TURBINE MASS FLOW EVALUATION IN A COMPRESSION TUBE FACILITY

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The VKI CT3 Facility

- Fully annular cascade facility
- Variable Reynolds and Mach number
- RPM equal to 6500
- Test time below 0.4 s
Modelisation of the compression tube

Shutter valve closed

\[ \Delta m_1 = m_1^i - m_1^{i-1} = \dot{m}_{in} \Delta t \] mass conservation

\[ m_1^i u_1^i - m_1^{i-1} u_1^{i-1} = \dot{m}_{in} h_{in} \Delta t \] energy balance

\[ P_1^i V_1^i = m_1^i RT_1^i \] perfect gas

\[ u^i = c_v T^i \]

Two logical step

→ the piston is blocked in its position

- Volume 1: injection of \( \Delta m_{in} \)

\[ T_{01}^i = T_{01}^{i-1} + \frac{x_1}{1 + x_1} (\gamma T_{in} - T_{01}^{i-1}) \]

\[ P_{01}^i = P_{01}^{i-1} \left( 1 + \frac{\gamma T_{in}}{T_{01}^i} x_1 \right) \]

\[ x_1 = \frac{\Delta m_{in}}{m_1^i} \]

→ the piston is sliding until \( p_2 = p_1 \)

- No mass is admitted

- Volume 1 and 2: isentropic evolution

\[ \frac{P_1^i}{P_1^{i-1}} = \left( \frac{V_1^{i-1}}{V_1^i} \right)^\gamma \]

\[ \frac{T_1^i}{T_1^{i-1}} = \left( \frac{P_1^i}{P_1^{i-1}} \right)^{\frac{y-1}{\gamma}} \]
Shutter valve opened

- No mass is admitted or ejected

- Volume 1: injection of $\Delta m_{in}$
- Volume 2: ejection of $\Delta m_{out}$

\[
\begin{align*}
T_{01,02}^i &= T_{01,02}^{i-1} \pm \frac{x_{1,2}}{1 + x_{1,2}} \left( \gamma T_{in,02}^{i-1} - T_{01,02}^{i-1} \right) \\
P_{01,02}^i &= P_{01,02}^{i-1} \left( 1 \pm \frac{\gamma T_{in,02}^{i-1}}{T_{01,02}^{i-1}} x_{1,2} \right) \\
x_1 &= \frac{\Delta m_{in}}{m_1^i} \\
x_2 &= \frac{\Delta m_{out}}{m_2^i}
\end{align*}
\]

the piston is blocked in its position

the piston is sliding until $p_2=p_1$

- Volume 1 and 2: isentropic evolution

\[
\begin{align*}
\frac{P_1^i}{P_1^{i-1}} &= \left( \frac{V_1^{i-1}}{V_1^i} \right)^{\gamma} \\
\frac{T_1^i}{T_1^{i-1}} &= \left( \frac{P_1^i}{P_1^{i-1}} \right)^{\frac{\gamma-1}{\gamma}}
\end{align*}
\]
Modelisation of the test section

Balance of mass flows and internal energy:

\[
T_{03}^i = \frac{\gamma (x_{out} T_{0out} + x_{Cool} T_{0Cool} - x_{Leak} T_{0Leak}) + T_{03}^{i-1}}{1 + x_{out} + x_{Cool} - x_{Leak} + x_S (\gamma - 1)}
\]

\[
P_{03}^i = \frac{m_3^i R T_{03}^i}{V_3}
\]
Mass flow $\dot{m}_{\text{out}}$ evolution

- Choked condition

$$\dot{m}_{\text{out}} = \frac{P_{02} A_v(t)}{\sqrt{T_{02}}} \text{ Const}$$

Shutter opening law $A_v(t)$ is implemented

- Unchoked condition

Static pressure $p_v$ is artificially coupled to $P_{02}$

$$P_{02}^i - P_v^i = \Delta P_c - \Delta P_{TS}^i$$

$\Delta P_{TS}^i$ $\rightarrow$ difference between $P_{02}(t)$ and $P_{03}(t)$

$\Delta P_c$ $\rightarrow$ difference between $P_{02}(t)$ and $p_v$ in steady condition (knowledge of Mach number)
Turbine stage

