Introduction to THERMOACOUSTICS

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summary

Heat available, waste heat…

- The temperature of heat represents its capability to generate « work ». It is called « exergy »
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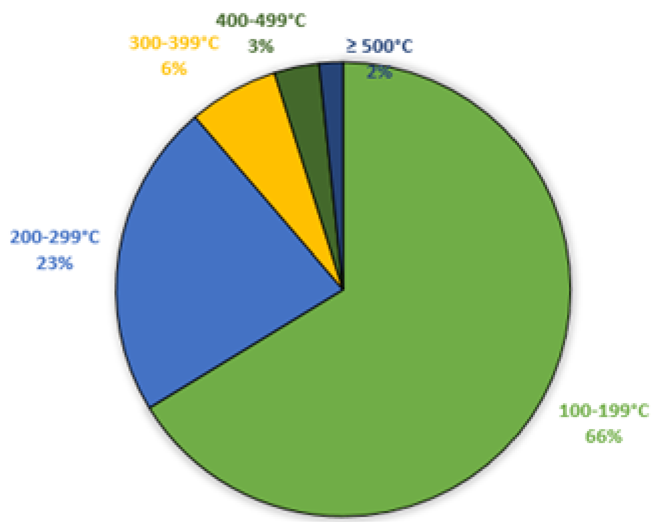
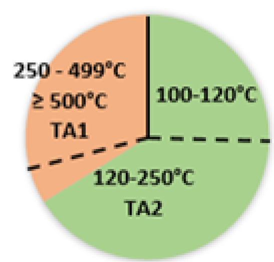




History

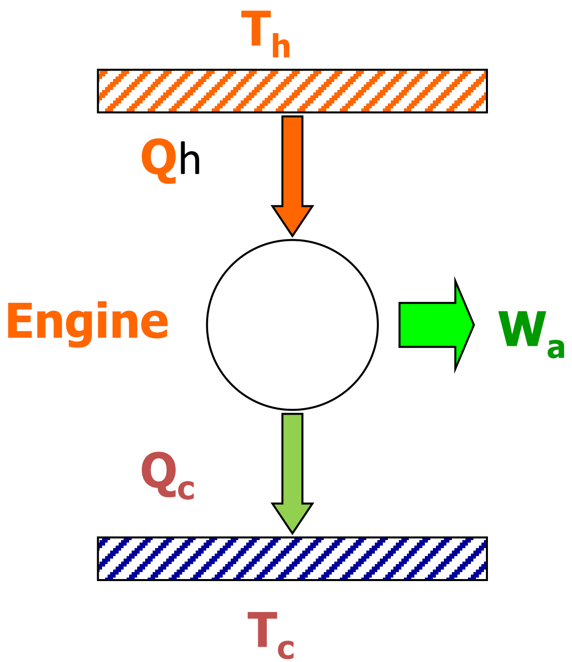
- **Glass blower**
- **Soundhaus Tube (1820)**
- **Rijke Tube(1859)**
- **Lord Rayleigh (1900) : Heat and sound**
- **Taconis (1948) : Thermoacoutic and Cryogenic**
- **Gifford et Longsworth (1965) : Pulse tube**
- **Ceperley (1978) : TA Stirling Cycle**

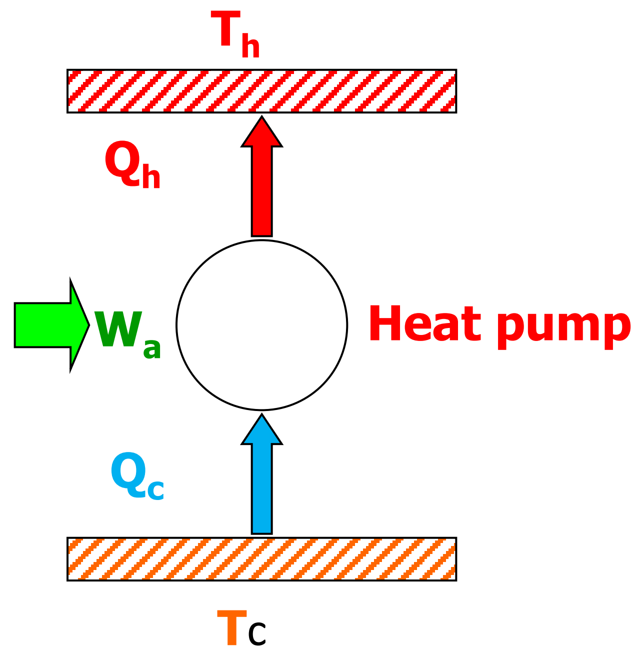
Introduction

- We want to understand why an acoustic wave may induce a thermodynamic cycle leading to an energy conversion process:
  - Heat → acoustic energy : engine
  - Acoustic energy → heat pumping
  - Acoustic energy → electricity generation
- We know how work a classical heat engine with internal combustion or a heat pump driven by a compressor or an electricity generator driven by heat engine..
- Are they also possible using thermoacoustic process. This is the purpose of this presentation

(1)Heat engine – Heat pump: Carnot principle

- 2 heat sources : Qh and Qc, a working fluid : **helium gas**, 2 actuators: Piston and displacer

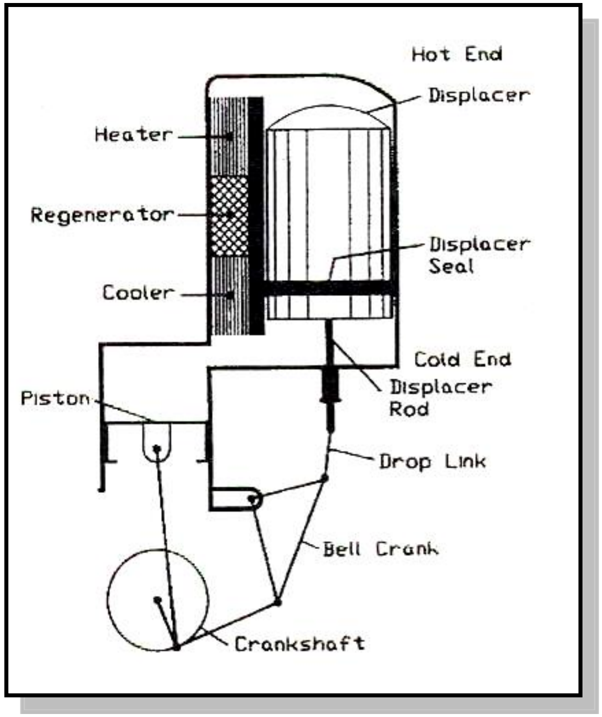




$$\eta_{carnot} = \frac{T_h - T_c}{T_h}$$

$$COP_{carnot} = \frac{T_c}{T_h - T_c}$$

(2)Heat and Stirling Engine



STIRLING ENGINE : (1820)

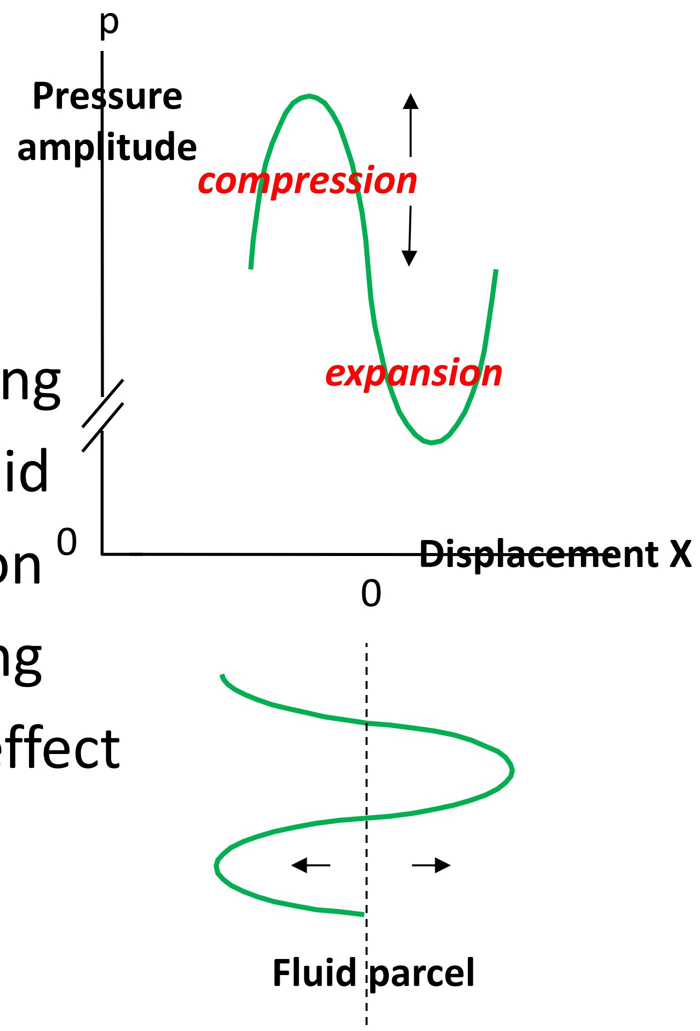
- Heat supplied by 2 external sources
- One hot Th, one cold Tc
- Piston et displacer, compression and displacement, out of phase:
- Heat supplied when pressure maximum
- Corresponding thermodynamic Cycle : 2 isochores, 2 isothermes ;
- Key component : Regenerator which stocks and gives back heat.

(3)Sound Wave engine ? piston and displacer?

