"Low operating temperature integral systems"

A novel hybrid configuration TA engine

Kees de Blok
Aster Thermoakoestische Systemen

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

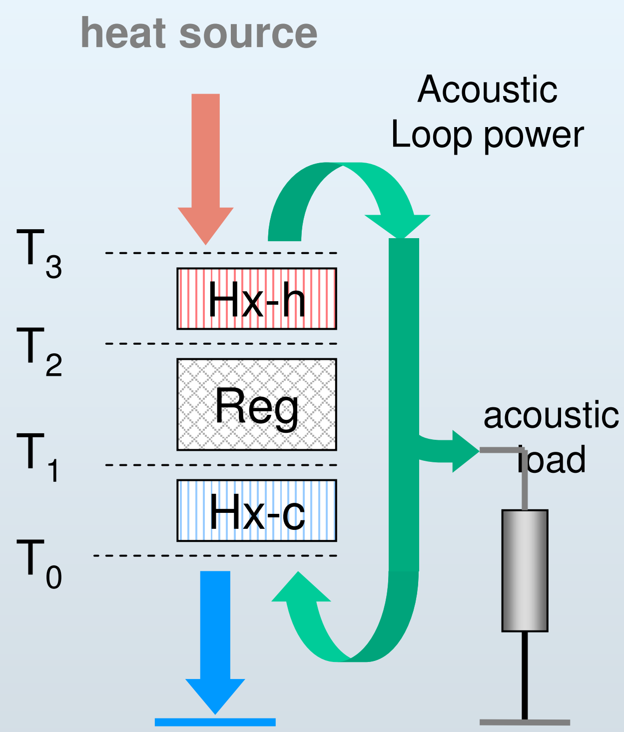
General system aspects

- Fixed power driven TA engines
  - $T_3 >> T_2$
  - gain "proportional" with load
  - Acoustic power ≈ constant
  - No or little "hot hex" losses

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

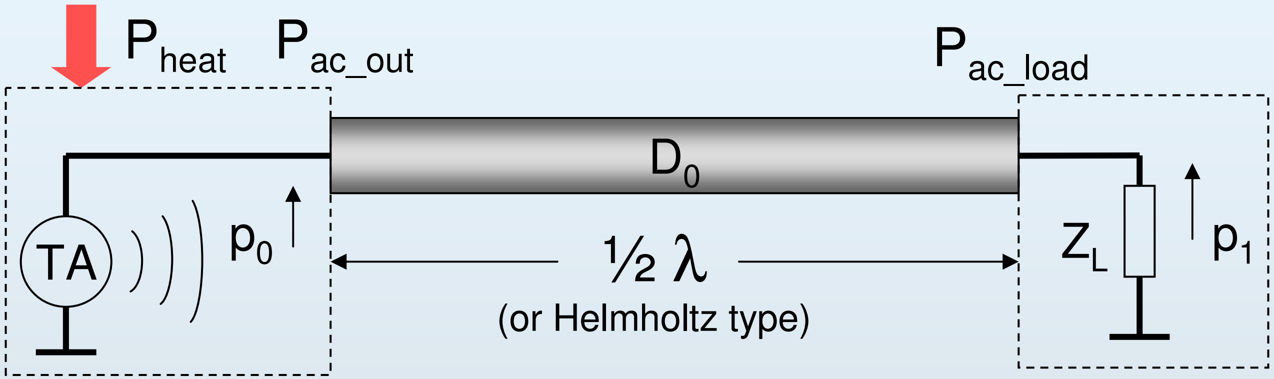
- Fixed temperature driven TA engines
  - $(T_3 - T_2) \Rightarrow$ to be minimized
  - fixed gain (per stage)
  - acoustic power inversely proportional to load
  - hex design crucial

