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Thermoacoustic energy harvesting

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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 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.

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1 An introduction to thermoacoustics

Thermoacoustics, as the name suggests, is a blend of two distinct disciplines; thermodynamics and acoustics. The field encompasses the thermo-fluid processes associated with the compression and rarefaction of the working gas as an acoustic wave propagates through a set of closely stacked plates in a thermoacoustic device. Figure 1 (a) shows a schematic of a thermoacoustic energy harvester fig 1 (b) shows the way in which an elemental parcel of gas oscillating between the plates of a thermoacoustic stack in an acoustic wave. The figure shows the parcel being compressed at one extremity of its displacement and rarefied at the other, experiencing as it does so associated changes in enthalpy. As a result of the presence of the temperature gradient applied to the plates, heat is added to the parcel when it has been compressed and has elevated enthalpy. At the other end of its displacement heat is removed when it has lowered enthalpy following its rarefaction. This has the effect of amplifying an existing acoustic wave and is, in fact, capable of initiating one from the natural perturbations in the gas, given a sufficient temperature gradient.

Thermoacoustic devices have several particularly interesting characteristics which are of interest in the field of energy harvesting:

(i) Mechanical energy in the form of an acoustic wave is generated directly from a temperature gradient applied across a closely spaced stack of thin plates.

(ii) The mechanical (acoustic) energy can be used to move a piezoelectric membrane or linear alternator to produce electrical energy.

(iii) The working fluid, in which the acoustic wave is generated, is generally noble and/or inert eliminating the need for harmful, ozone depleting refrigerants.

(iv) The process involves no phase change and therefore is extremely versatile and capable of operating over a wide range of temperatures; this is in contrast to devices which operate using the vapour compression cycle and as such, are governed by the characteristics associated with an 'application specific' working fluid.

(v) Control systems can be proportional rather than binary. Binary control has inherent inefficiencies owing to overshoot and tolerance around the ideal temperature (compressors cutting in and out); proportional control allows the device to be run at the correct power output for a given load.

(vi) There are few moving parts, they are inherently simple devices and therefore offer the possibility of being both reliable and economic to produce.

(vii) They are able to operate in hostile or inaccessible working environments.

Figure 2 is a schematic representation of the way in which the temperature gradient amplifies the acoustic wave using the 'bucket chain' effect. It can be seen that associated with each displacement (in the x direction) there is an inertial component (dL) which must be overcome, a viscous resistance $(r_v dx)$, a compliance (dC) and associated thermal relaxation (r_κ/dx).

In energy harvesting, heat is supplied to the heat exchanger at the hot end of the stack and is used to generate a standing acoustic wave, this is in turn used to produce electrical energy using either a linear alternator or piezoelectric transducer. Since energy density is a function of frequency it is preferable to be able to drive these devices at high frequencies. The inertia of linear alternators limits their operating frequency, piezoelectric transducers offer an alternative mechanism for converting the acoustic energy to electrical energy; capable of operating at high frequencies as a result of their low inertia (mass) as investigated by Jensen and Raspet [1]. Nouh et al. [2] have explored mechanisms whereby the careful re-introduction of a small amount of mass to the system can be used to dynamically magnify the strain values attained when an acoustic wave is used to flex a piezoelectric transducer.

