PROJECT:
THERMAE
THERMOACOUSTIC ENERGY

Thermoacoustic Energy Harvesting - Sound Engineering?

Abstract:
Thermoacoustics have a key role to play in energy harvesting systems; exploiting a temperature gradient to produce powerful acoustic pressure waves. As the name suggests, Thermoacoustics is a blend of two distinct disciplines; thermodynamics and acoustics. The field encompasses the complex thermo-fluid processes associated with the compression and rarefaction of a working gas as an acoustic wave propagates through closely stacked plates in the regenerator of a thermoacoustic device; and the acoustic network that controls the phasing and properties of that wave.

Key performance parameters and appropriate figures of merit for thermoacoustic devices are presented with particular emphasis upon the critical temperature gradient required to initiate the acoustic wave and the thermal properties of the key component; namely the 'stack' or 'regenerator'. Mechanisms for coupling a Thermoacoustic prime mover with electromagnetic harvesters and piezoelectric transducer materials are also presented which offer the potential to enhance the energy density attained beyond that possible with linear alternators

Numerical modelling strategies are presented which enable parametric sweeps of the geometric and thermal properties, which influence the efficiency, and performance of the key components of such devices. Potential coupling and non-linear effects are examined.

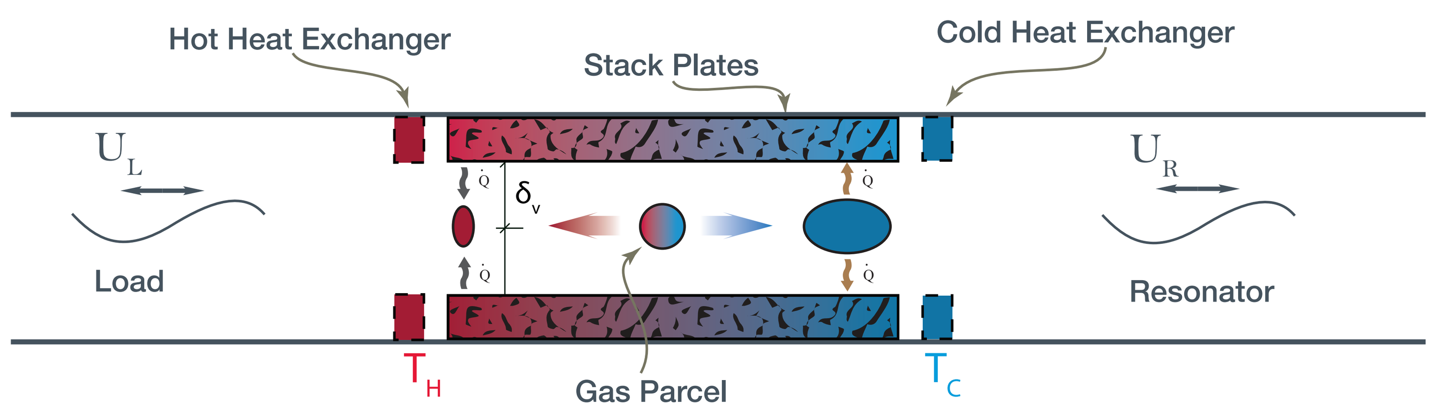


Figure 1. - An elemental parcel of gas oscillating between parallel plates in a thermoacoustic stack

The critical temperature gradient along the length of the plates (Figure 1) at which acoustic oscillations are initiated. The temperature versus position of an elemental gas parcel is plotted in figure 2 illustrating the difference between a thermoacoustic engine (a) and refrigerator. In the prime mover, heat is added to the parcel whilst it is at maximum pressure/temp.