- Acoustic wave propagating through the parcel fluid will induce:

- the ***wave*** acts as the *displacer* leading to an *oscillating* displacement of the fluid parcel in the (axial) propagating direction
- the ***wave*** acts as *compressor* leading to *heating* and *expander* with *cooling* effect

- Human voice at 1kHz : **10^{-4}°K**



(4) Heat sources in sound wave engine?

- They can be localized:

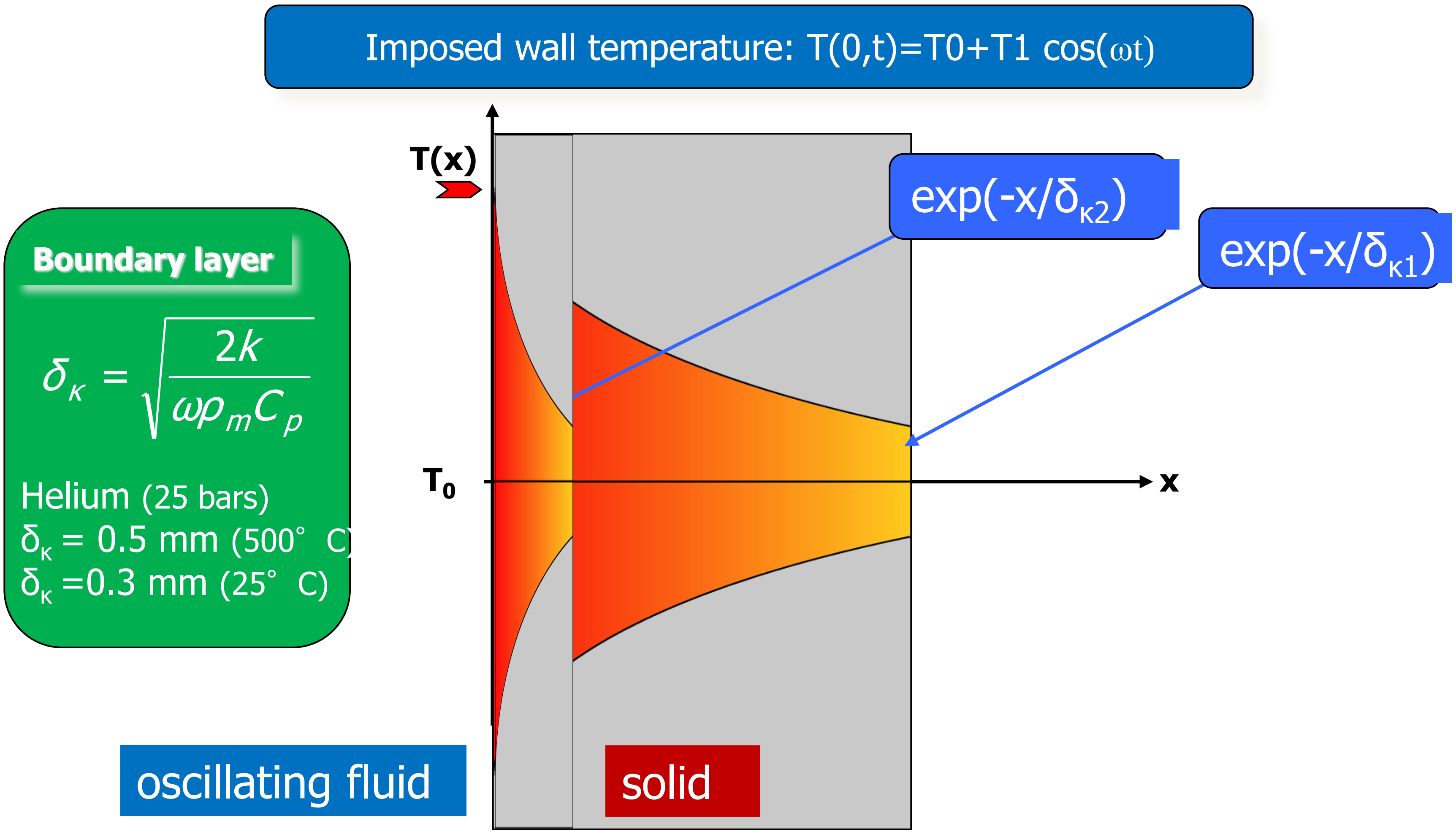
*Inside the gas filled tube by means of a flam: **Rijke tube**

Or distributed:

*On the heated wall tube with a temperature profil and filled of gas : soundhaus tube, Taconis effect, **our thermoacoustic effect**

Then, the gas exchange heat with the wall

- (5) About Interaction between oscillating fluid and solid wall: access to heat source



Acoustic wave characteristics (1)

- *In axial propagating direction OX*:
- **Wavelenght λ** = c/f. Note that resonant structure are currently **λ/2 or λ/4**
- For helium gas: c=1000m/s, **λ= 10m** . Air c= 330m/s: **λ= 3,3m**
- **Acoustic displacement**|x1|, and velocity |u1|= ω*|ξ1|
    - 1/10mm < ξ 1 <few cm

- *In the direction oy* :
- **Thermal** δ_k **and viscous** δ_v **boundary layer»**
- $\delta_k = \{2k/\omega\rho\ c_p\}1/2 = \{2\kappa/\omega\}1/2 \sim 1/10mm$
- $\delta_v = \{2\mu/\omega\rho\}1/2 = \{2\nu/\omega\}1/2 \sim 1/10mm$
- $\{\delta_v / \delta_k\}^2 = \mu . C_p/k = \sigma \leq 1$: Prandtl

Acoustic wave characteristics(2)

- **δk**, **δν** are the characteristic lenght of thermal or viscous oscillating fluid - solid interaction

- *If the fluid parcel is farer from the wall than* **δk**, **δν, it has no thermal or viscous link with the wall. Its behavior may be see as « adiabatic »**

- *If the fluid parcel is near the wall as ≈* **δk**, **δν it has some bad thermal or viscous link with the wall. Its behavior may be see as « not perfect adiabatic »**

- *If the fluid parcel is very closed he wall such as <<* **δk**, **δν it has a strong thermal or viscous link with the wall. Its behavior may be see as « isothermal with the wall»**

- **Conclusion**: in a thermoacoustic process, the useful volume is only concerned by the boundary layer volume

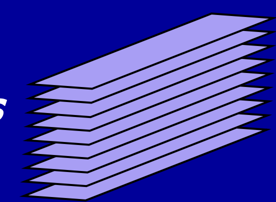
Acoustic wave characteritics (3)

- Heat exchange between acoustic fluid and solid wall takes place in a small volume: It is necessary to multiply the effects
- Acoustic displacements must be small compared to the stack or regenerator lenght : some mm < some cm. They are also the characteristic thickness of heat exchanger
- Thermoacoustic effect that is ‘’heating effect’’ due to acoustic compression are important only if acoustic pressure is very high : 1 bar! (200dB)

SMALL EFFECTS BECOMING IMPORTANT(4)

- Using many boundary layers acting in parallel and resonance amplification

  - Increasing heat exchange area
    - ***Porous medium: many plates***

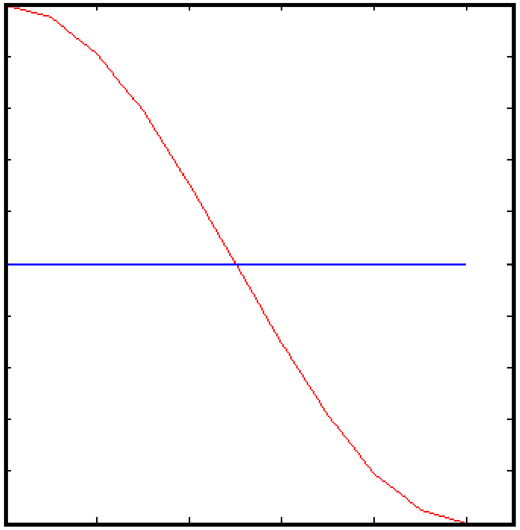


  - Increasing acoustic pressure:
    - ***RESONATOR***

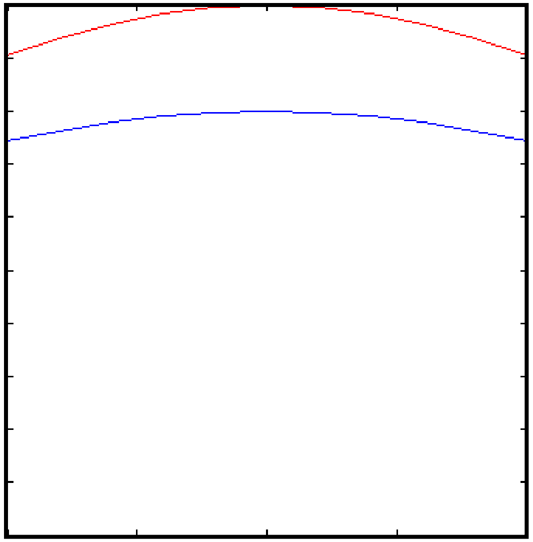
  - 2 HEAT EXCHANGERS :2 HEAT SOURCES

What kind of resonant acoustic wave easily doing? (5)