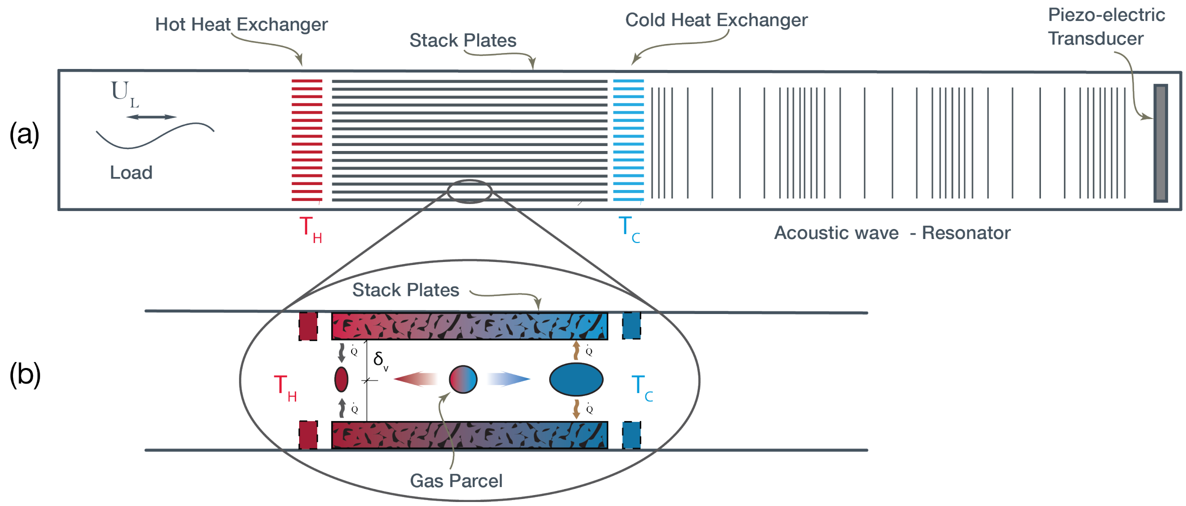

Figure 1: Schematic of a thermoacoustic energy harvester (a) and expanded view of plates (b).

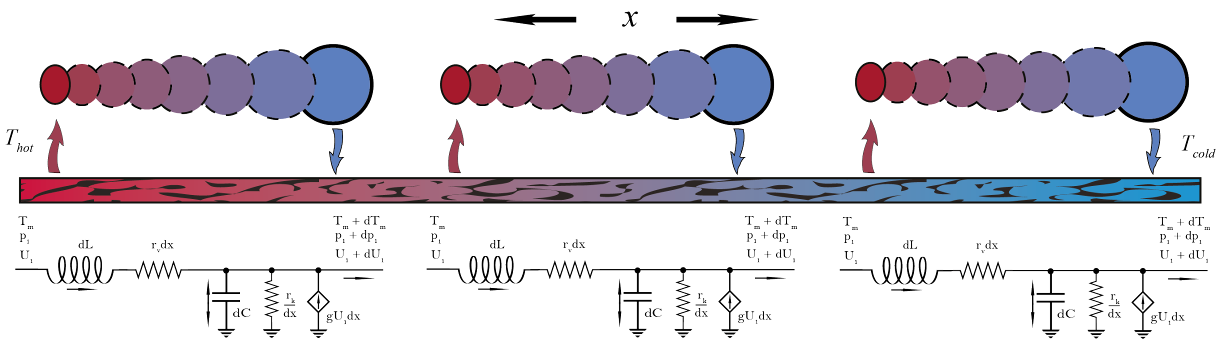

Figure 2: The bucket-chain effect.

1.1 Primary figure of merit in energy harvesting - Onset temperature gradient

The critical temperature gradient is the gradient through the length of the stack, in the direction of acoustic wave propagation, above which the device will function as a prime mover (or engine) and below which it will function as a refrigerator (or heat pump). The critical temperature gradient in the inviscid limit is given by (Swift [5]):

$$\nabla T_{critical} = \frac{\omega \, A \, |p_1|}{\rho_m \, c_p \, |U_1|}$$

where ω is the angular frequency of the wave, A is the cross sectional area between the plates, ρ_m is the mean density of the working fluid, c_p is the specific heat capacity of the working fluid at constant pressure, $|U_1|$ and $|p_1|$ are moduli of the 1st order complex volume flow rate and pressure respectively. The equation represents the enthalpy changes undergone by an elemental parcel of woking fluid as it is compressed and rarefied through an acoustic cycle.

In an energy harvesting context, a more useful figure of merit is the 'onset temperature gradient'. This is the temperature gradient at which the natural perturbations in the gas are amplified sufficiently to overcome the viscous and thermal attenuation illustrated in figure 2, producing an acoustic wave. Figure 3 shows the relationship between the critical temperature gradient and the onset gradient; minimising the difference in these gradients results in the lowest onset temperature for a given device.

The onset temperature gradient is dependent upon only two aditional variables, the position of the stack in the standing wave with respect to the pressure and velocity anti-nodes $(x - x_0)$, (viscous attenuation being greatest near a velocity anti-node) and the plate spacing (y_0) (thermal relaxation becoming the dominant loss at larger plate spacings). The coordinate system for the following calculation is defined in figure 4.

The hydraulic radius r_h is defined as the maximum distance a parcel of fluid can be from a boundary for a given geometry, for a parallel plate stack this is given by;

$$r_h = \frac{A}{\Pi} = y_0$$

where A is the area of the plate and Π is the length of its perimeter, which in the case of a parallel plate arrangement yields y_0.