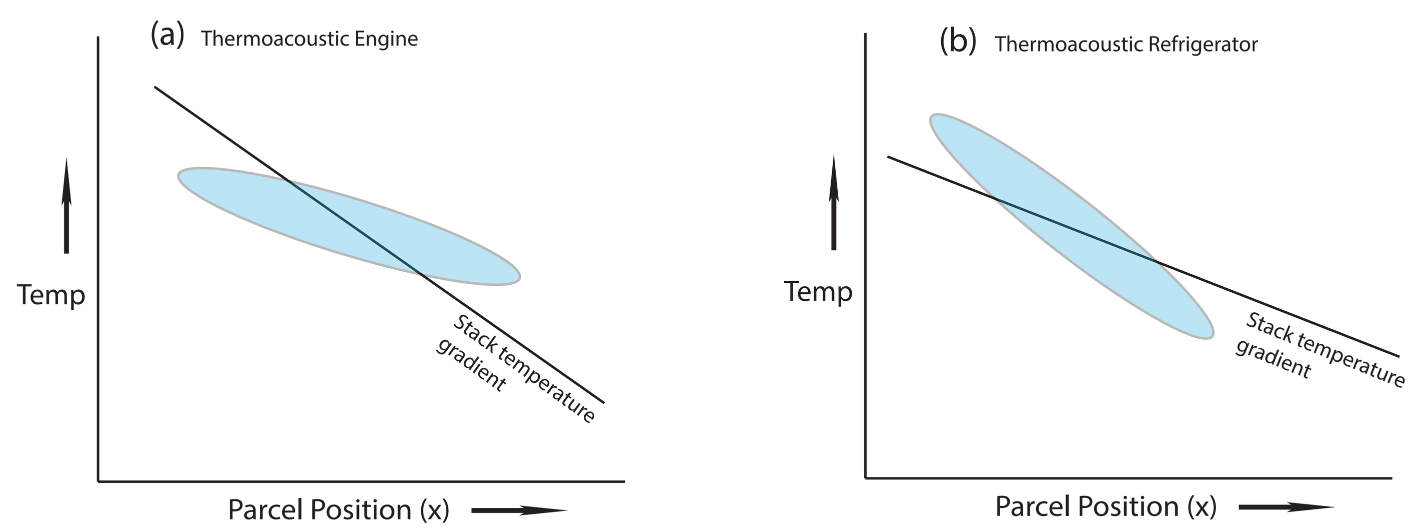


Figure 2. - Influence of temperature gradient

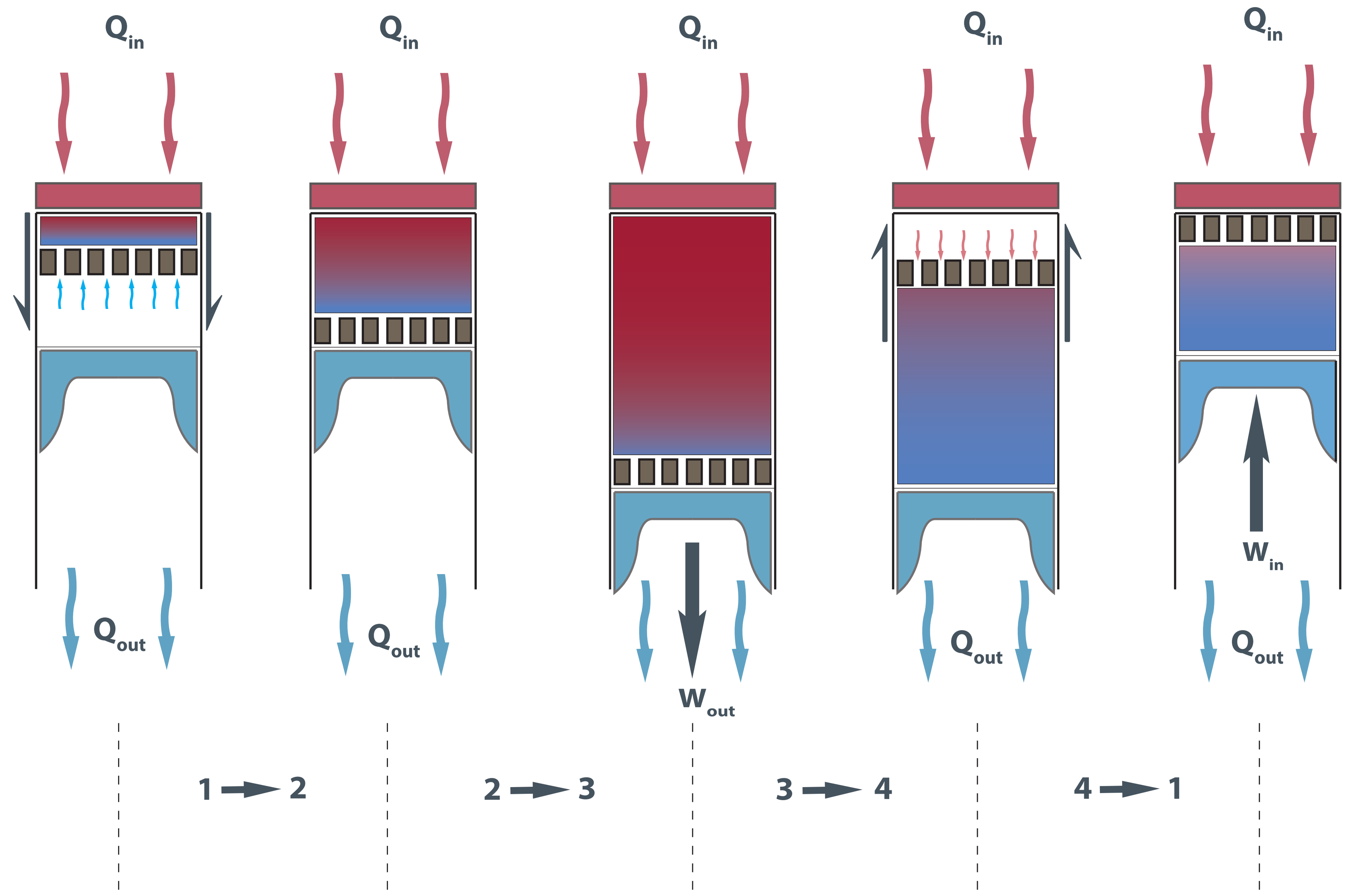


Figure 3. - Improved Stirling Cycle

The cycle executed in the regenerator is best described by the improved Stirling cycle (with displacer) as shown in figures 3 and 4 - Isochoric heating (1-2), Isothermal expansion (2-3), Isochoric cooling (3-4) and Isothermal compression (4-1). The porous displacer (brown blocks) is acting as a temporary heat store; pre-warming the air as it passes (stage 1-2) and pre-cooling it (stage 3-4).