Standing wave



Traveling wave



- Pressure
- volume flow rate

Which performs a Brayton cycle operating for engine or heat pump as well

Which performs a Stirling Cycle operating for engine, amplifier and heat pump

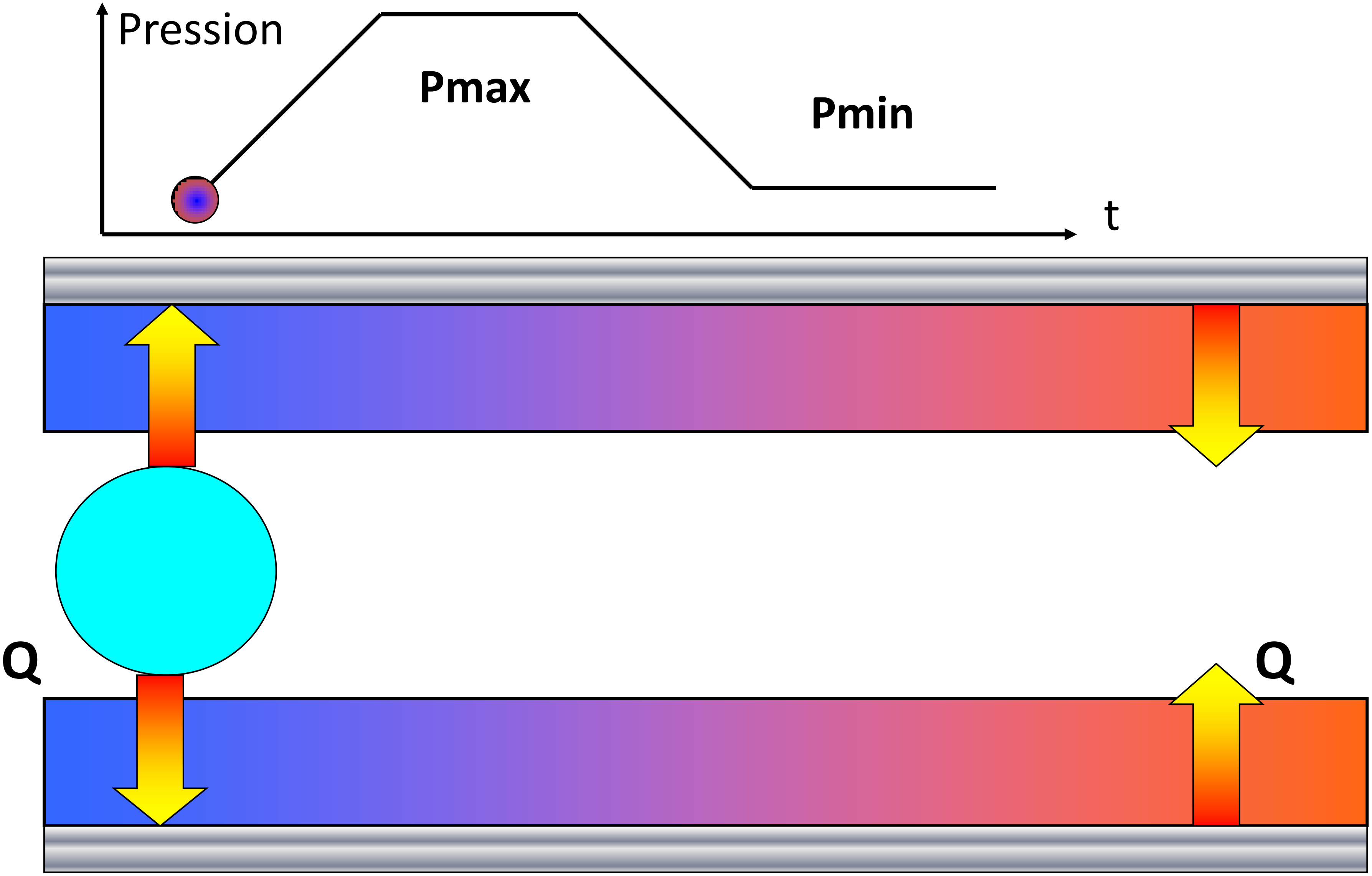
Consequences for thermodynamic cycle (6)

- **Standing wave**: *Displacement and pressure actions (+/-) are in phase : fluid parcel is heated up while moving in the wave propagation direction from one temperature towards another. Thermal link between gas parcel and wall must be weak in order to avoid any heat transfer during the displacement (irreversible) from one heat source to another. hydraulic radius, gap between plate* :$r_h \approx \delta_k$ *: BRAYTON : irreversible*
- **Traveling wave**: Displacement and pressure actions (+/-) are out of phase. Displacement must be isothermal with the wall with a perfect (reversible) thermal link between gas and wall: $r_h \ll \delta_k$ STIRLING ET ERICSSON (CARNOT efficiency)

Acousitc field and TA cycles

Standing wave and Brayton Cycle

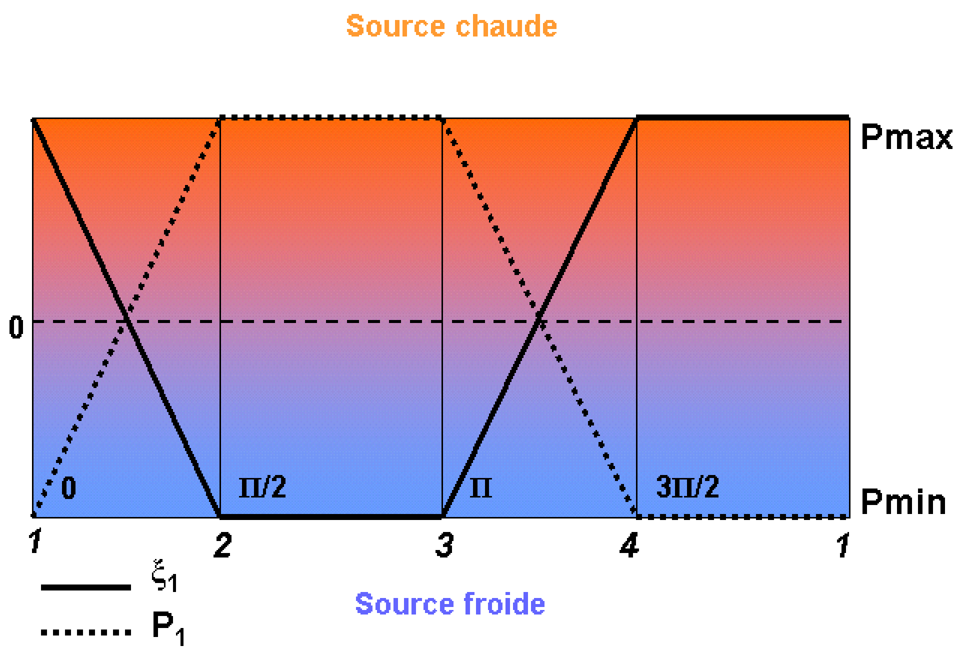
Traveling wave and Stirling cycle

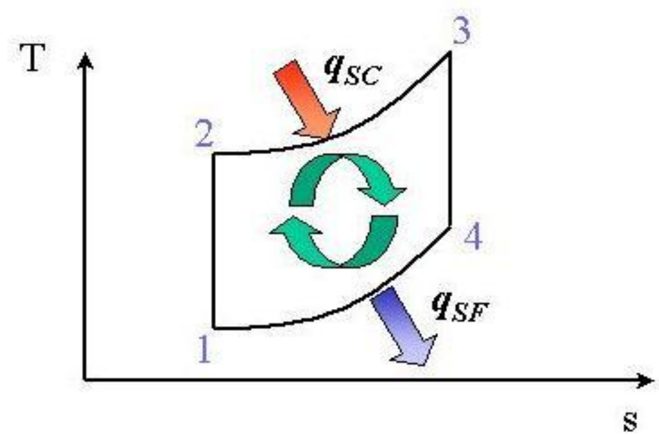


Standing wave mode for Engine

Standing wave mode

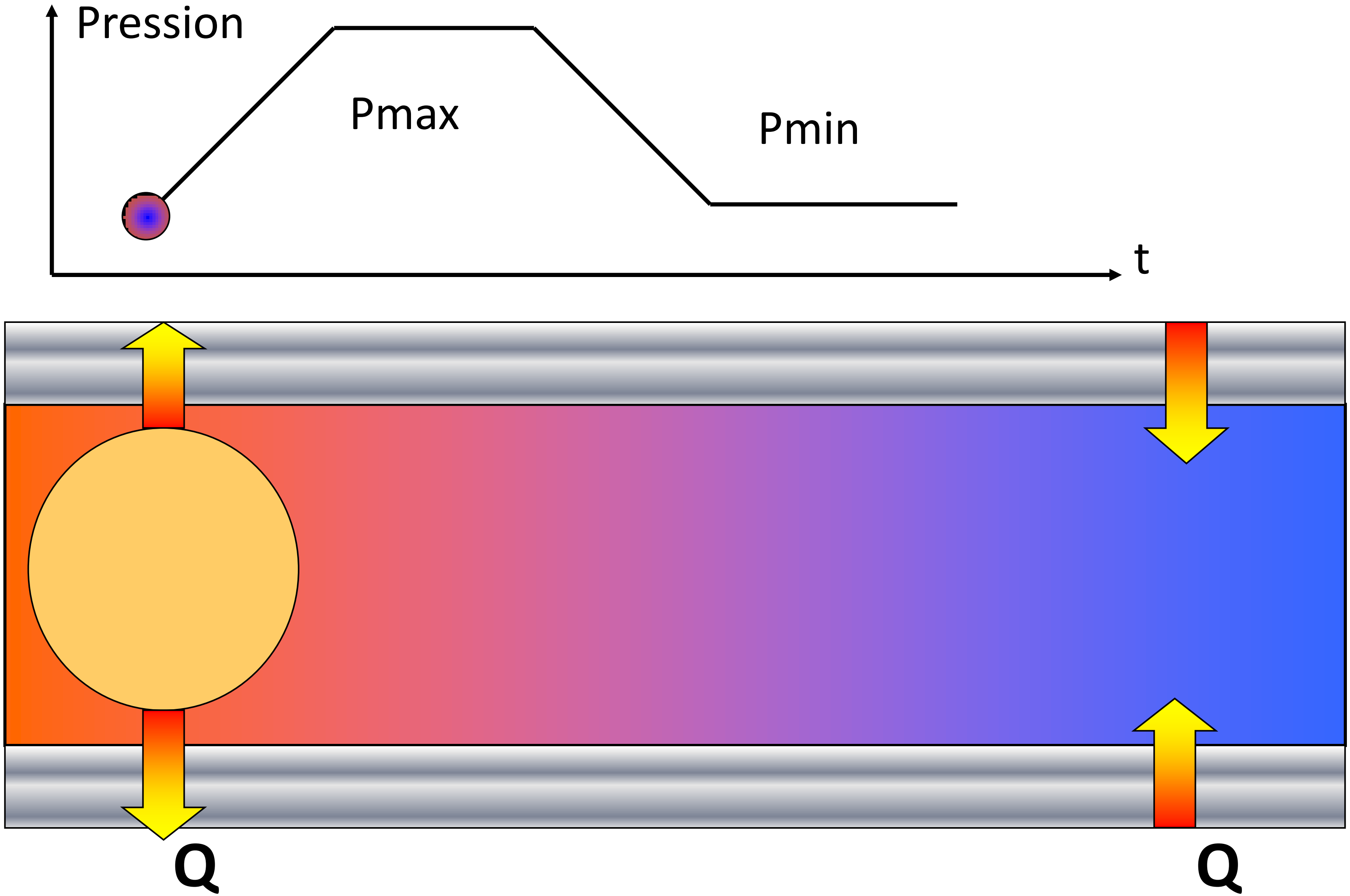
- fluid parcel displacement inside the boundary layer but $r_H \approx \delta_\kappa$
- r_H : spacing between plate stack leading to poor heat transfer between fluid and solid plate





