SPACE TRIPS SUMMER SCHOOL

Theme 9: SPACE

Riga Latvia
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Thermoacoustics for cold production

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SUMMER SCHOOL ON:
THERMO ACOUSTIC AND SPACE TECHNOLOGIES
RIGA JUNE 17-20 2014

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www.aster-thermoacoustics.com

Thermoacoustics for cold production

Introduction to thermoacoustics

Some physics behind

Implementation

Thermoacoustic engine

Thermoacoustic heatpump

Multi-stage traveling wave engines

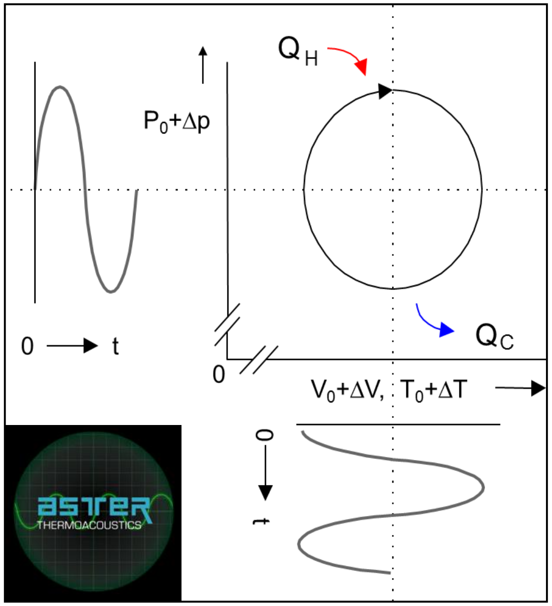
Solar powered thermoacoustic cooling

Heat powered low temperature cooling

Conclusions

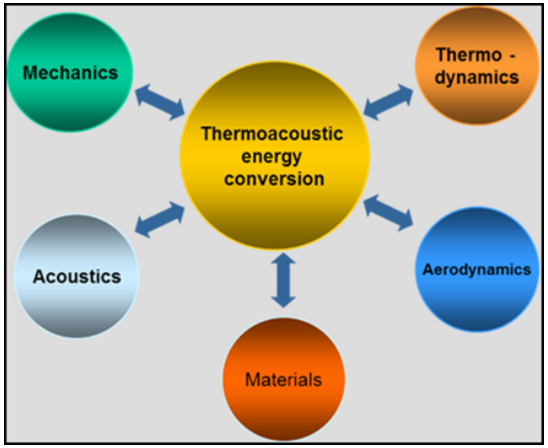
What is thermoacoustics?

A key enabling energy conversion technology based on "classic" thermodynamic cycles in which compression, displacement and expansion of the gas is controlled by an acoustic wave rather then by pistons and displacers.



Characteristics

- No mechanical moving parts in the thermodynamic process
- Maintenance free
- Simple construction
- Large freedom of implementation
- Low noise
- High efficiency (>40% of the Carnot factor)
- Large temperature range
- Scalable from Watt’s to MegaWatt’s
- Inert gas like helium, argon or even air as working medium



What can we do with thermoacoustics?

Converting heat into acoustic energy (= mechanical energy)

⇒ Heat engine

- Heat supply at high temperature from arbitrary heat source
- Onset temperature difference ≈ 30ºC
- Operating temperature differerence >100ºC

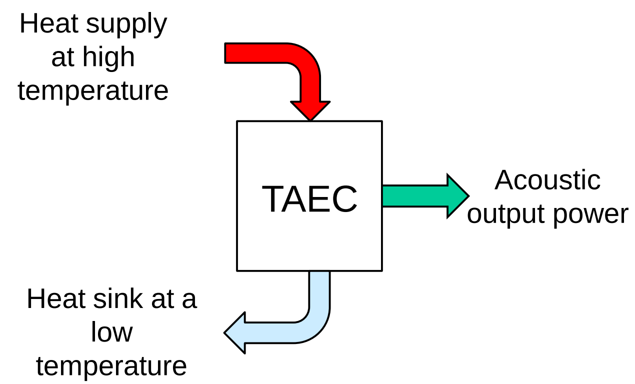
Converting the acoustic output power into electricity

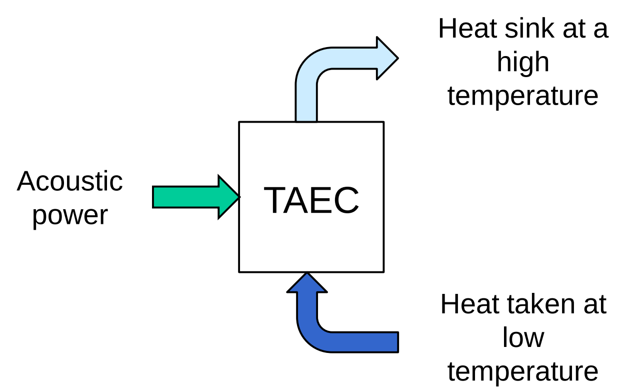
- Linear alternator (loudspeaker in reverse)
- Bi-directional turbine

Converting acoustic energy into a temperature lift
(By reversal of the thermodynamic cycle)