Pertain to nearly all practical applications



General system aspects

- Loop, transferred and available power



Minimize ratio acoustic loss / transfered 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

$$P_{ac\_loop} = \frac{A_{reg} . p_0^2}{2.\mathrm{Re}(Z_{reg})}$$

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

$$P_{Loss\_lam} \approx \alpha . p_0^2 . A_{wall}$$

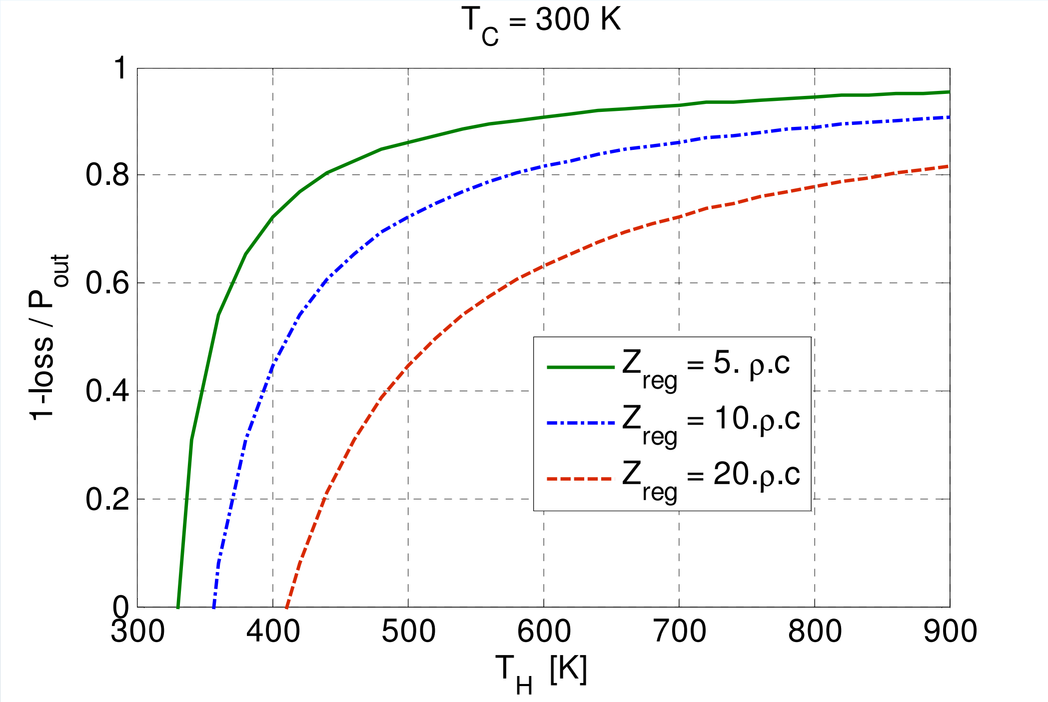
$$P_{Load} = \frac{A_0 . p_1^2}{2.\mathrm{Re}(Z_L)}$$

General system aspects

- Impact of average regenerator impedance on available acoustic power

Assumptions:

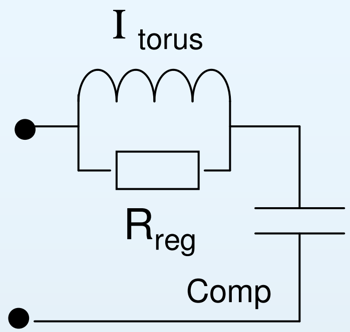
- "ideal" 1 stage engine
  - $\omega\tau \Rightarrow 0$
  - $R \Rightarrow 0$
  - $\eta_2 \Rightarrow 1$
- Impedance setting ≠ f (Rreg)
- loss calculated for ½λ resonator
- small signal regime (laminar)



- Onset and small signal behavior depends on configuration and geometry only
- Acoustic loop power times gain less than acoustic loss for Zreg= 20.ρ.c and T_H < 410 K