BRAYTON CYCLE (2 adiabats, 2 isobars)

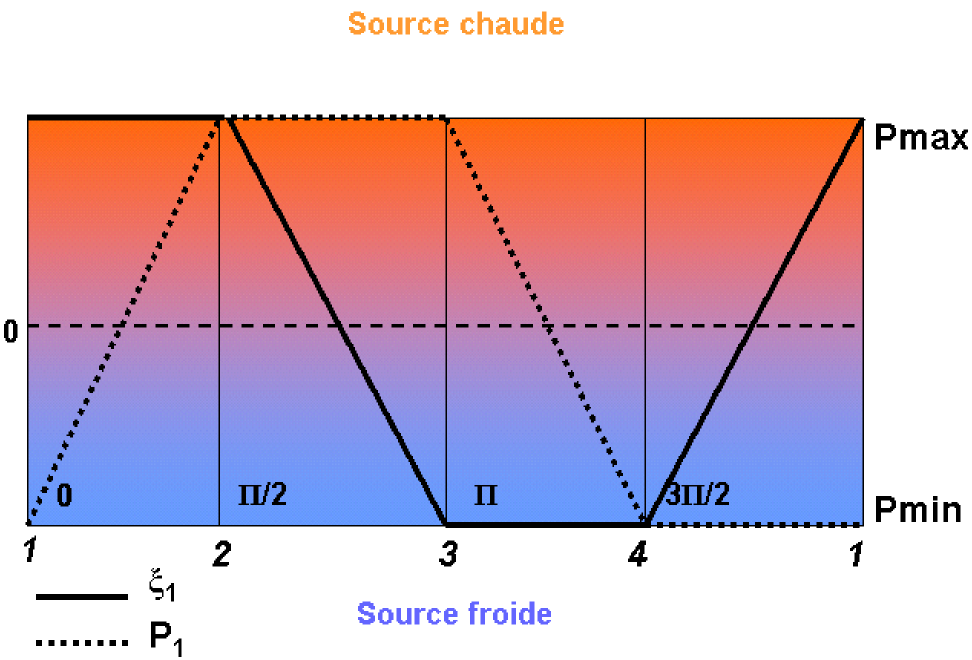
Efficiency lower than Carnot efficiency

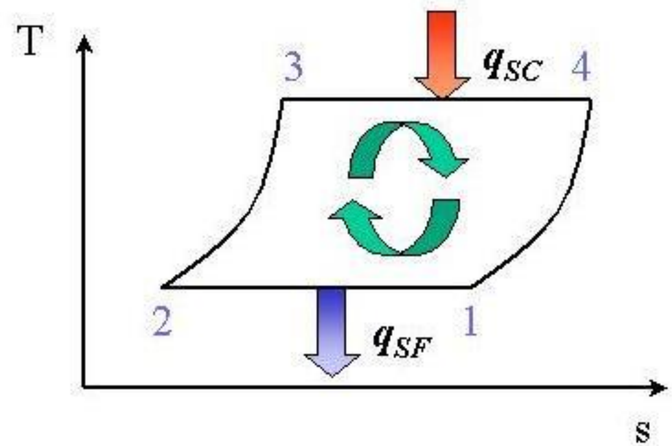


TRAVELING WAVE MODE : for heat pumping

TRAVELING WAVE MODE

• fluid parcel displacement inside the boundary layer but :
Hydraulic radius of grids pack about few 10 microns : $r_H << \delta_\kappa$
• High heat transfer solid - fluid





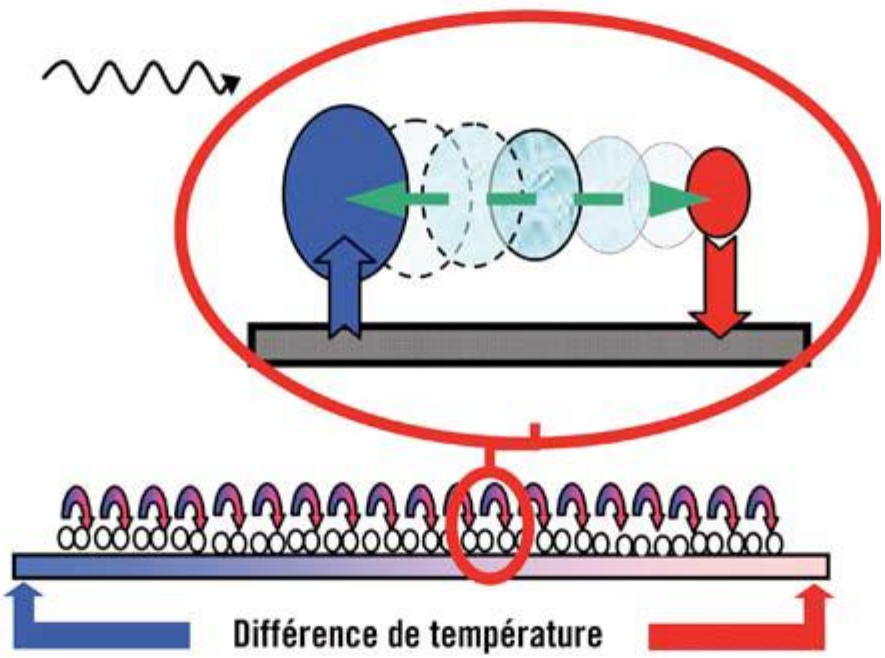
Ericsson Cycle(2 isothermal, 2 isobare)
efficiency equivalent to Carnot efficiency

Remarks

- 1.Standing wave acoustic field properties must be combined with **Stack** (*$r_h \approx \delta_k$) configuration and lead to irreversible Brayton cycle and low efficiency: 20% of Carnot
- 2. Travelling wave acoustic field properties must be combined with **regenerator** (*$r_h << \delta_k$) configuration and lead to Stirling cycle and good efficiency up to 70% of Carnot
- * hydraulic radius, gap between plate :r_h