⇒ Heat pump or refrigerator

- Temperature lift: > 80ºC
- Temperature range: -200ºC up to 250ºC





Introduction

Typical operating characteristics

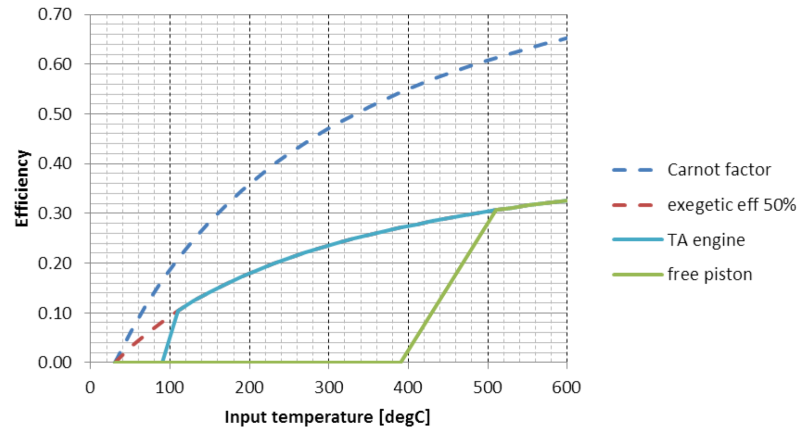
Low onset and operation temperature

- No wear and mechanical friction

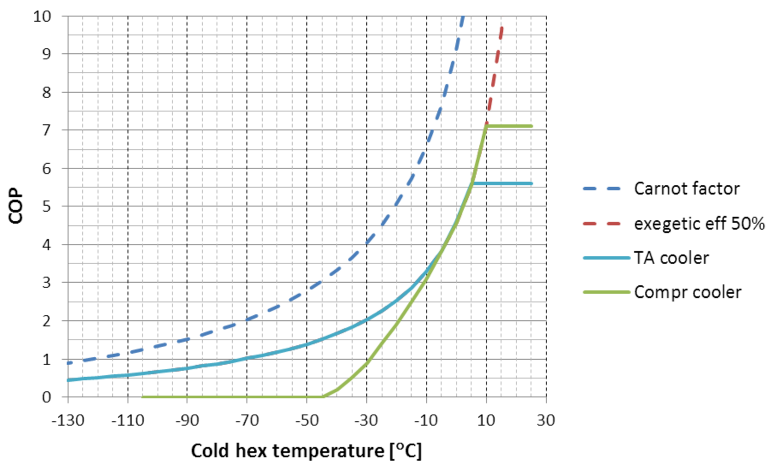
Large temperature range

- No phase change of working gas

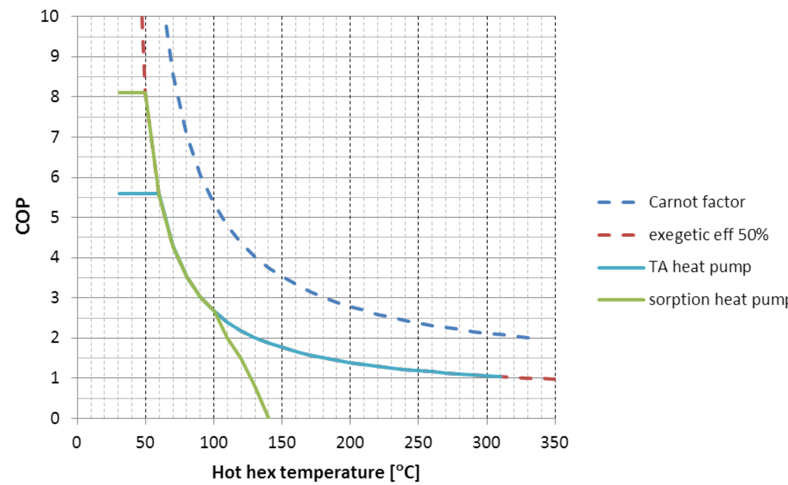
Thermoacoustic Heat Engine



Thermoacoustic cooler



Thermoacoustic heat pump

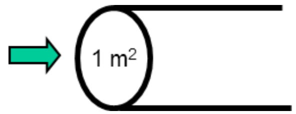


Some physics behind

Cyclic compression and expansion

(At atmospheric pressure (≈98 kPa)

- 1 Pa = 0.0012 W.m-2 (90dBa)
- 1000 Pa = 1200 W.m-2
- 10000 Pa = 120 kW.m-2



Mass-spring system

- Force (F) in phase with stroke (s)
- Force 90º out of phase with moving mass velocity

Crank + piston

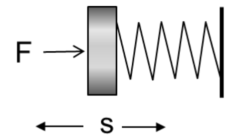
- Pressure (P) in phase with piston stroke
- Pressure 90º out of phase with piston velocity

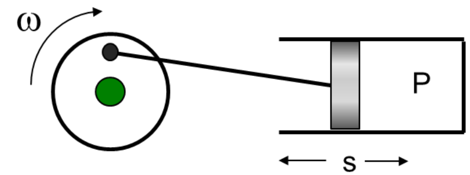
Standing waves (e.g. organ pipe)

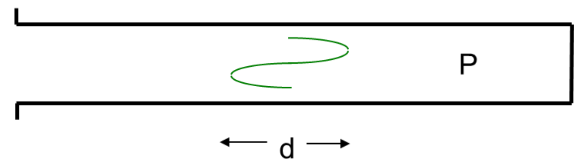
- Pressure (P) in phase with gas displacement
- Pressure 90º out of phase with gas velocity (Φ_{PV})

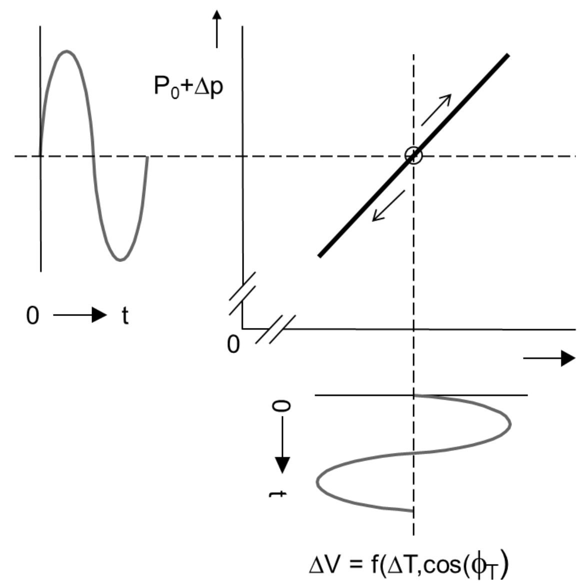
Output power $\propto$ P . v . cos(Φ_{PV})

No work done !









Cyclic compression and expansion with heat exchange
(Standing waves)

Crank + piston

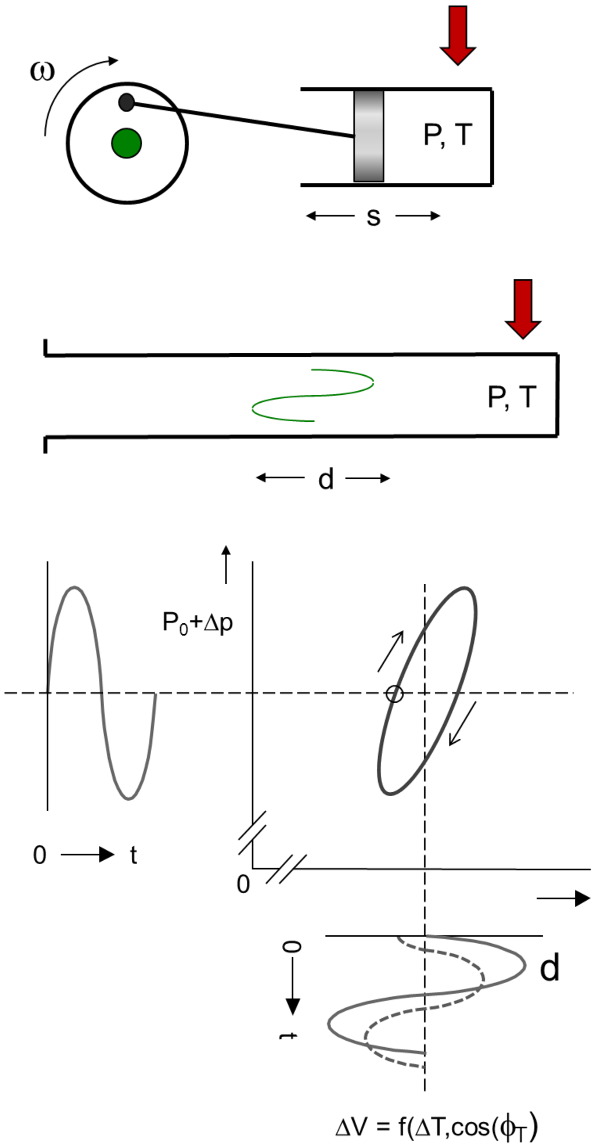
- Pressure in phase with piston stroke
- Pressure 90º out of phase with piston velocity
- Heat transfer lags pressure by Φ_T

Standing waves (organ pipe)

- Pressure in phase with gas displacement
- Pressure 90º out of phase with gas velocity
- Heat transfer lags pressure by Φ_T

Output power $\propto$ P . ΔT . v . cos($\Phi_{PV} + \Phi_T$)

Work done at the cost of some irreversibility !



