).
- Axisymmetric formulation.
- OpenFOAM (rhoCentralFoam)
- Shock capturing (central-upwind schemes) from Kurganov and Tadmor.
- Time discretization: implicit 2\textsuperscript{nd} order backward.
- TVD 2\textsuperscript{nd} order accuracy (Gauss linear interpolation, Van Leer limiter)
- Laminar/Turbulence model: Spalart Allmaras, k-\omega SST and k-\varepsilon Realizable.
- Smooth multi block mesh
- Domain Sensibility and Near wall refinement
- Various sensitivity tests: mesh scalability, wall refinement, \( \rho \cdot U \) profile extraction and interpolation, boundary layer sensor based on the vorticity,
- Qualitative various classical test cases (shock tube, nozzle 1D, Sajben...)

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Numerical Part

The famous test case of the transonic diffusor (Sajben) works well here for the strong shock configuration \((p/p_0=0.72)\):
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Numerical Part

Total topology and mesh sensitivity analysis
- Simulation 2D axisymmetric
- On a structured mesh
- Multi-block decomposition for parallelisation
- Refinement in the area of interest

Inlet:
- $P_0 = 3-60$ bar
- $(Re_D = 4.5 \times 10^5 - 8.9 \times 10^6)$
- $T_0 = 300$ K
- $Nut = 1E-05$

Outlet:
- $P_{atm}$ (Pa)
- Wave Transmissive

Nozzle wall: no slip

Convergent

Throat

Axis: axis conditions

Divergent

- Working fluid: air ($\gamma = 1.4$) at $T_0 = 300$ K
- $Pr = 0.72$
- Viscosity evaluated with Sutherland law.
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Numerical Part

Mesh topology
- Structured mesh
- Multi-domain (Refinement in the area of interest)
- Parallelisation

Refinement of 1mm close to the wall and elliptic smoothing of the grid everywhere else.
Discharge coefficient evaluation

\[ C_D \text{ Evaluation is less than } 0.1\%. \]
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Numerical Part

Discharge coefficient evaluation

Low variation of the Cd evaluation within the cylindrical part. Less than 0.025%.
Discharge coefficient evolution (with the input pressure conditions)

- Initialisation with different method pressure ramps
- Macroscopic performances
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Numerical Part

Global flow structure

- extensive verification of influence of mesh resolution
- observed with various numerical schemes
- observed with various turbulence models
- observed in purely inviscid simulations
- depends on the initialization
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Numerical Part

Displacement thickness evolution with inlet pressure
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Numerical Part

Complexed equilibrium within the flow
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Conclusion and perspective

• Observed experimentally effects of roughness
• Validation of the numerical strategy
• Observation of original structure especially in the throat (non typical structure) needs to be more extensively characterised
• Possible formation of hystericize depending on the initialisation condition (violent or not)
• The need for a better characterisation of the parameters that drive the flow.

Further investigation is needed:
- Check the existence of hysteresis phenomena
- Detail the link between the change in the whole flow structure
- Identify -> what is due to the BL thickening ?
  -> what is due to the inviscid flow region ?
- Minimal phenomenological model describing the interaction between the boundary layer evolution (displacement thickness) and overall inviscid region.
• The end.
• Thank you for your attention.
• Please feel free to ask for any further explanation.