COOPERATIVE CYCLES

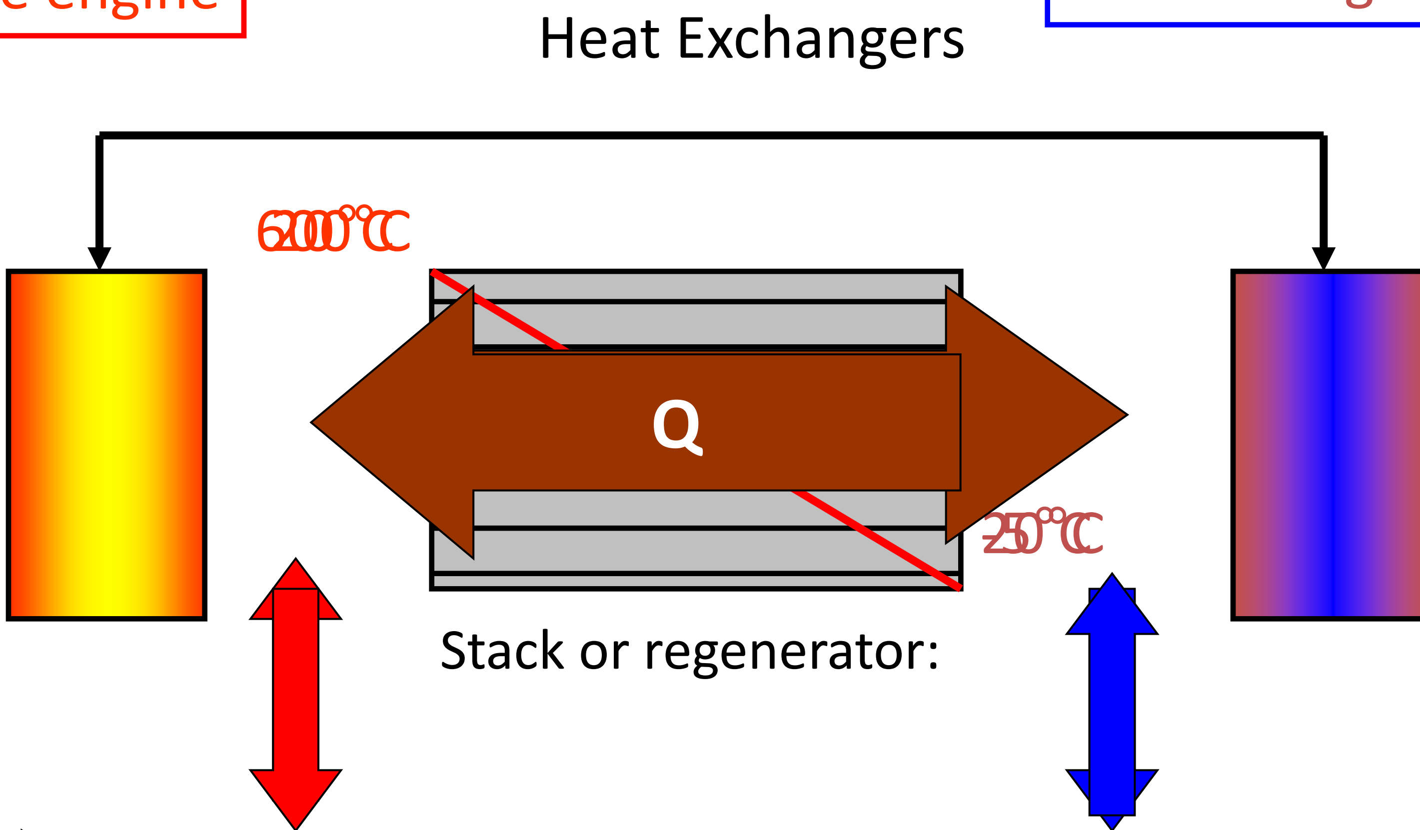
- As ξ 1, acoustic displacement << regenerator lenght, cooperative cycles, synchronised by the wave, occur along the « plate » connected to the two heat exchangers



SUMMARY

Mode engine

Mode refrigerator

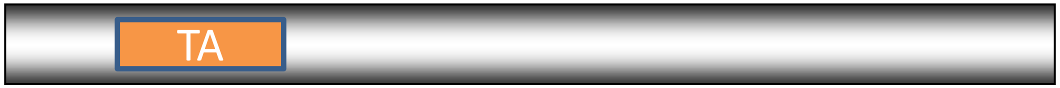


Many channels working in parallel

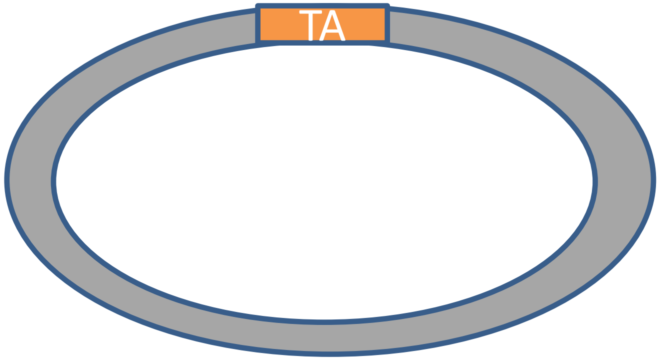
Acoustic topologies (1)

- *Basic acoustic resonators used for thermoacoustic wave generation*:

- SW: L= λ/2 if closed tube, and L= λ/4 if open tube (experiment). High acoustic quality needed. Brayton cycle

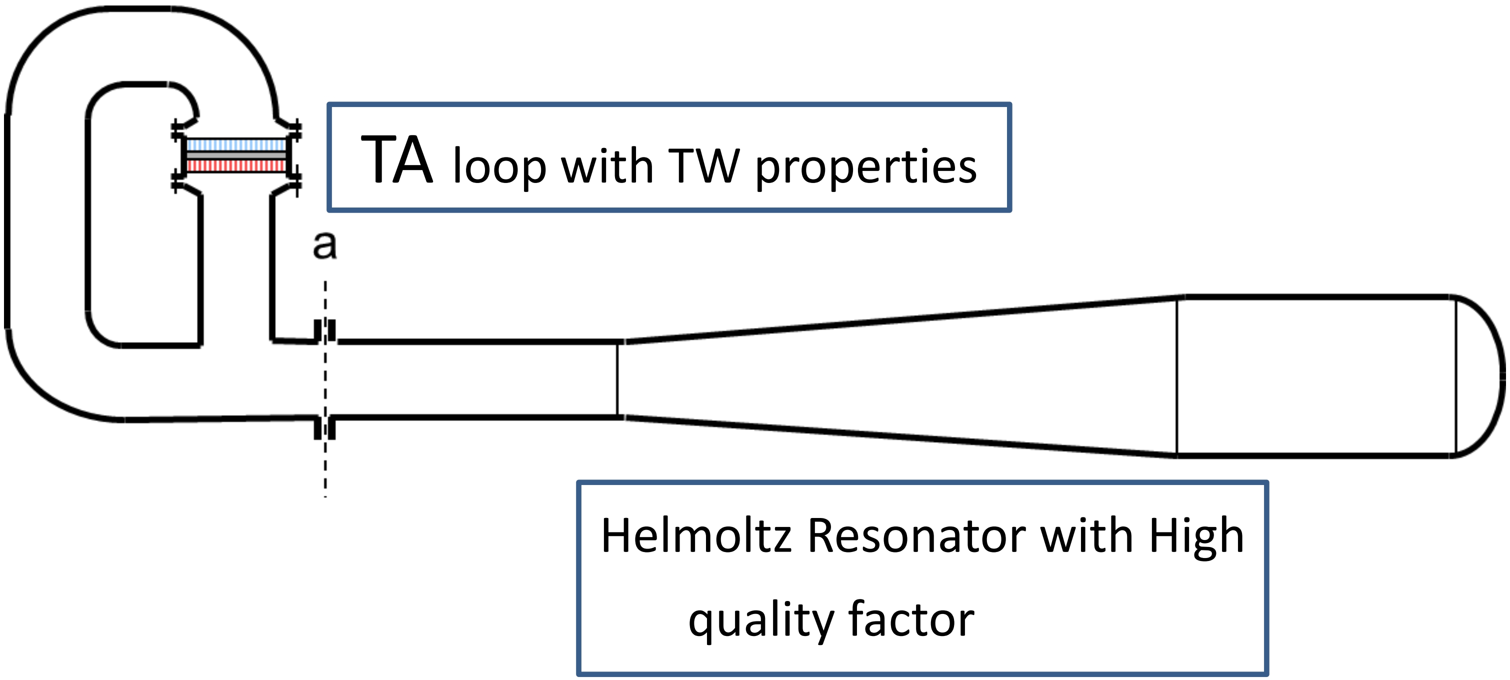


- TW: L= λ : Ceperley configuration : Stirling cycle



Acoustic topologies(2)

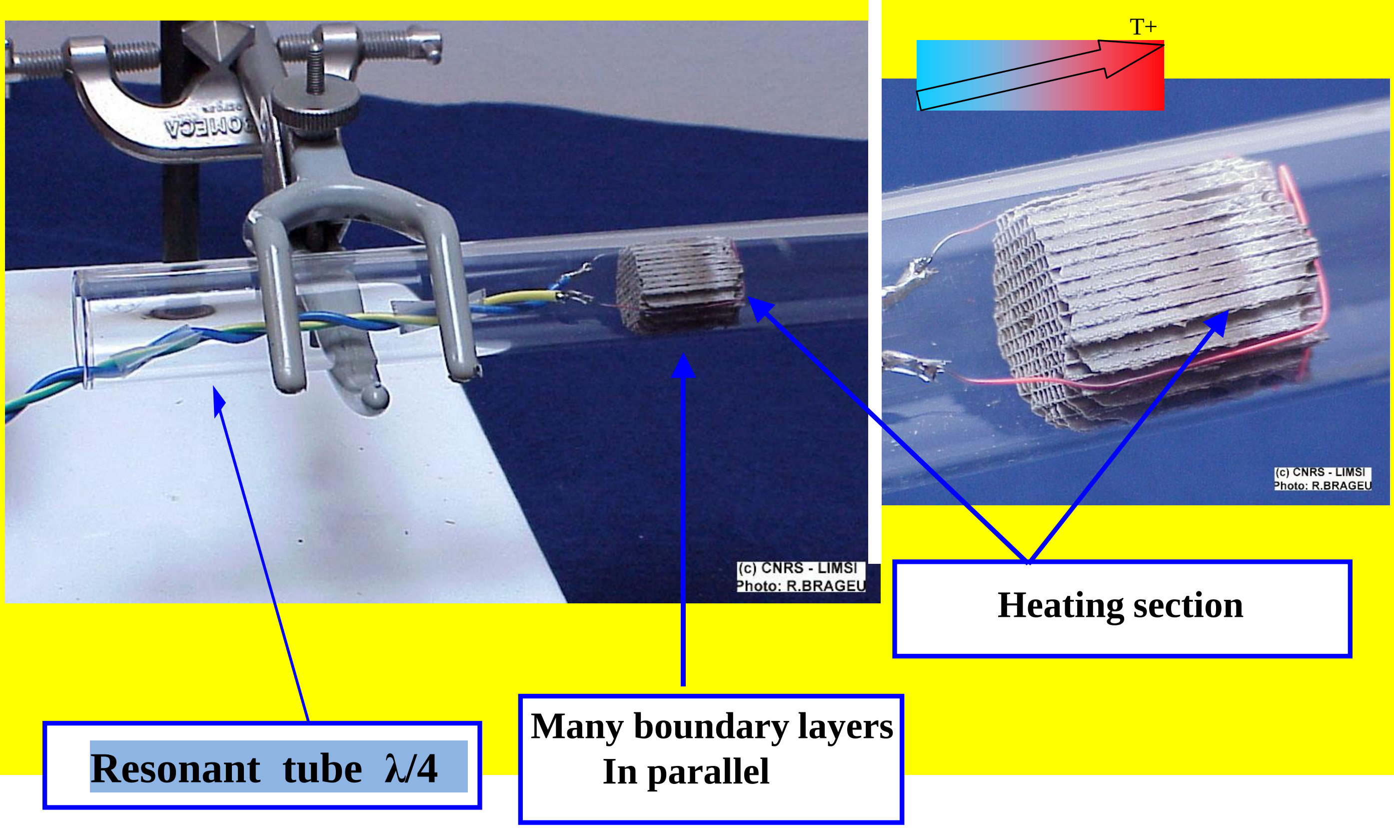
- High quality SW resonator but locally with a traveling wave acoustic field properties: benefit of TW properties (Stirling Cycle)