Cyclic compression and expansion with heat exchange

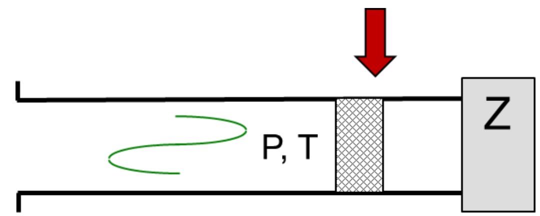
Traveling wave

- Pressure is in phase with gas velocity ($\Phi PV \approx 0$)
- Displacement leads pressure by 90º
  - No reflection
  - Terminated with charateristic impedance
  - virtually infinite long tube
- Heat transfer in phase with displacement

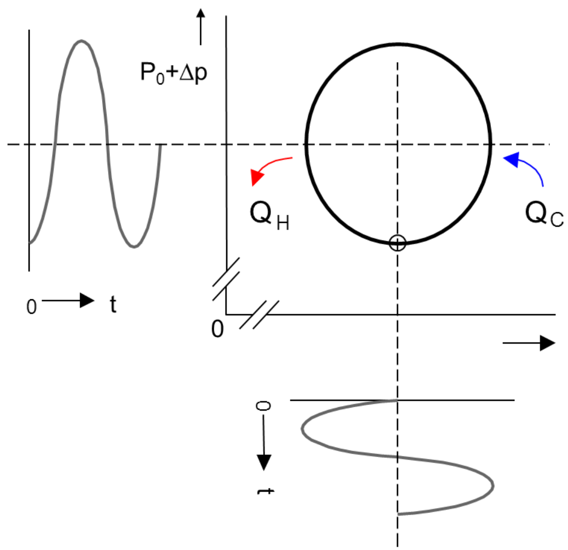
Output power $\propto$ P . ΔT . v . cos (0)

Note that this is similar to the timing in a Stirling cycle

- No irreveribility
- Efficiency Stirling cycle $\Rightarrow$ Carnot cycle
- Exegetic efficiency of today TA engines > 40%



Termination with Z = ρ.c



ΔV = f(ΔT,cos(ϕT))

Regenerator clamped between two heat exchangers

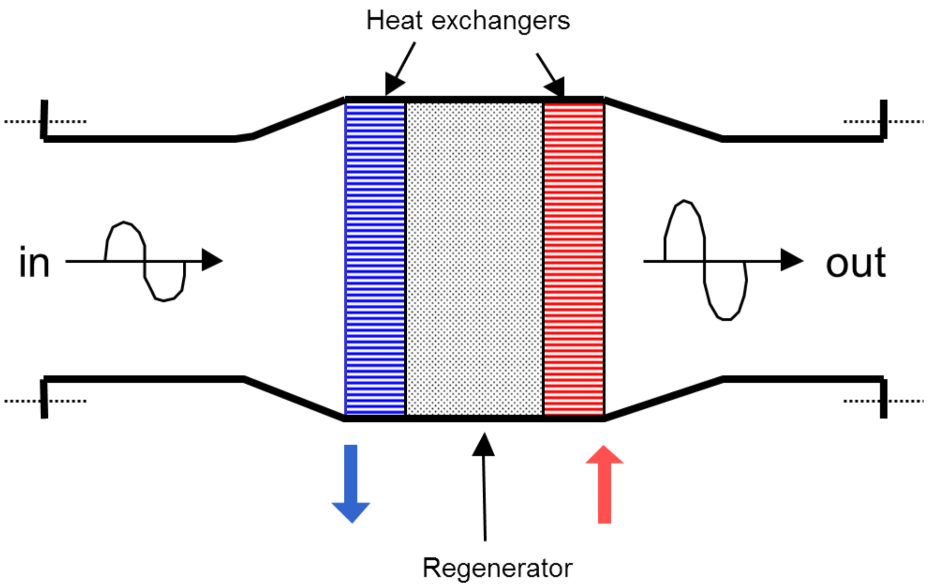
Heat engine

- Heat supply at high temperature (T2)
- Warmte sink at lower temperature (T1)

Positive temperature gradient

Acoustic power gain equals the ratio of the absolute temperatures of the hex's

$$Gain_{TA} = \frac{T_{H\_eng}}{T_{C\_eng}} \qquad (T_H > T_C)$$



Regenerator clamped between two heat exchangers

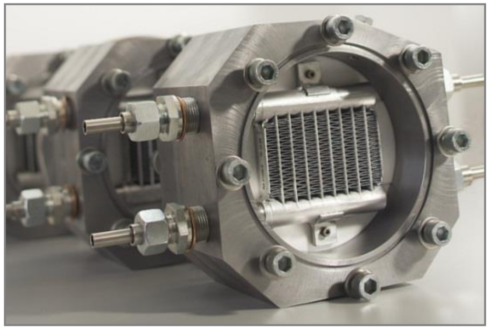
Heat pump

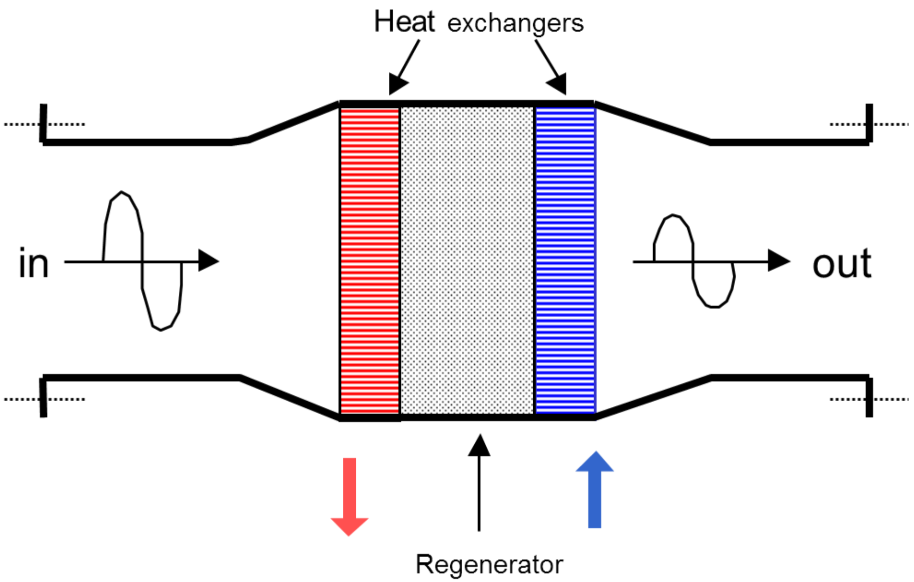
- Heat absorption at low temperature (T2)
- Heat rejection at high temperature (T1)