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

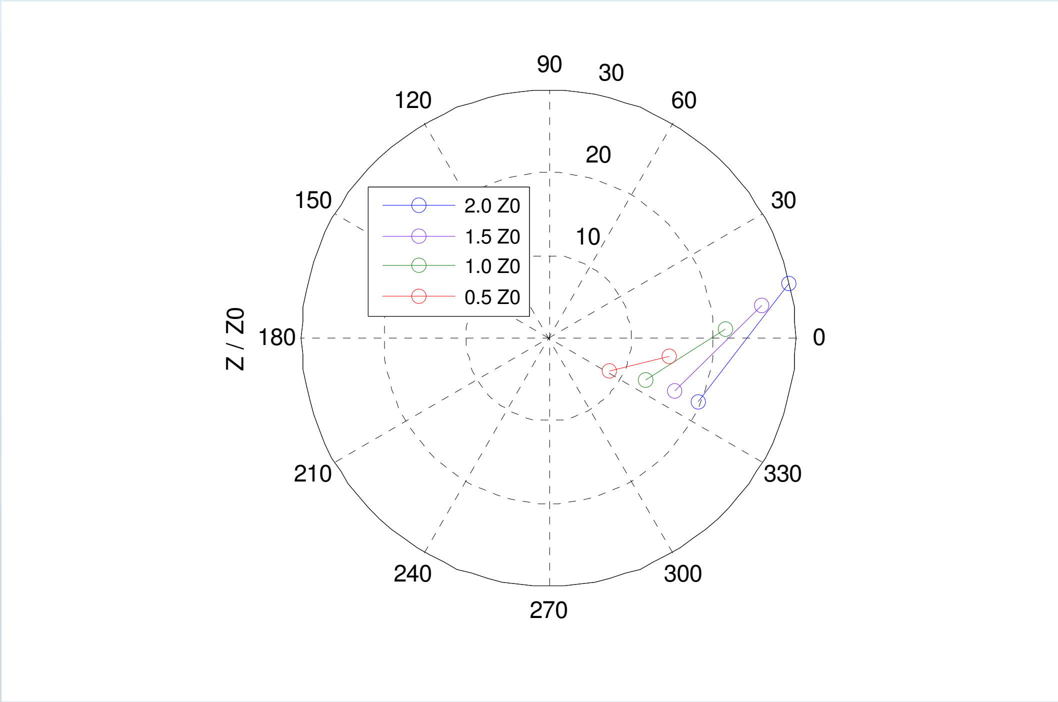
Reduction of average regenerator impedance



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

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

Typical impedance versus R_{reg} / ρ.c



Consequences:

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

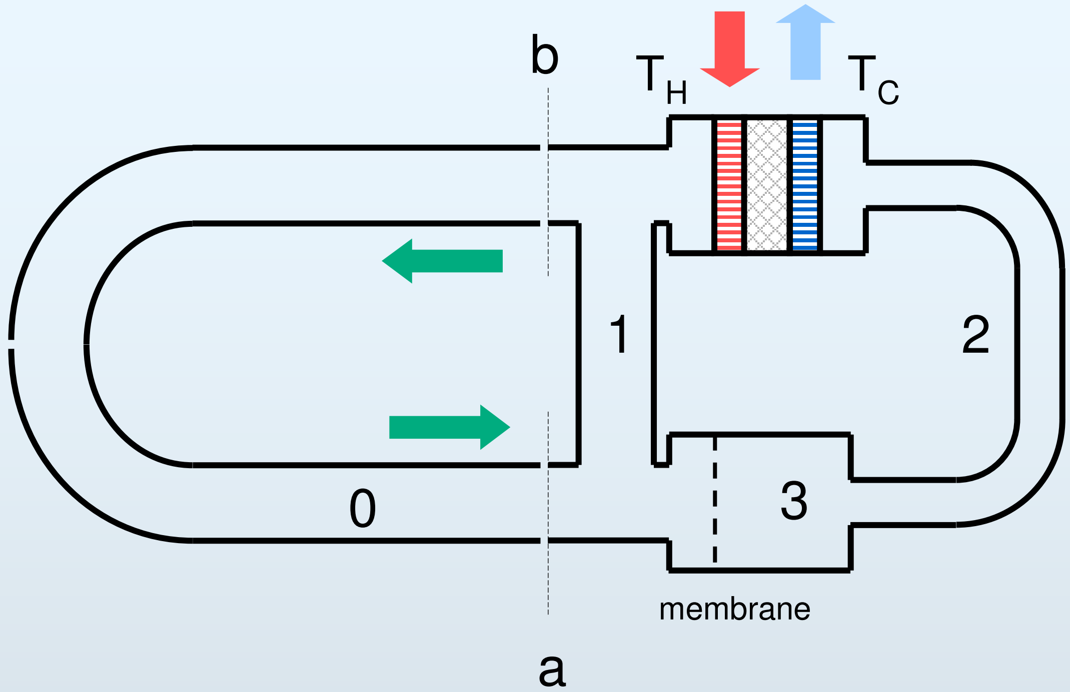
Little options left for impedance reduction