Experiment : standing wave engine

- *Injected heat (joule effect) on one stack side, the temperature gradient along the stack channels exceeds a critical value and every pre existing noise may be amplify. The resonator selects its resonance frequency.*

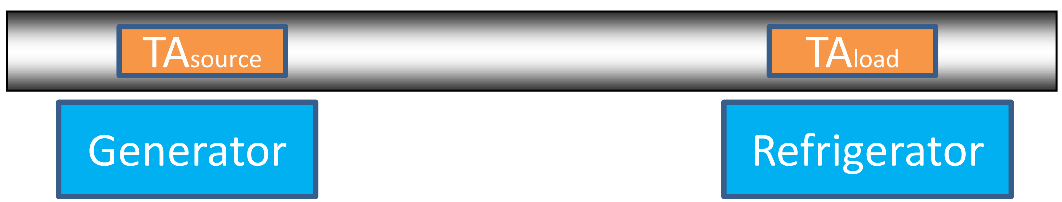
$\nabla_x T$



Using acoustic energy (1)

- The load could be:

1. Thermoacoustic cell providing « heat pumping »



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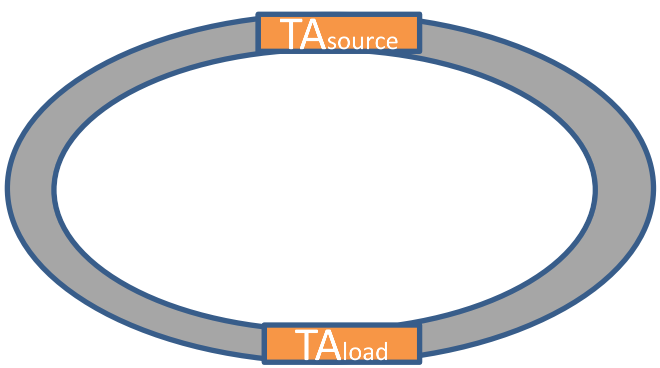
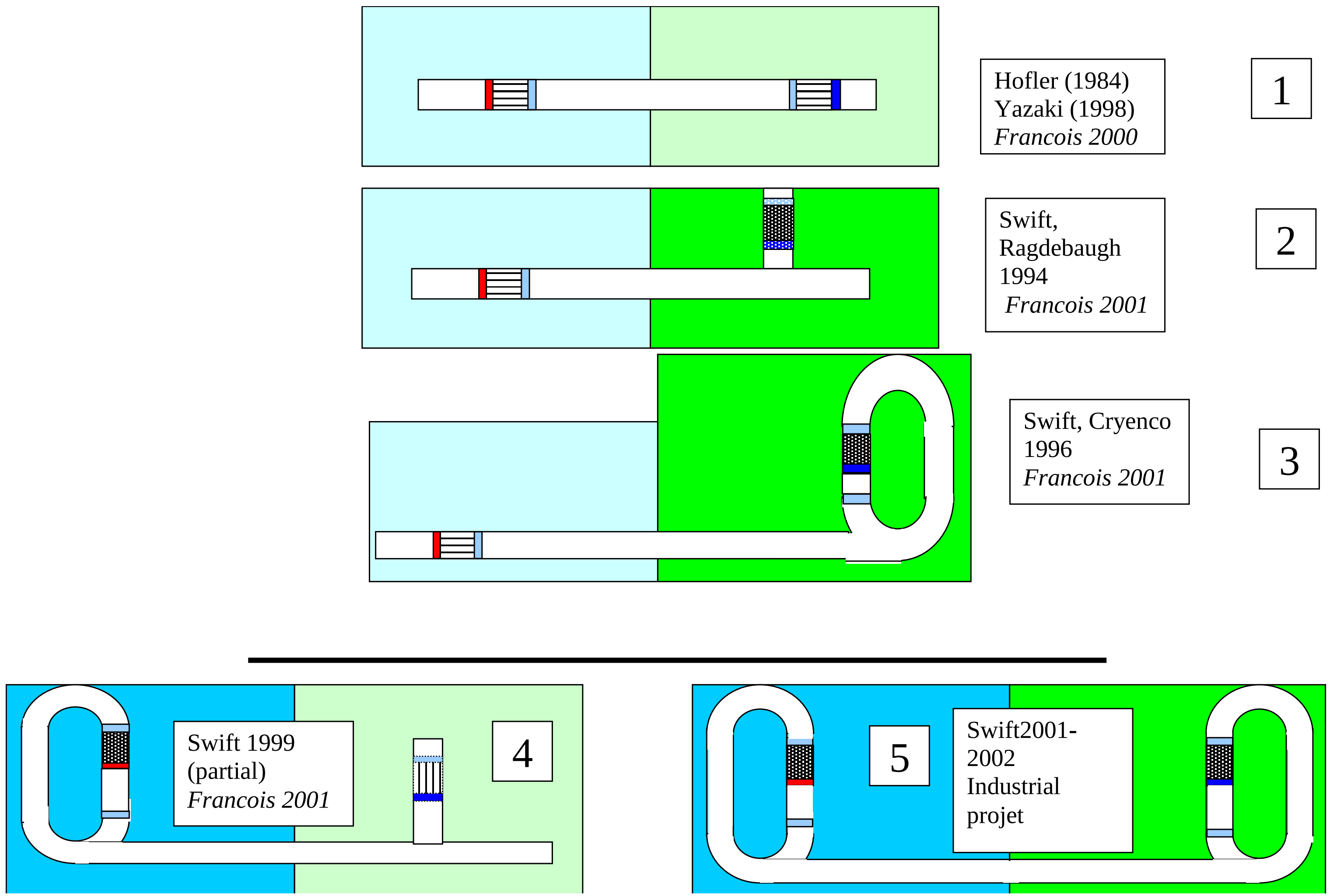


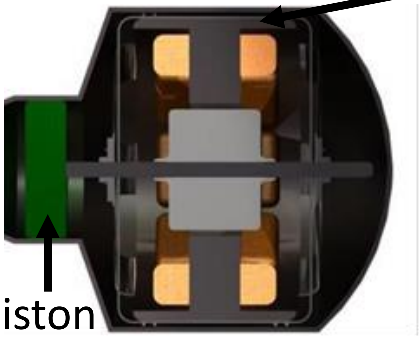
Using acoustic energy (2)



Using acoustic energy (3)

*The load could be a magnetic piston into a coil connected to an electric load:

Qdrive technology:

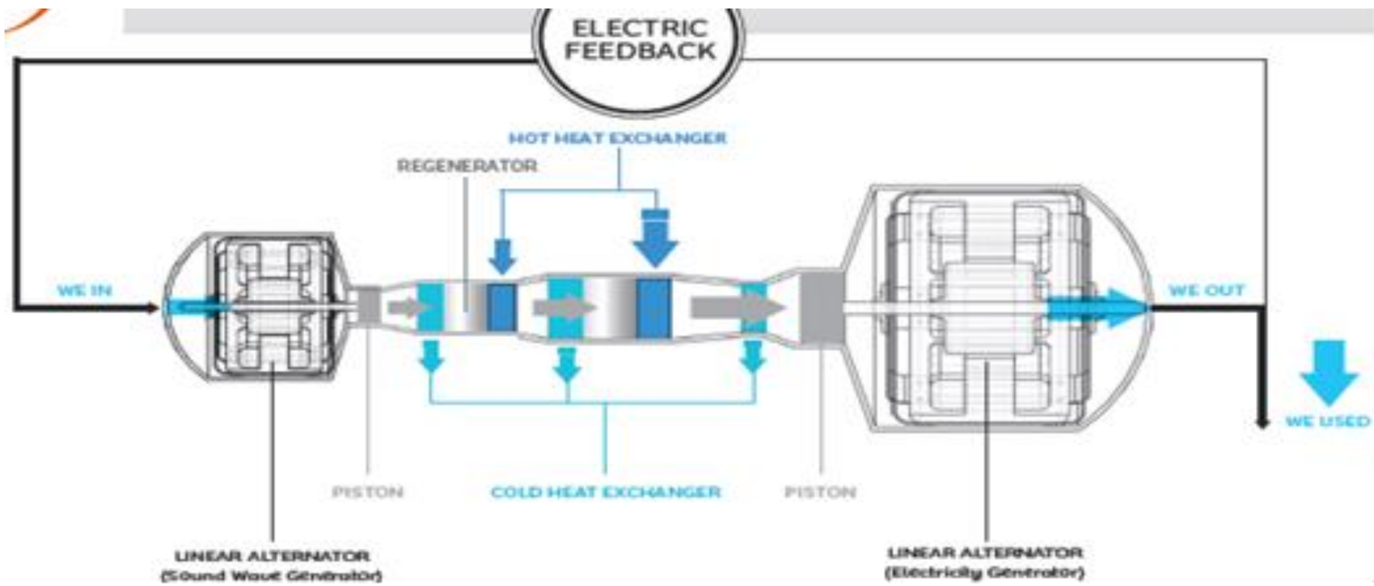


*instead of piston use a bi-directional turbine which transforms linear movement into rotative one and associate a rotative alternator connected to an electric load