Negative temperature gradient

Acoustic attenuation equals the ratio of the absolute temperatures of the hex's

$$Att_{TA} = \frac{T_{C\_HP}}{T_{H\_HP}} \quad (T_C < T_H)$$



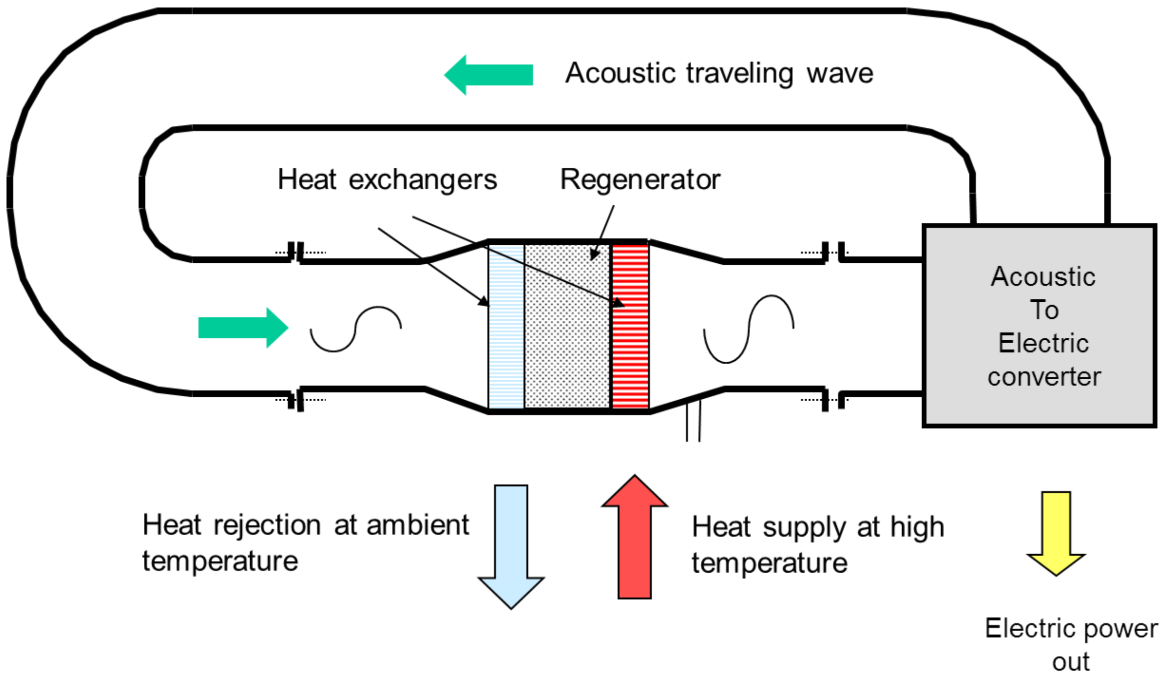


Basic geometry of a thermoacoustic engine

- Above onset temperature acoustic power gain exceeds losses and oscillation start
- Oscilllation frequency is set by (acoustic) length of the feedback tube
- At increasing input temperature (above onset) part of the acoustic loop power can be extracted as net output power

Acoustic output power can be converted to

- electricity …
- drive a thermoacoustic heat pump



Oscilation if:

$$\emptyset_{ac} = n.2.\pi$$

$$\frac{T_{Heng}}{T_{Ceng}}.(1 - loss_{ac}).(1 - \frac{P_{out}}{P_{ac\_loop}}) \geq 1$$

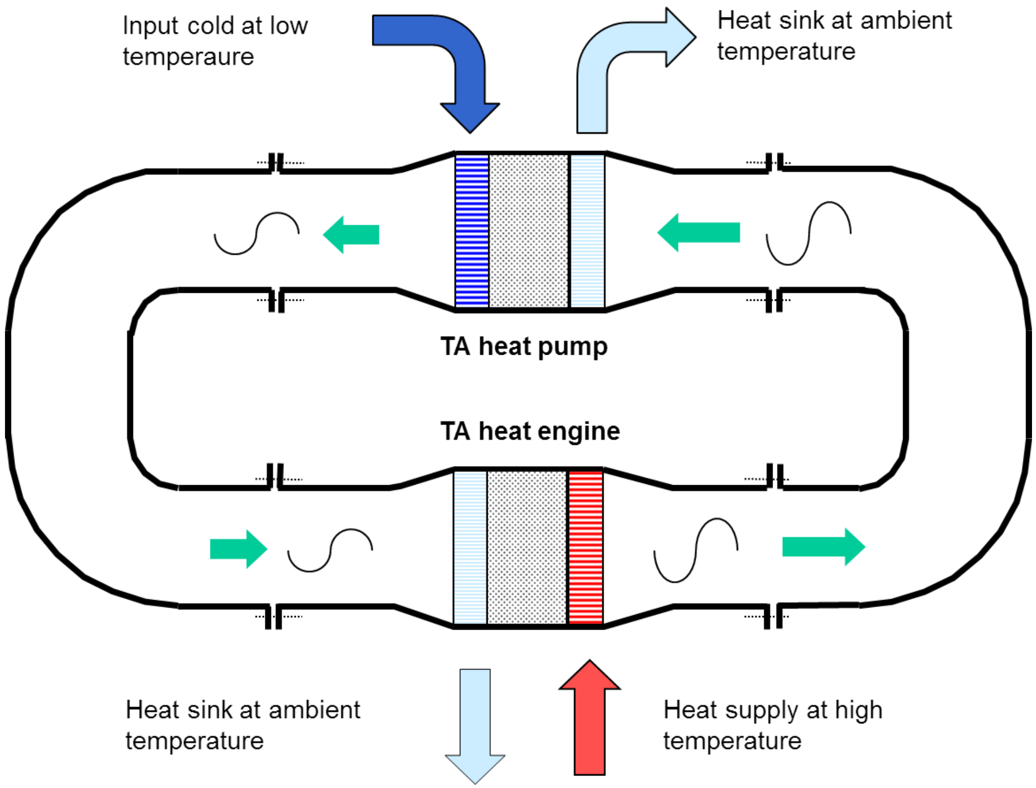
Basic geometry of a heat driven thermoacoustic heat pump

- Acoustic output power of the heat engine section is used to generate a temperature difference (temperature lif) between both heat exchangers of the heat pump section
- Cooling or heating is set by connectiong the heat exchangers to the approprate heat supply or heat sink circuit

Oscillation if:

$$\emptyset_{ac} = n.2.\pi$$

$$\frac{T_{H\_eng}}{T_{C\_eng}} \cdot \frac{T_{C\_HP}}{T_{H\_HP}} \cdot loss_{ac} \geq 1$$



Features of multi-stage traveling wave thermoacoustic engines

- Acoustic power gain proportional with number of stages
- More heat exchange surface
- Less acoustic loop power relative to the net acoustic output power (more compact design)

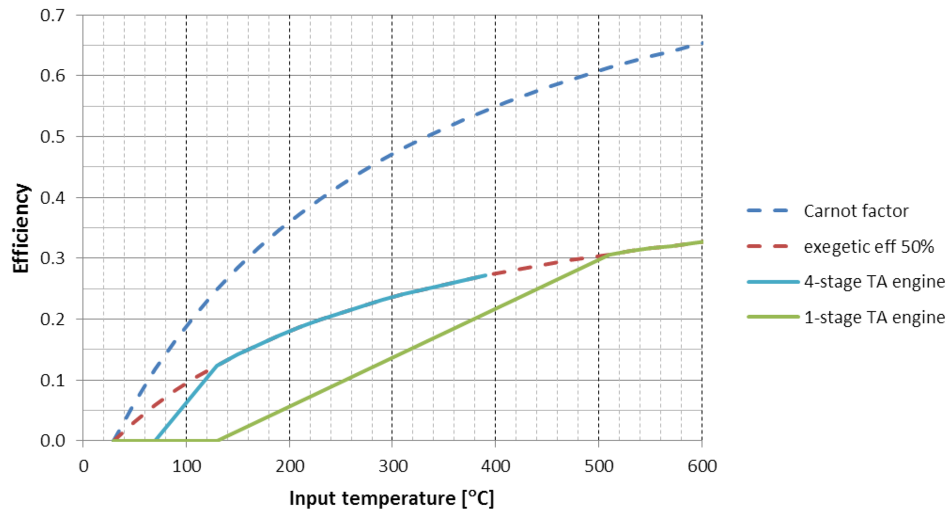
⇩

- Onset temperature difference < 30 °C
- Minimum "economic" operating temperature difference ≥ 100 °C
- Temperature lift ≥ engine input temperature