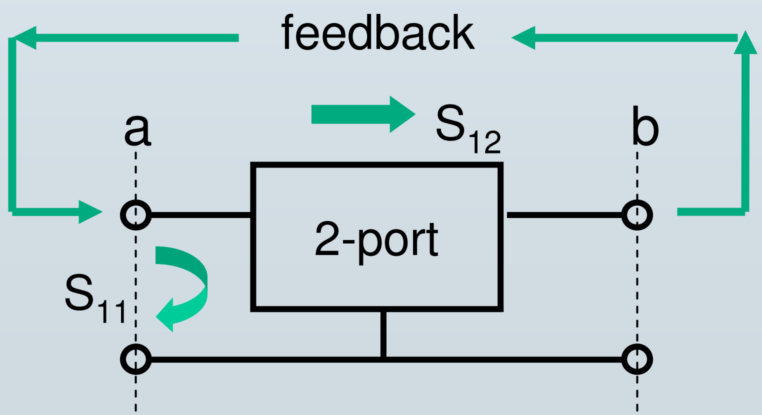
THERMOAKOESTISCHE SYSTEMEN

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)**
  - $A_{reg} > A_0$





ASTER THERMOAKOESTISCHE SYSTEMEN

Hybrid configuration

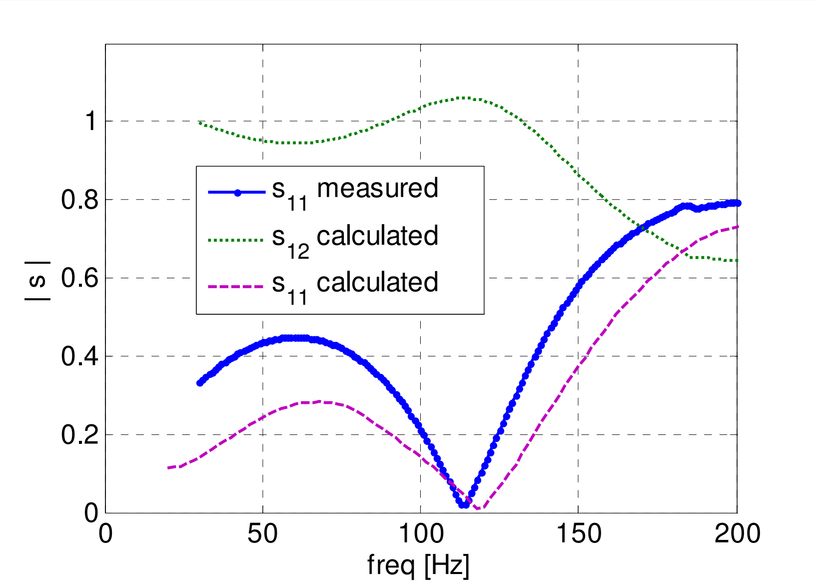
Feedback loop

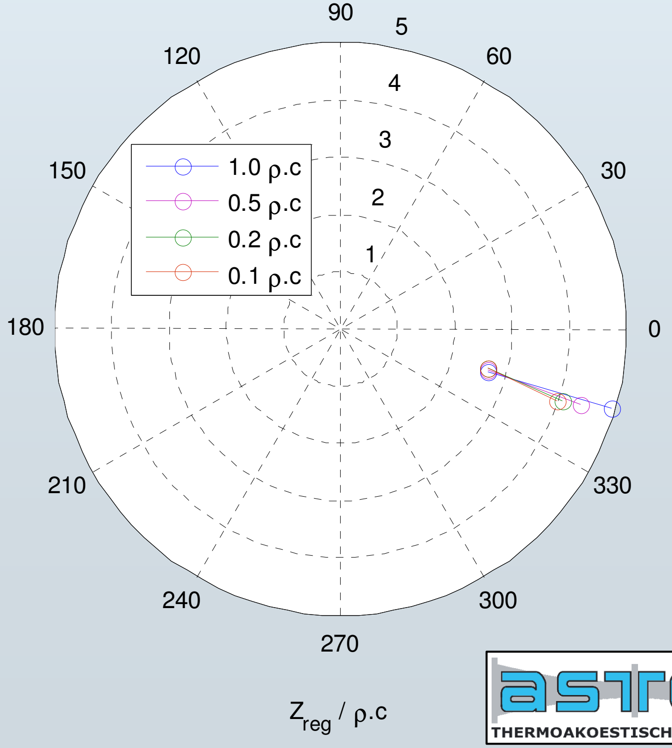
- Travelling wave if
  - $S_{11} \Rightarrow 0$ (no reflection)

$$Z_0 = \frac{\rho.c}{A_0}$$

- Oscillation if
  - net forward acoustic power gain ≥ 1
  - phase delay of 2-port plus feed back loop equals $2.\pi$ (= λ)