ASTER – HEKYOM technology

Using acoustic energy (3)

- *Another way is to use heat energy to **amplify** acoustic energy in a linear and compact topology**
- *Here the generated wave is amplified two times and acts on a acoustic to electric converter generating electricity*
- *An electric feedback circuit allows such a system being autonomous*



- *HEKYOM technology

Thermoacoustic process as a efficient tool using heat as energy supply: **challenges** (1)

- Heat to be transfered from the source to the thermoacoustic system hot heat exchanger : the process may consume large temperature difference decreasing efficiency if no heat pipe are available for the temperature level required
- SW generator requires heat at high temperature T>250°C – TW generator may use heatt at low temperature T> 100°C
- Energy conversion in TA active cell are limited by viscous losses and the local acoustic field must be very well chosen.

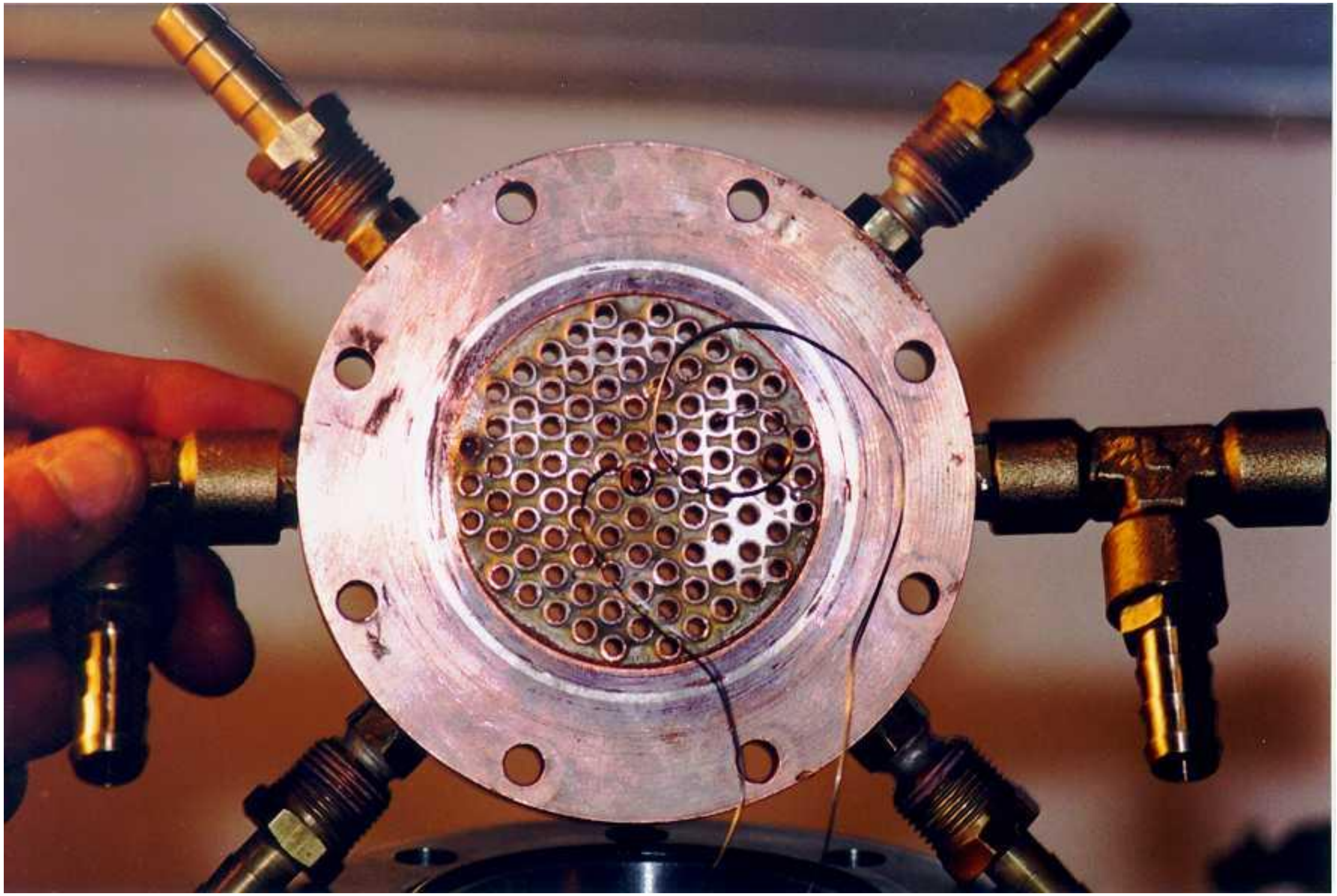
challenges (2)

- Thermoacoustic wave generator efficiency is limited by acoustic losses in the resonator :10% to 30%
- Coupling to the load requires perfect impedance matching
- Coupling of TA amplifier to the acoustic source requires perfect matching
- Electroacoustic converter like Qdrive have got a limited efficiency < 85%
- All these coupling effects acting in series are thermally and acoustically dependant.

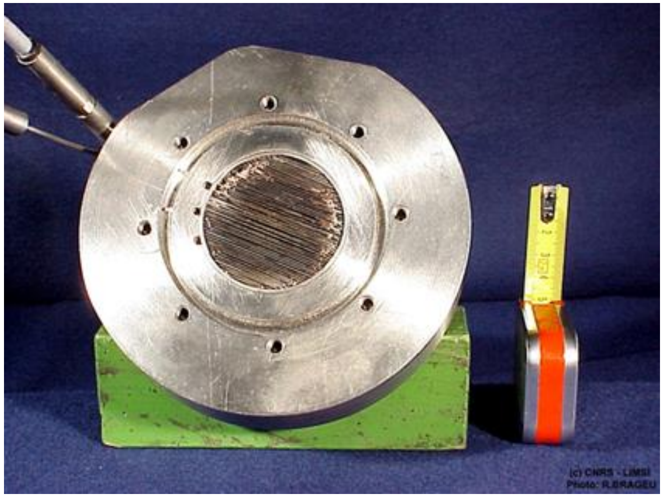
Thermoacoustic technology

- Cold and hot Heat exchanger
- Stack
- Regenerator
- Linear alternator

Heat exchanger at ambiant temperature (water)