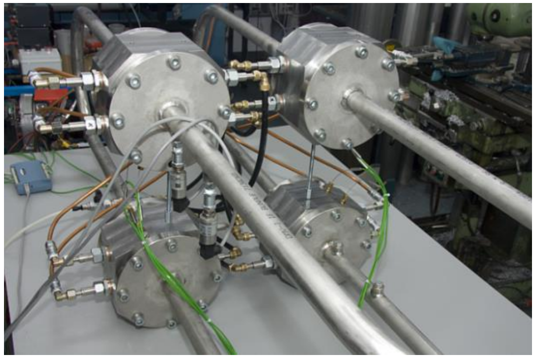
Enables low and medium temperature heat sources as useful input heat

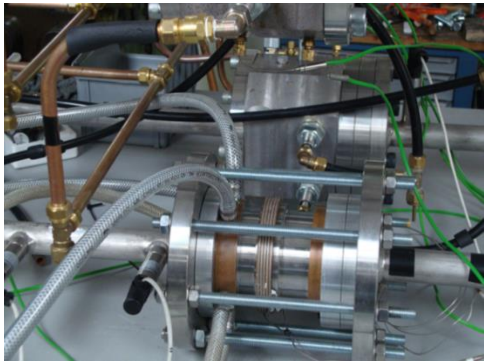
- Waste heat (industry)
- Flue gas (e.g. CHP, …)
- Solar heat (vacuum tube collectors)
- ……..

Typical TA engine operating temperatures



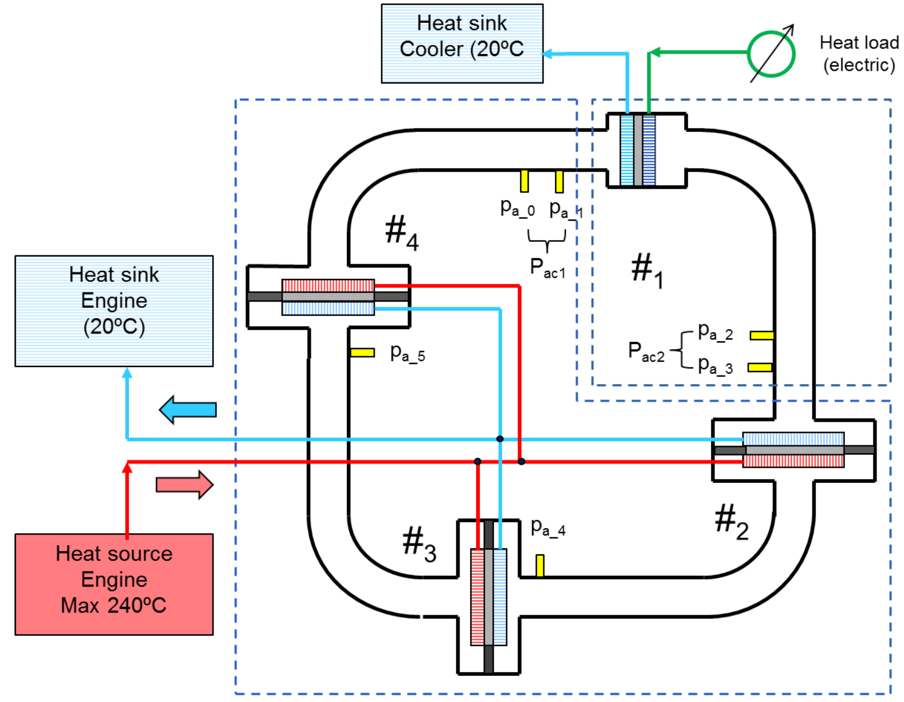
4-stage thermoacoustic traveling wave engine/cooler (THATEA project)



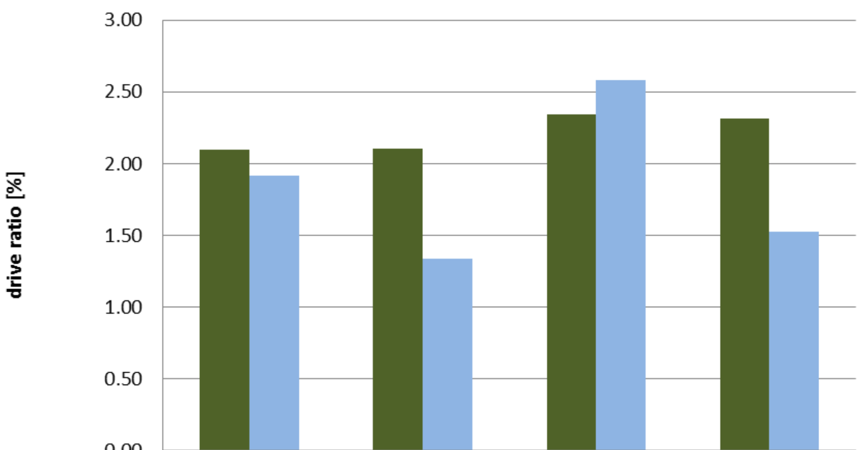


Heat driven cooler
(THATEA project 2009-2011)

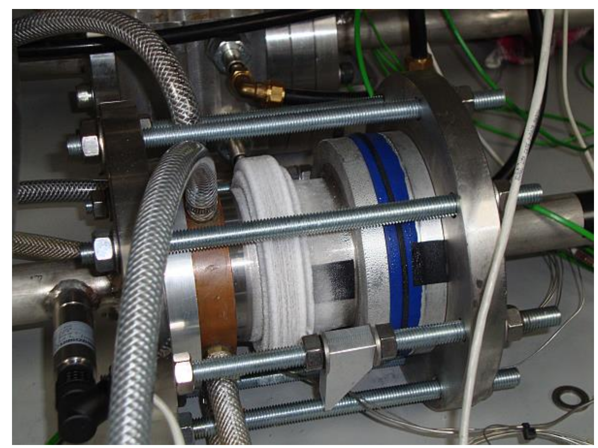
3 engine stages (#1, #2, #3)
1 cooler stage (#4)
Heat source: thermal oil heater
Heat sink: water circuit



Pressure amplitude distribution



	pa#2	pa#3	pa#4	pa#1
cold hex +20C	2.10	2.11	2.34	2.31
cold hex -40C	1.92	1.34	2.58	1.53