- from the stage pressure ratio:

\[ P_{0\text{ex}} = \frac{P_{03}}{\pi} \]

\[ T_{0\text{ex}} = T_{03} \left[ 1 - \eta \left( 1 - \pi \frac{1-\gamma}{\gamma} \right) \right] \]

Mass flow \( \dot{m}_S \) evolution

- from the pressure ratio \( P_{0\text{ex}}(t)/p_4(t) \):

\[ \dot{m}_S = \frac{p_4}{RT_4} A_S \sqrt{\gamma RT_4} \]

\[ \dot{m}_S = \frac{P_{0\text{ex}}(t)}{\sqrt{T_{0\text{ex}}(t)}} A_S \cdot \text{Const} \]

\( A_S \)

Dump tank

\[ \rightarrow \] closed volume with injection of \( \dot{m}_S \)
Validation against the experimental data

Initial conditions: initial tube pressure and temperature

Two parameters are needed: $m_{in}$ and $A_s$

Fitting of the tube pressure evolution

The model is able to calculate the mass flow for each test

$\frac{m_{in}}{\rho_{in}} = \frac{m_{out}}{\rho_{out}}$

significant test to test variation of the pressure slope non perfect matching
Validation against the experimental data

piston displacement

- piston is decelerating until the shutter opens
- piston velocity is constant during the blowdown
- good agreement between calculated and measured detection signals

isentropic assumption is reasonable
Validation against the experimental data

Pressure and temperature in the test section

- the steady value of $P_{03}$ and $T_{03}$ is set by imposing the losses
- the transient and test time is well predicted
- the peak in the temperature is due to the sudden compression in the settling chamber
- the mass flows are matching after the transient time

- the difference between $\dot{m}_{out}$ and $\dot{m}_S$ is provided by the coolants and the leakage flows
Mass flow evaluation: uncertainty analysis

- most critical parameter: sonic throat area

1% of area variation $\rightarrow$ 0.62% in the mass flow

- Uncertainty in the slope detection provides an inaccuracy in the sonic throat area computation

- The uncertainty is larger at High Reynolds than at Nom Reynolds
Mass flow evaluation: using P.W.A. Data

Mass flow calculation from the integration of the pitchwise averaged data $P_{0ex}, T_{0ex}, \alpha_{ex}$,
- Most sensitive parameter: Downstream Total pressure

![Graphs showing Mass flow evaluation using P.W.A. Data](image.png)
### Mass flow evaluation: results

<table>
<thead>
<tr>
<th></th>
<th>1 stage</th>
<th>Ct3 Model</th>
<th>P.A.Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P/p$ Nom Re Nom</td>
<td>10.55</td>
<td>10.55</td>
<td></td>
</tr>
<tr>
<td>$P/p$ Nom Re Low</td>
<td>10.1</td>
<td>10.52</td>
<td></td>
</tr>
<tr>
<td>Uncertainty</td>
<td>+/- 0.82 %</td>
<td>+/- 3.92 %</td>
<td></td>
</tr>
<tr>
<td>Dispersion</td>
<td>+/- 1.43 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1 and ½ stage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>without rotor cooling</strong></td>
<td>15.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2% rotor cooling</td>
<td>15.35</td>
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</tr>
<tr>
<td>3% rotor cooling</td>
<td>15.36</td>
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<tr>
<td>Uncertainty</td>
<td>+/- 1.6 %</td>
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</tr>
<tr>
<td>Dispersion</td>
<td>+/- 0.21 %</td>
<td></td>
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</tr>
</tbody>
</table>
Conclusions

- A model of the VKI CT3 facility is developed and validated
  - simple approach
  - the isentropic compression assumptions is reasonable
  - good agreement between calculated and measured values

- Better understanding of the flow parameters in the test rig

- Stage mass flow calculation is performed
  accurate evaluation for each test (uncertainty of +/- 0.82% or +/- 1.6 %)
  compared with P.W.A. profile calculation

- Easily usable for compression tube facilities

- Usable to predict and/or design different test conditions