- 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

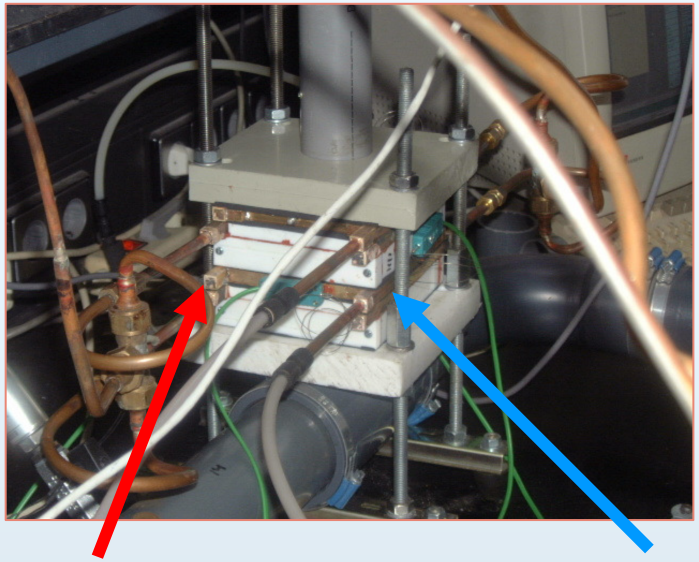
Experimental verification

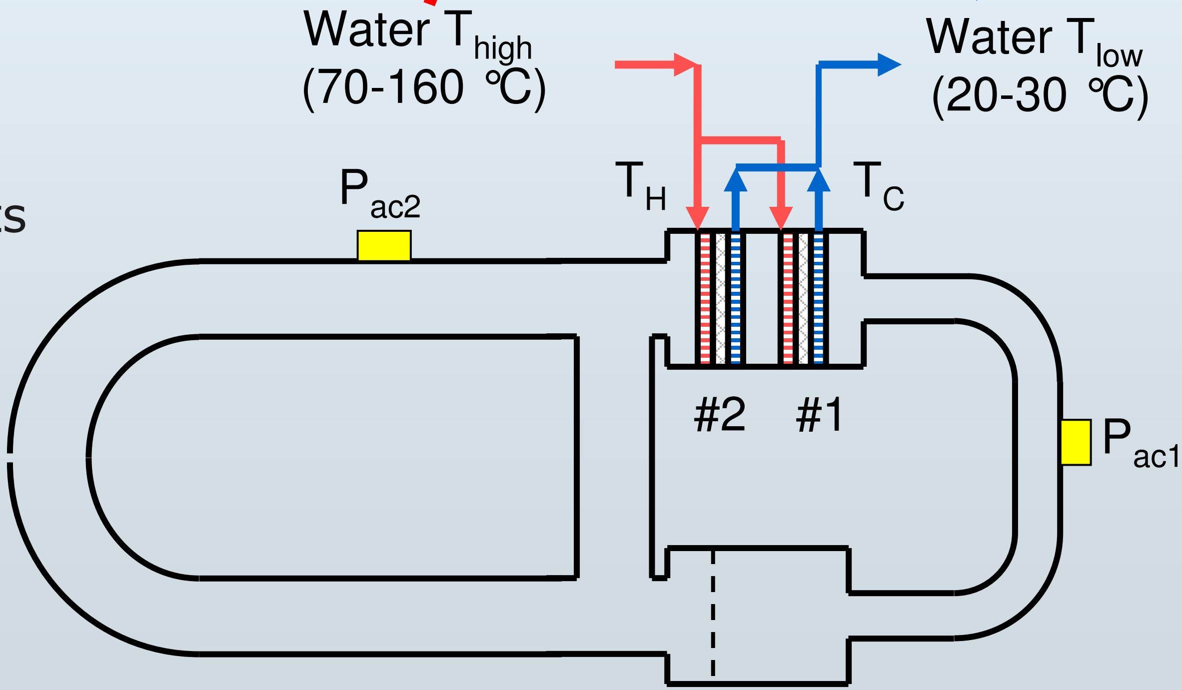
Measurement setup 2 stage engine

- Water circuits
  - High temperature
    - Gas fired water heater
    - Max 160 ℃ (10 bar)
  - Low temperature
    - Car radiator to air
    - Flow 1.5 $l.min^{-1}$