Solar powered Thermoacoustic cooling

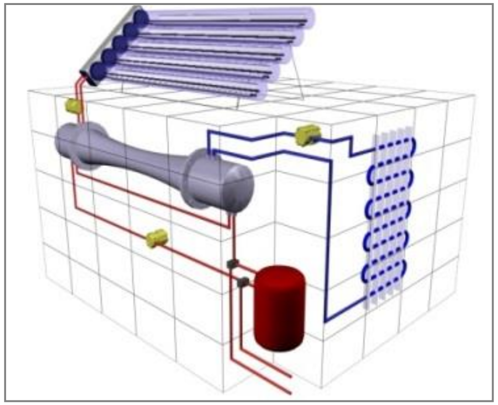
The idea behind SOTAC

- Add-on for vacuumtube collector systems
- Combined heating and cooling

Concept studied already in 2004-2005 by Aster and ECN (NEO programme)

Conclusion at that time

- vacuumtube collectors too expensive
- Thermoacoustics need some improvement

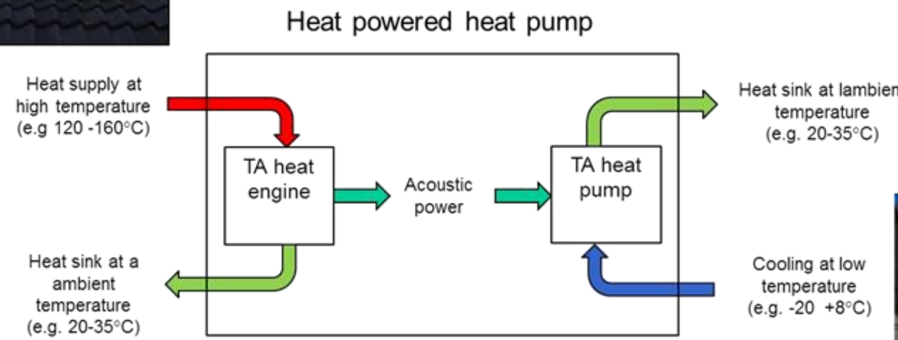


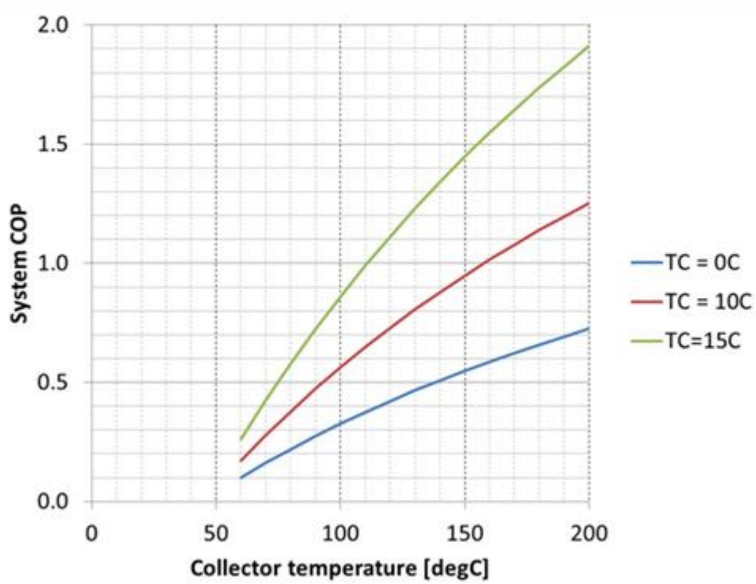
Progress made to solar powered cooling concepts since 2010

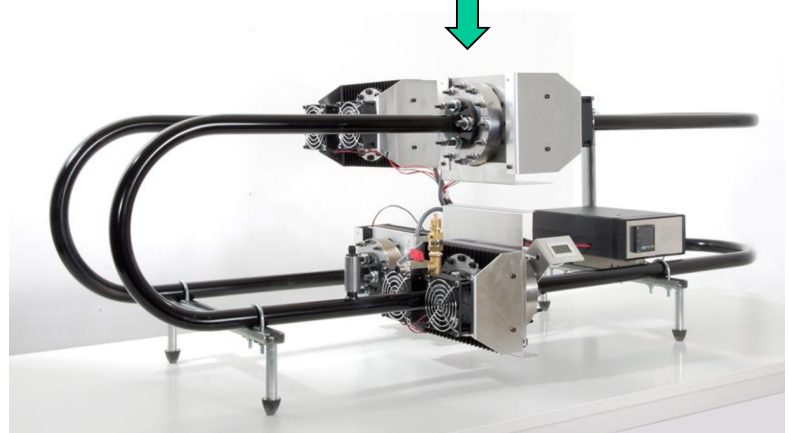
- Introduction multi-stage traveling wave thermoacoustic engines
  - Low onset and operating temperature
  - Thermoacoustics more compact
- Cost of vacuumtube collectors declined significant

Solar powered cooling (SOTAC)

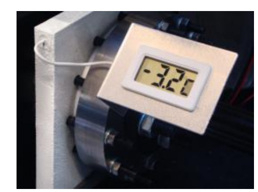
- Add-on for vacuumtube collector systems
- Latitude <35°: Cooling only
- Latitude >35°: Combined heating and cooling







SOTAC demonstration setup (2012)