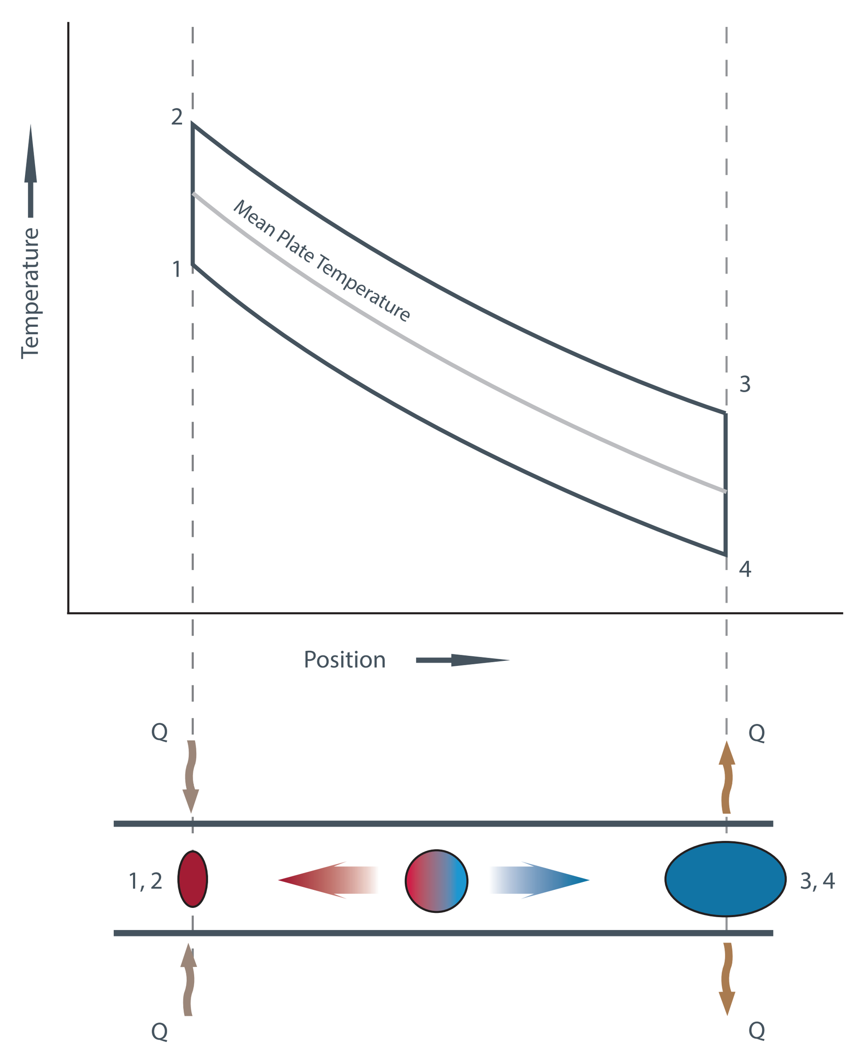


Figure 4. - Idealised Stirling cycle in the regenerator.

The fluid dynamics and heat transfer process in the regenerator is complex, both in the literal sense and in terms of the underpinning mathematics. The spacing of the plates in the stack is dependent upon the viscous and thermal penetration depths given by:

$$\delta_v = \sqrt{\frac{2\mu}{\omega\rho}} \qquad \delta_\kappa = \sqrt{\frac{2k}{\omega\rho c_p}}$$

The Prandtl no. is given by the square of the ratio of these two values and is a key design parameter:

$$Pr = \frac{\mu c_p}{k} \text{ or } \left(\frac{\delta_v}{\delta_\kappa}\right)^2$$

A working fluid with a Prandtl no. approaching unity is best in a stack where it is important to maintain the correct phase difference between velocity and pressure amplitude. In a regenerator with much closer plate spacing, a low Prandtl no. is a desirable figure of merit (<0.1); minimising viscous losses.

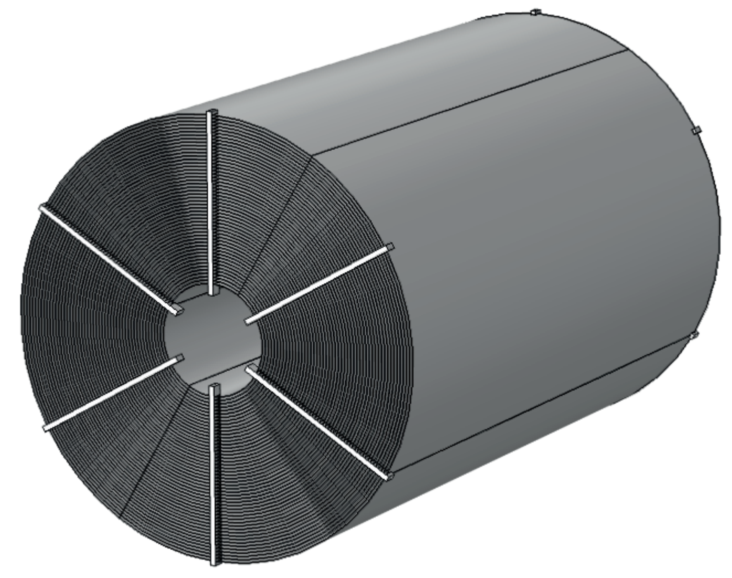


Figure 5. - Concentric stack, 50µm plate thickness, 250µm spacing.

The primary focus for the THERMAE project is the optimisation of the stack (figure 5); the thermal and mechanical properties of the material used to fabricate this component have a critical effect upon the performance of the device.

