“Low operating temperature integral systems”
A novel hybrid configuration TA engine

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General system aspects
Reduction of average regenerator impedance
Novel hybrid configuration
Experimental verification
Conclusions
General system aspects

- **Fixed power driven TA engines**
  - $T_3 \gg T_2$
  - gain “proportional” with load
  - Acoustic power $\approx$ constant
  - No or little “hot hex” losses

  - Useful in TA experiments
  - **Little practical use**

- **Fixed temperature driven TA engines**
  - $(T_3 - T_2)$ $\Rightarrow$ to be minimized
  - fixed gain (per stage)
  - acoustic power inversely proportional to load
  - hex design crucial

  Pertain to nearly all practical applications
General system aspects

- Loop, transferred and available power

\[ P_{\text{ac\_out}} = \frac{A_{\text{reg}} \cdot p_0^2}{2 \cdot \text{Re}(Z_{\text{reg}})} \]

\[ P_{\text{ac\_loop}} = P_{\text{ac\_out}} \cdot \left( \frac{T_H}{T_C} - 1 \right) \]

Minimize ratio acoustic loss / transferred power

Two way strategy

1. Minimize acoustic losses
   - Avoid high local amplitude (no standing waves)
   - Shape and wall finish (in turbulent regime only)
   - **Lower limit** by thermal and viscous boundary layer losses!

2. Maximize transferred or loop power
   - Decrease average regenerator and load impedance

\[ P_{\text{Loss\_lam}} \approx \alpha \cdot p_0^2 \cdot A_{\text{wall}} \]

\[ P_{\text{Load}} = \frac{A_0 \cdot p_1^2}{2 \cdot \text{Re}(Z_L)} \]
**General system aspects**

- Impact of average regenerator impedance on available acoustic power

**Assumptions:**
- "ideal" 1 stage engine
  - $\omega \tau \Rightarrow 0$
  - $R \Rightarrow 0$
  - $\eta_2 \Rightarrow 1$
- Impedance setting $\neq f (R_{\text{reg}})$
- Loss calculated for $\frac{1}{2} \lambda$ resonator
- Small signal regime (laminar)

- Onset and small signal behavior depends on configuration and geometry only
- Acoustic loop power times gain less than acoustic loss for $Z_{\text{reg}} = 20 \cdot \rho \cdot c$ and $T_H < 410 \text{ K}$

**Average regenerator impedance should be set to a minimum value for low and medium operating temperatures**

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Reduction of average regenerator impedance

- For default torus or bypass geometry
  - $Z_{reg}$ commonly set to $> 15.\rho.c$
  - Inertance$_{torus} << R_{regenerator}$

- Timing or phase $(p_a, v_a) = f(R_{reg})$
  - $R_{reg} \Rightarrow 0$, Phase $\Rightarrow 90^\circ$

**Consequences:**
- More regenerator mass (length) than required from heat capacity ratio
- Low system power density
- Efficiency proportional with regenerator flow resistance but less power

Little options left for impedance reduction
Hybrid configuration

Back to basics!
(re-arranging acoustic circuitry and apply all “tricks” from the past)

- Traveling wave loop (0)
  - Initial used by Ceperly for timing
  - Now used to avoid high local amplitudes

- Torus or bypass
  - Compliance (3)
  - Inertance (2)

- Velocity reduction
  - Additional bypass (1)
  - $A_{\text{reg}} > A_0$
Hybrid configuration

Feedback loop
• Travelling wave if
  ■ $S_{11} \Rightarrow 0$ (no reflection)
  \[ Z_0 = \frac{\rho c}{A_0} \]
• Oscillation if
  ■ net forward acoustic power gain $\geq 1$
  ■ phase delay of 2-port plus feedback loop equals $2\pi$ ($= \lambda$)
• Average regenerator impedance
  ■ absolute value relatively low
  ■ phase nearly independent of regenerator flow resistance
Hybrid configuration

Comparison with the “classic” torus or bypass configuration

- Regenerator impedance can be set to arbitrary (lower) value
  - Absolute value depends on geometry and regenerator flow resistance
  - Phase (timing) depends primarily on geometry
- Regenerator mass can be minimized
  - Lower onset temperature
  - Steeper slope $\Delta P_{ac} / \Delta T$
  - Becomes a function of acoustic power (related to heat capacity)
  - Efficiency improves for lower regenerator flow resistance (as should be the case for thermo-dynamic systems in general)
- Reduced impedance allows for multiple regenerator units
  - Extended “soft spot”
- High acoustic power at given amplitude (near traveling waves)
  - System more compact
  - Low acoustic loss / power ratio (no extreme local amplitdes)
- Streaming suppression (e.g. membrane) on convenient location
Experimental verification

Measurement setup 2 stage engine

- Water circuits
  - High temperature
    - Gas fired water heater
    - Max 160 °C (10 bar)
  - Low temperature
    - Car radiator to air
    - Flow 1.5 l.min⁻¹
    - 20-30 °C

- Acoustic power measurements
  - Pressure gradient method

- Temperature measurements
  - Water in – out \((T_0, T_3)\)
  - Regenerator high – low \((T_2, T_1)\)

Water \(T_{\text{high}}\) (70-160 °C)

Water \(T_{\text{low}}\) (20-30 °C)

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Experimental verification

Typical pressure amplitude distribution at oscillation (Measured Values in kPa)

- $D_0 = 67$ mm
- $A_{reg} = 100 \times 120$ mm
- $L_{reg} = 1.58$ mm
- Por = 0.74
- $L_{hex} = 0.56$ mm

- Air @ 98 kPa
- Frequency = 132 Hz
- $T_{water\_in} = 148$ °C
- $T_{water\_uit} = 28$ °C

- Near traveling wave in feedback loop (SWR < 1.2)
- No extreme amplitude maxima or minima
- High acoustic power while only 3.5% drive ratio in feedback loop ("resonator")
- Reduced regenerator impedance ($Z_{reg} \approx 3 \rho . c$)
Experimental verification

- Onset temperature same for air and argon

\[ \Delta T_{\text{ext}} - \Delta T_{\text{int}} \text{ proportional with power} \]
  - \( G_{\text{HEX}} \approx 7 \text{ W.K}^{-1} \) (air)

- Hex temperature drop related to gas heat conductivity

- Slope \( \Delta P_{\text{ac}} / \Delta T \) related to viscosity

- Slope \( \Delta P_{\text{ac}} / \Delta T \) increases with power
  - better heat exchange (Re, Nu)
  - Higher efficiency

\[ \Delta T_{\text{Onset}} \]
\[ \Delta T_{\text{Available}} \]
Conclusions

- Classic standing wave resonator combined with a high regenerator impedance (set by torus or bypass) impede low and medium temperature applications.

- To overcome these limitations an example of a novel hybrid configuration is proposed.

- Experimental results agree well with theory behind and indicate a significant improvement in onset temperature and power density.
  - With air at atmospheric pressure:
    - applied onset temperature difference 63 K
    - acoustic power 42 W at 3.5% drive ratio

- For efficient low temperature operation at 160 °C onset temperature and hex temperature drop still to high.

- Hybrid configurations allows for further optimizing TA engines in the low and medium operation temperature regime.