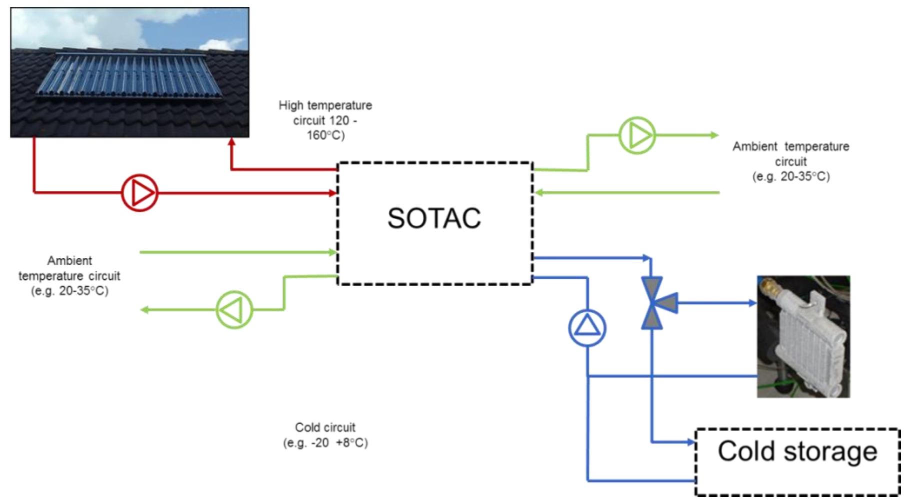
Extend system operating time

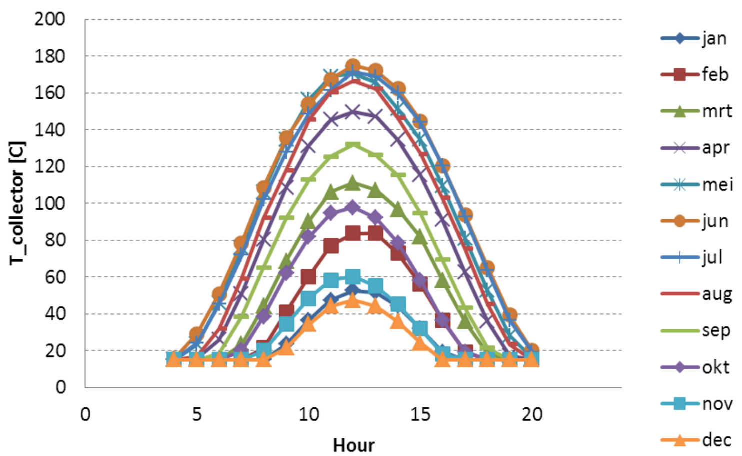
Daily cycle

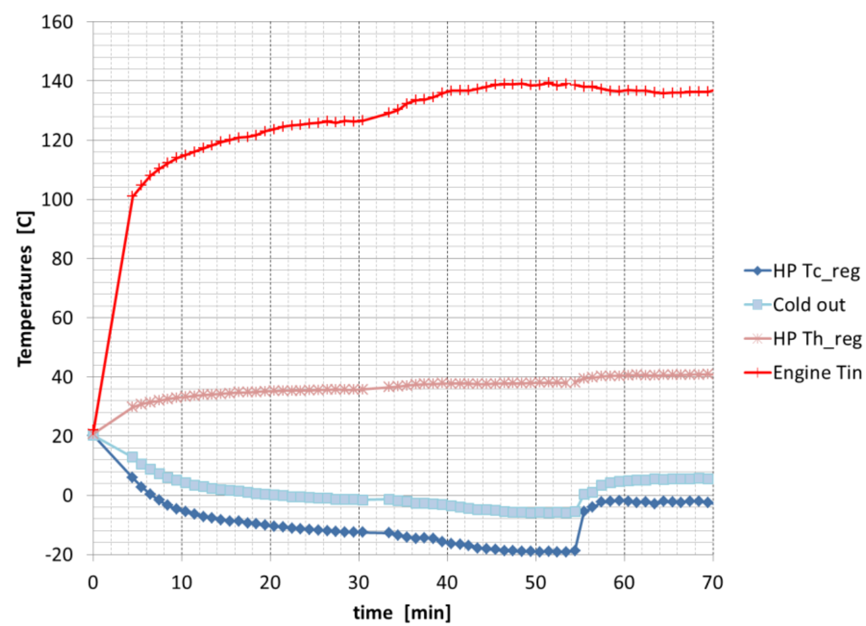
- Charging a cold buffer during peak irradiation

Year cycle

- Combine heating and cooling







Pulse tube cryocoolers or cold heads

- Since 1980
- Driven by (E-A) pressure wave generator
- Commercially available today

Image: www.qdrive.com

Thermoacoustic engines with standing wave resonator

- Since 1997
- High efficiency
- High onset and operating temperatures
- Large internal (resonator) volume
- Most studied / copied configuration

Multistage thermoacoustic engines with traveling wave resonance and feedback circuits

- Since 2008
- Low onset and operating temperatures
- Small internal (feedback) volume
- Prototypes build up to 100kWT at 160°C

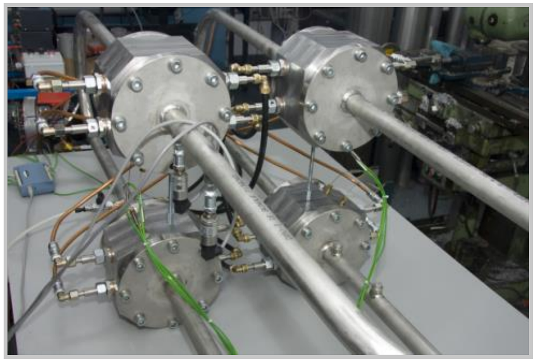


Image: www.aster-thermoacoustics.com

ASTER THERMOACOUSTICS

Thermoacoustic liquefaction of natural gas (LNG)

Basic idea since 1998 by LANL (Swift), Cryenco (later Praxair)

Thermoacoustic Stirling heat engine (TASHE) drives multiple pulse tubes sharing the same standing wave resonator

Minimum engine input temperature:

- TH_engine = TC_engine . TH_cooler / TC_cooler
- In theory: TH_engine = 330*300/110 = 900K (627°C)

In practice: TH_engine > 900°C

- High temperature (red) hot hex and pressure vessel
- Limited heat reduction burned gas (1300 °C ⇒ 900 °C)
- Recuperation required, but limited by high exhaust temperature
- High temperature contruction materials required

⇒ Construction cost too high to become economic viable

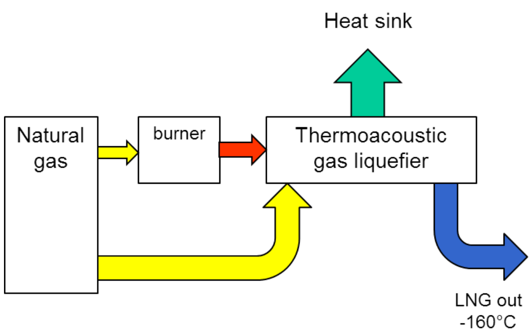


Image: www.lanl.gov

Thermoacoustic liquefaction of natural gas (LNG) or bio gas for transport and storage

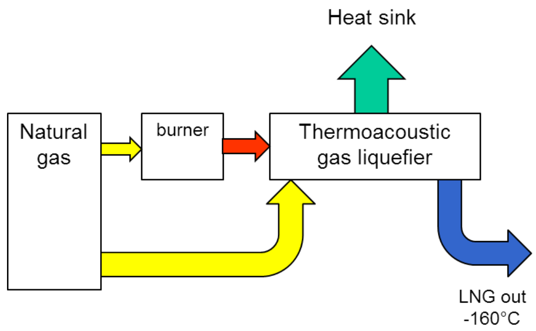
The idea behind:

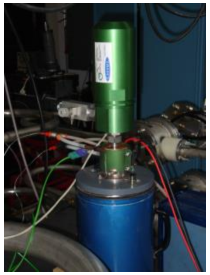
Combine high performance pulse tube(s) with medium input temperature multi-stage traveling wave thermoacoustic engine to lower input temperature

- Reduce minimum engine input temperature by # stages
- Typical engine input temperature now less than 300°C
- Improved heat reduction burned gas (1300 °C ⇒ 300 °C)
- Recuperation not required (optional)
- Allows for use of ordinairy construction materials

⇒ Cost reduction brings back the concept on stage

- Simple construction
- Scalable
- No moving parts
- Little or no maintenance
- Stand-alone operation





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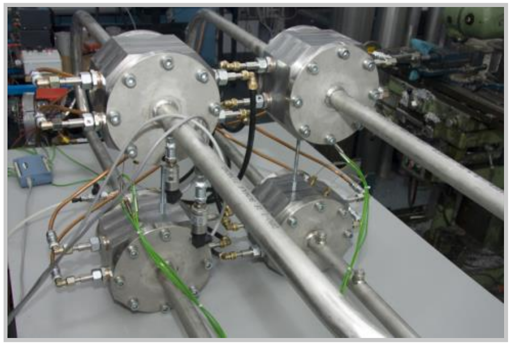


The experiments:

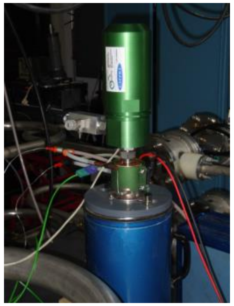
- Gas mean pressure: 2.4 Mpa
- Heat source: thermal oil heater
- Heat sink: water cooling

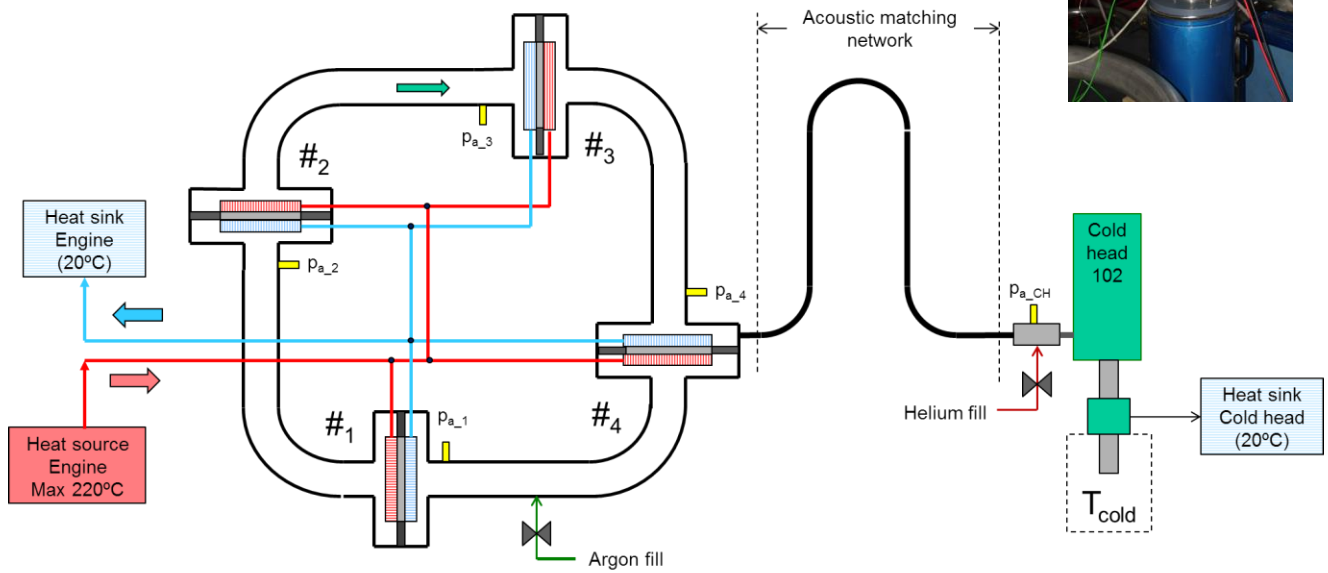
4-stage traveling wave engine

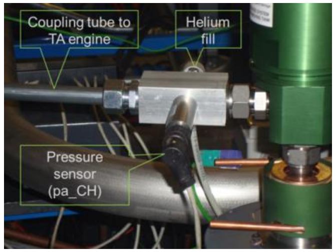
- Available at Aster-thermoacoustics
- Gas: helium-argon
- Frequency: 50-77Hz
  - (set by ratio helium-argon)
- Pressure amplitude cold hex #4: 65 kPa (dr: 2.7%)
- Theat source : 224°C
- Theat sink : 25°C

Cold head

- Type 102 supplied by Qdrive
- Gas: helium
- Operating frequency: 60Hz
- Pressure amplitude cold head: 226 kPa (dr: 9.4%)
- Electric heater: 5.2Ω







Heat powered low temperature cooling

Results

First experiment

- Reached a cold head temperature of -110°C
- Proved the concept

Recent experiment

- Reduction of engine losses
- Heat load added to cold head
- Modified gas filling system for tuning the engine frquency

⇩

Cold head

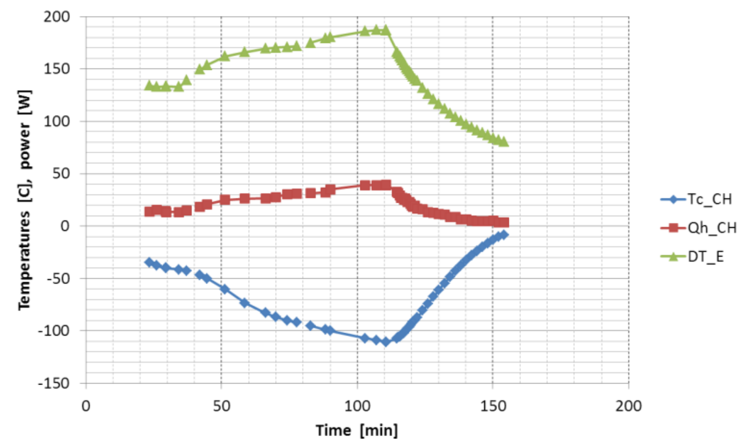
- temperature: -160°C
- Heat sink cold head 25°C

But even more important!

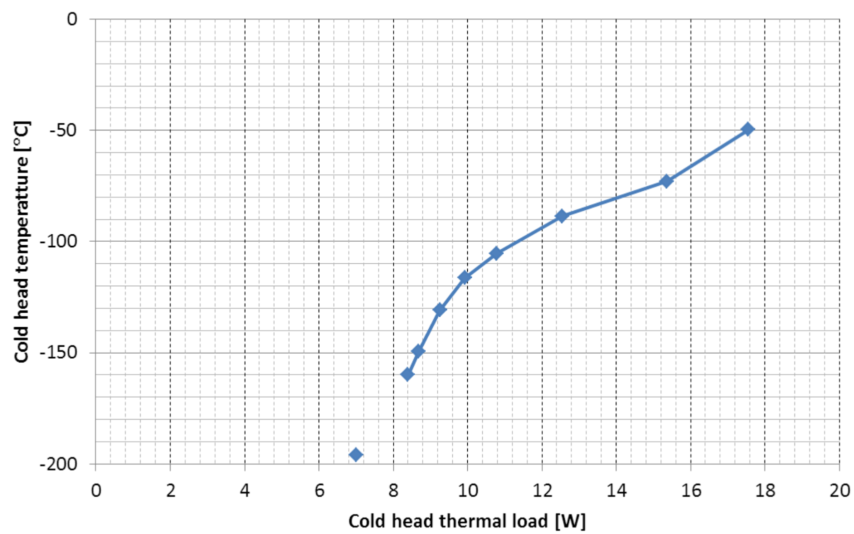
TA engine

- Heat input temperature: 224°C
- Heat sink: 25°C

First experiment january 2014



Cold head cooling power at engine input temperature of 224°C



Conclusions

Thermoacoustics is a key enabling technology for the conversion of low and medium temperature heat into acoustic (=mechanical) energy and vica verse

- Converting heat into acoustic energy ⇒ heat engine
- Converting the acoustic output power into electricity ⇒ Thermoacoustic generator
- Converting acoustic energy into a temperature lift ⇒ Heat pump or cooler

Low onset and operating temperature

Large temperature and power range

Cooling power and cold temperature proportional with heat input temperature

Minimal maintenance and operational cost

No environmental issues

Thermoacoustic energy conversion allows for applications not feasible with conventional technology for economic/ technical reasons