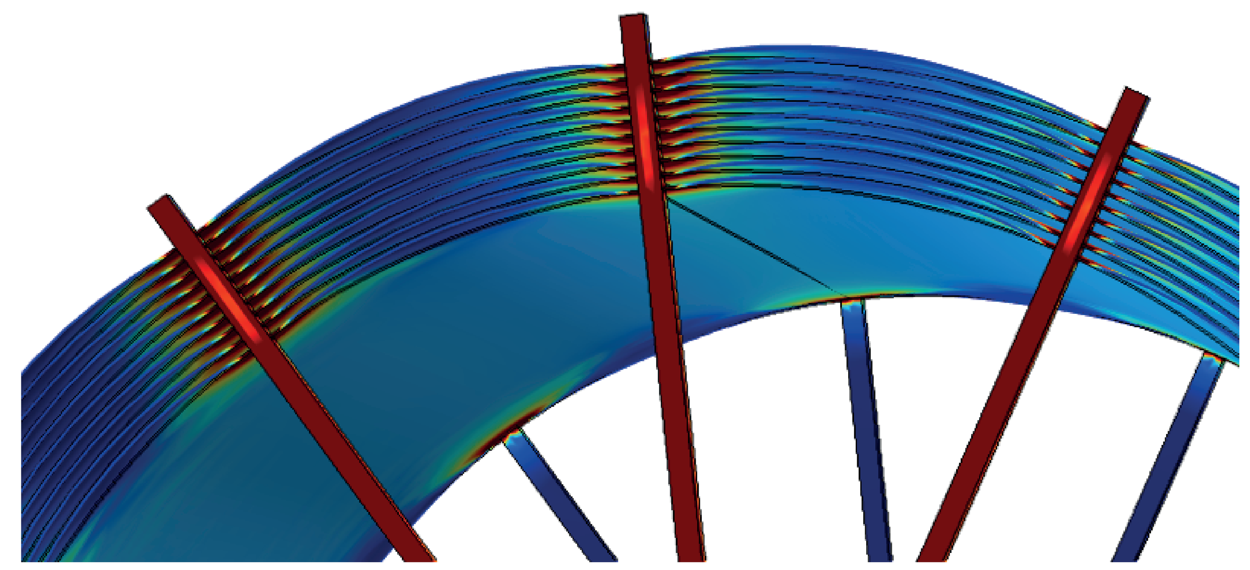
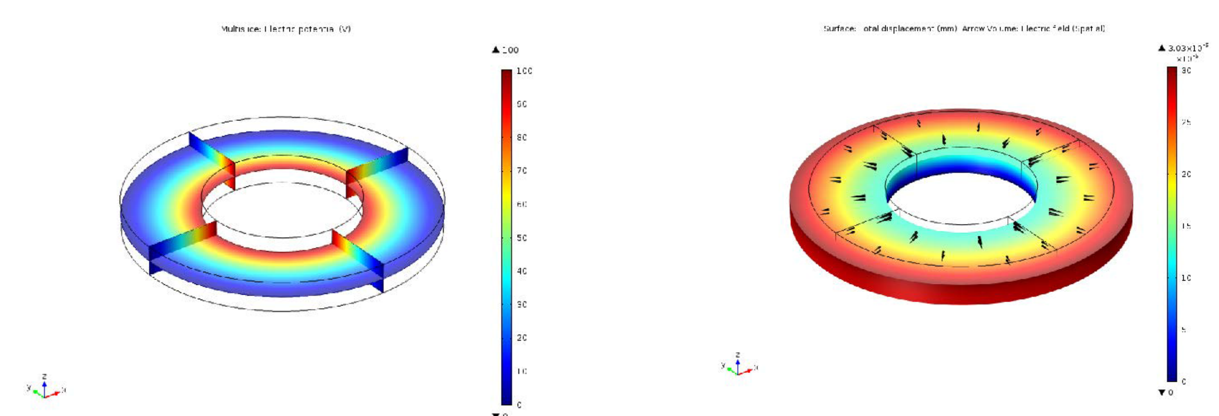


Figure 6. - Deformation plot from COMSOL multiphysics analysis of a stainless steel stack with a temperature gradient of 300K applied.

Preliminary finite element investigations relating to the mechanical integrity of the stack (figure 6) illustrate the importance of the appropriate choice of materials and fabrication techniques in the design of this critical component. The material must have the correct thermal and mechanical properties, limiting heat flux through the stack, facilitating rapid heat transfer, possessing appropriate thermal capacity and structural integrity.



Harnessing the acoustic power generated by the device is a specific challenge; since energy density is a function of frequency, Piezoelectric transducers are favoured, enabling the device to be operated at a high frequency (500 - 700 Hz). Other mechanisms are being investigated in collaboration with other members of the NEMESIS energy harvesting team at the University of Bath (UK).

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