    - 20-30 ℃

- Acoustic power measurements
  - Pressure gradient method

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



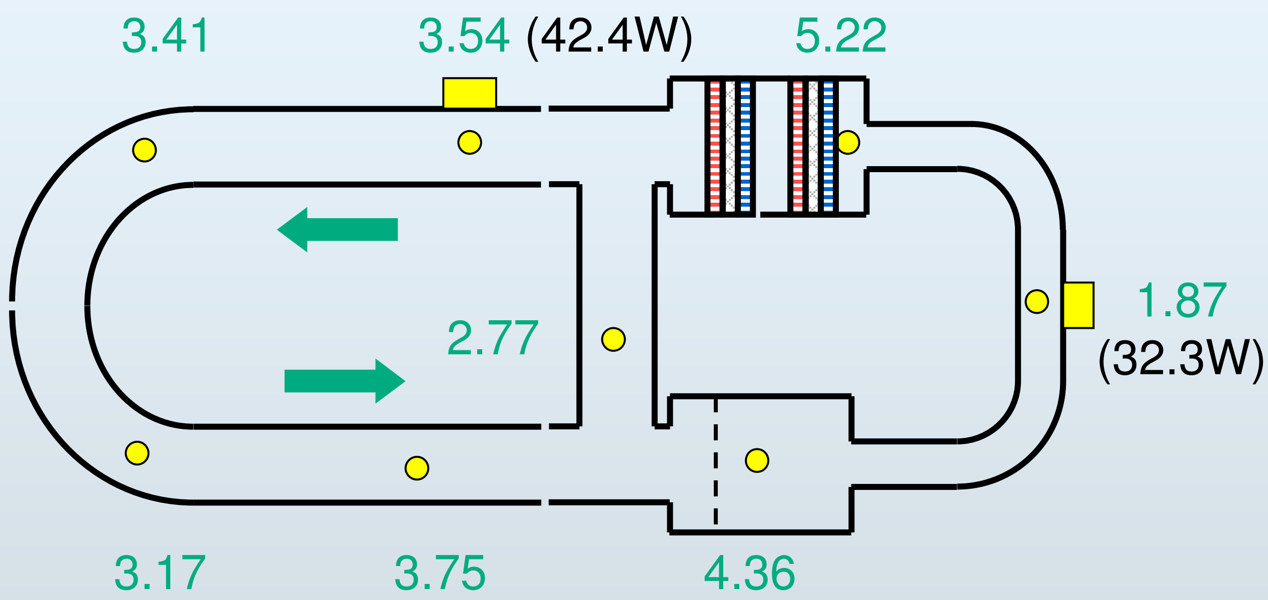


Experimental verification

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

- D_0 = 67 mm
- A_{reg} =100 x 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 ℃
- T_{water_uit} = 28℃