first handmaid stack



REGENERATOR

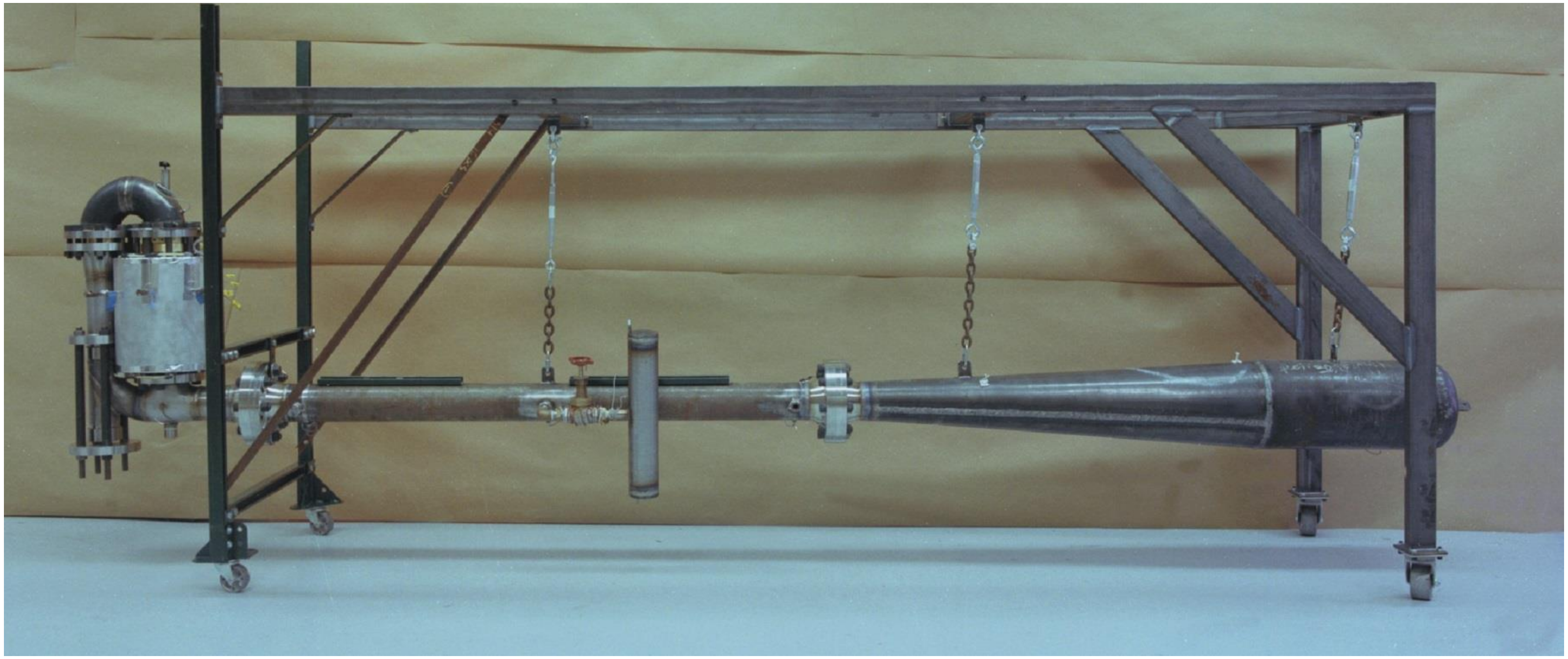
HOT HEAT EXCHANGER

HEKYOM

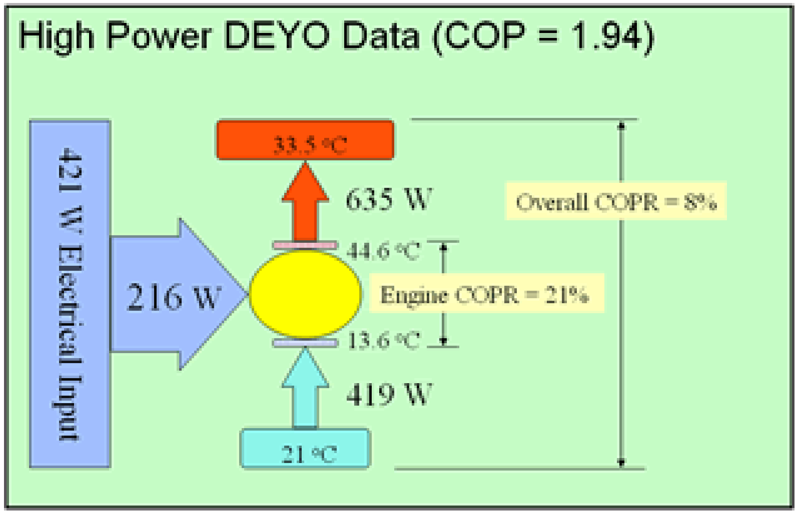
SWIFTbook

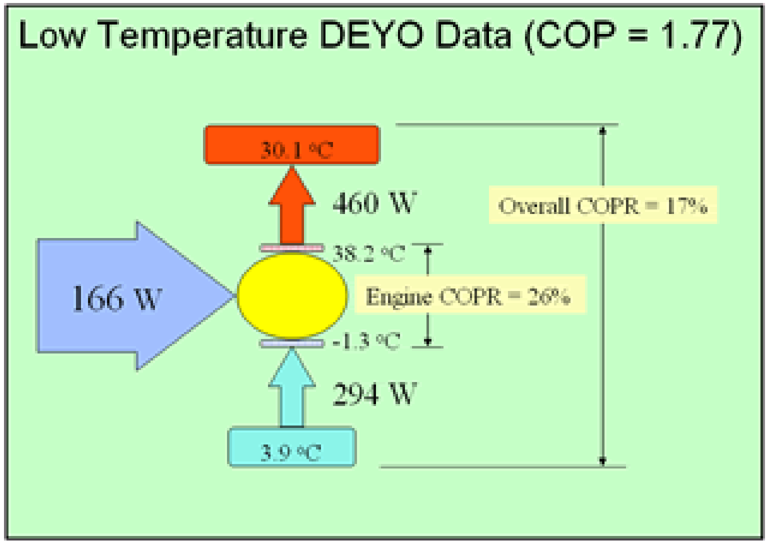
Some important prototypes

- 1-TASHE thermoAcoustic Stirling Heat Engine (Backhaus and Swift, Nature 1999)

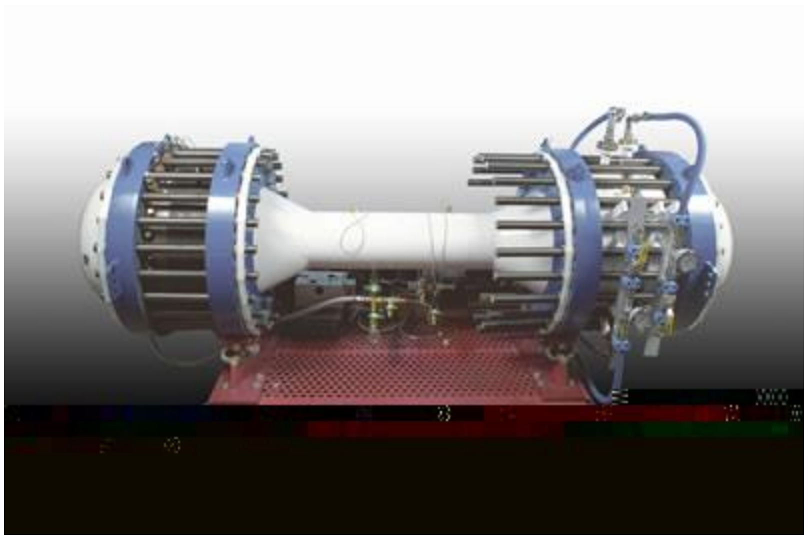


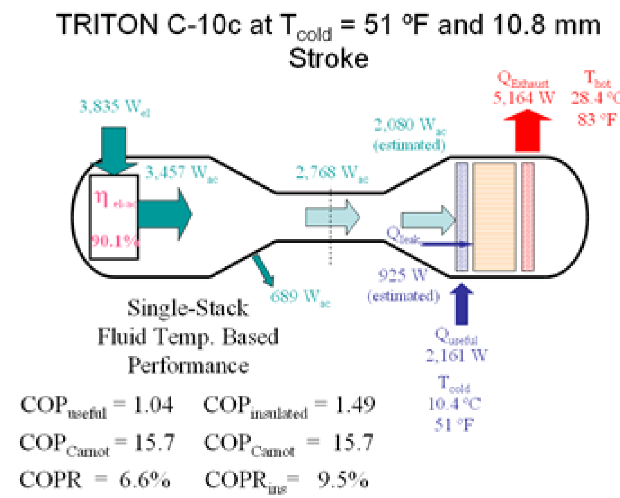
2- SETAC project: Shipboard Electronics Thermoacoustic Chiller





3. TRITON: Shipboard Thermoacoustic Cooler

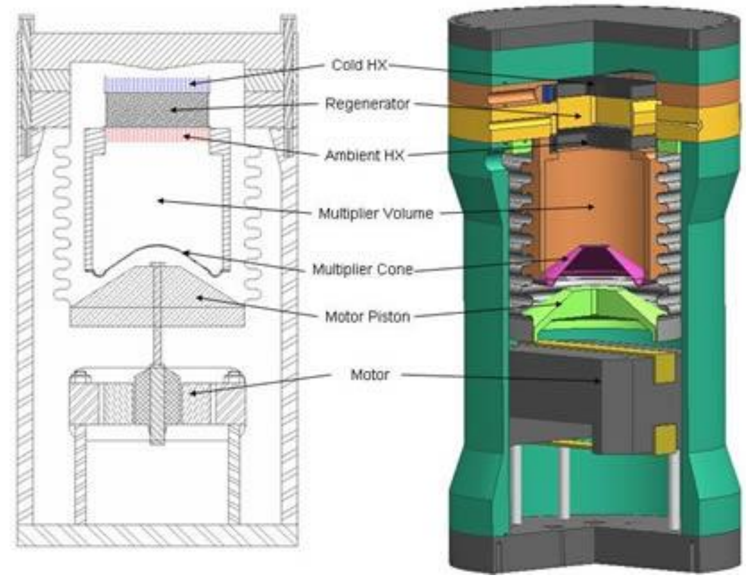




The TRITON Project, funded by the Office of Naval, research was started in 1996 and the design was completed in May 1998.

- Cooling capacity of 10 kW
- Tcold=51 °F

4. Ice cream refrigeration 2004 (Unilever)



- ❖10 inches (25.4 cm) in diameter ,19 inches (48.3 cm) tall;
- ❖ Cooling capacity:119 W at a temperature of -24.6 ºC.
- ❖ The overall coefficient-of-performance: 0.81
- ❖ 19% of the Carnot COP

5. Thermoacoustic Natural Gas Liquefier

Project of TADOPTR:

Phase I: 1997, liquefaction capacity of 140gpd (2 kW of refrigeration power at – 140°C); 60% burned and 40% liquefied

Phase II: 1999, liquefaction capacity of 500gpd; 30% burned and 70% liquefied

Phase III: 2001-2005, liquefaction capacity of 10-20,000 gpd, 20% burned and 80% liquefied

6. Thermoacoustic Natural Gas Liquefier 2

- **Prototype Praxair (9 kW)**
  - Spécifications
    - Capacité: 500 gal/jour
    - Puissance moteur 30 kW
    - Puissance totale: 9 kW
    - Gaz liquéfié: 70 %
  - Conception
    - Moteur type Stirling à ondes progressives
    - Cellule de réfrigération de type ‘’tube à orifice pulsé ‘’
    - 3 cellules de refroidissement en cascade
    - Fréquence : 40 Hz
  - Remarques
    - Problèmes de soudure (échangeur chaud)

Futur of TA devices

- *Electricity generation in Space and on earth*
- *Waste heat recovering with high efficiency and conversion into electricity or cooling*
- *Solar driven thermoacoustic cooler*
- *Heat pump at high temperature > 180°C*

A GOOD Educational BOOK

Thermoacoustics: A unifying perspective for some engines and refrigerators,

by Greg Swift (*swiftatlanldotgov*), is available from the Acoustical Society of America, either as a paperback or a pdf e-book.