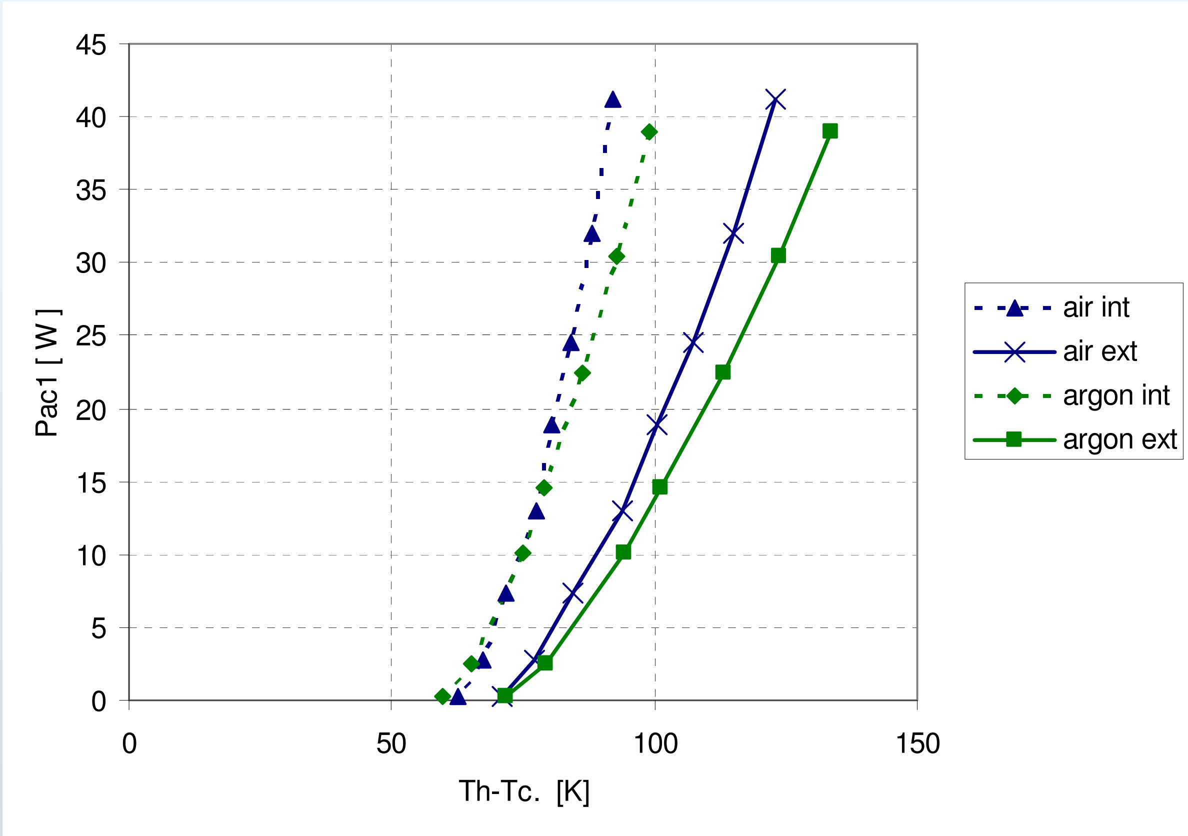


- Near traveling wave in feedback loop (SWR < 1.2)
- No extreme amplitude maxima or minima
- High acoustic power while only 3.5% drive ratio in feed back loop (“resonator”)
- Reduced regenerator impedance ($Z_{reg} \approx 3\ \rho.c$)

aster THERMOAKOESTISCHE SYSTEMEN

Experimental verification

- Onset temperature same for air and argon
- ΔT_{ext} - ΔT_{int} proportional with power
  - $G_{HEX} \approx 7\ W.K^{-1}$ (air)
- Hex temperature drop related to gas heat conductivity
- Slope ΔPac / Δ T related to viscosity
- Slope ΔPac / Δ T increases with power
  - better heat exchange (Re, Nu)
  - Higher efficiency



ΔT_{Onset}

$\Delta T_{Available}$

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