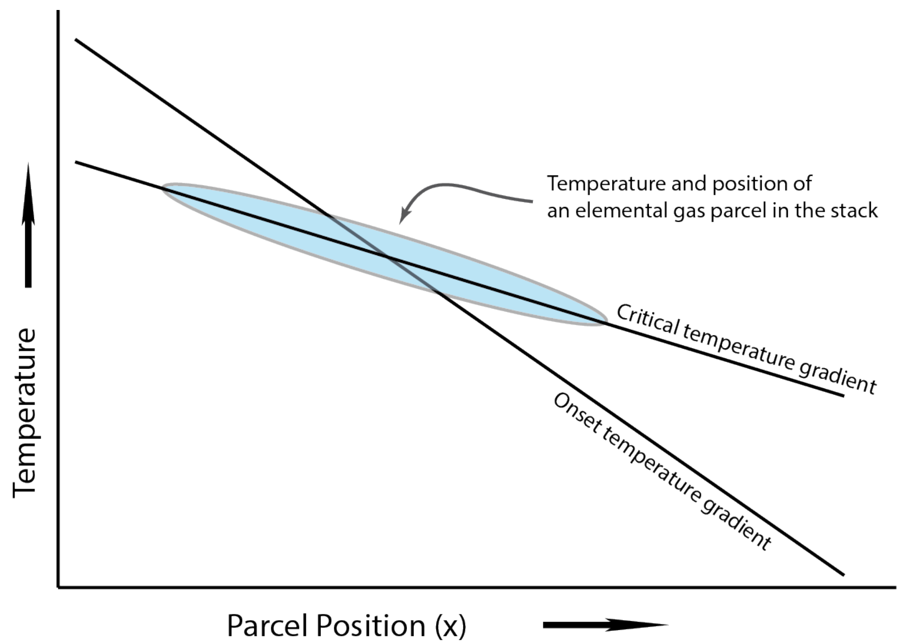

Figure 3: Onset and critical temperature gradients for a thermoacoustic engine.

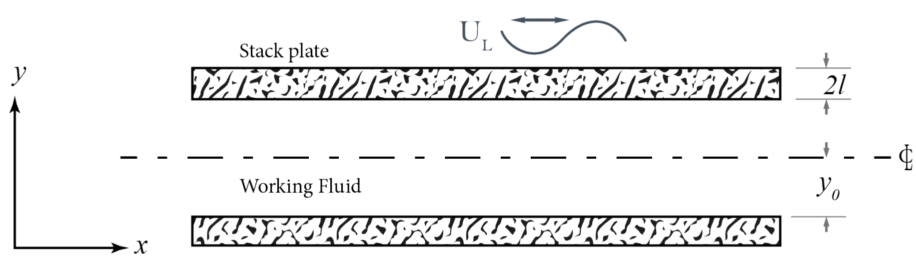

Figure 4: Coordinate system for parallel plate stack.

According to Yu and Jaworski [6], the critical onset temperature gradient is given by;

$$\Theta_{crit} = 2\pi \frac{(\mathrm{Im}[-f_v]/|1 - f_v|^2) + (\gamma - 1)\mathrm{Im}[-f_v]tan^2[2\pi(x - x_0)/\lambda]}{\mathrm{Im}-(f_k - f_v)/[1 - f_v)(1 - \sigma)]tan[2\pi(x - x_0)/\lambda]} \tag{1}$$

where from Swift [5, p. 88], Nikolaus Rott's dissipation function [4] (viscous, subscript v and thermal, subscript κ) h for a parallel plate stack is given by;

$$h = \frac{cosh[(1+i)y/\delta]}{cosh(1+i)y_0/\delta} \tag{2}$$

and its spacial average f by;

$$f = \frac{tanh[(1+i)y_0/\delta]}{(1+i)y_0/\delta} \tag{3}$$

and where λ is the characteristic wavelength of the device, σ is the Prandtl number of the working fluid and γ is its ratio of specific heat capacities, δ is either the thermal or viscous penetration depth as required which are given by;

$$\delta_\kappa = \sqrt{2k/\omega\rho c_p} = \sqrt{2\kappa/\omega} \quad \text{and} \quad \delta_v = \sqrt{2\mu/\omega\rho} = \sqrt{2\nu/\omega} \tag{4}$$

Yu and Jaworski [6] numerically evaluated equation 1 for a range of plate spacings (expressed as r_h/δ) in a parallel plate stack and at several positions in the standing wave. It was found that the lowest onset temperature occurs at a plate spacing of $y_0/\delta = 1.5$ and when the stack was placed at $5\lambda/32$ from a velocity antinode. Using Helium as a working fluid at atmospheric pressure, critical onset temperature differences below 20K were predicted. Nouh et al. [3] have carried out a numerical evaluation of the onset temperature using SPICE^{TM} software, modelling the processes in the stack using an AC circuit analogy (commonly used to model thermaocoustic processes) which appear to confirm the results of Yu and Jaworski [6]. It is intended to undertake a similar analysis, adjusted for the particular operating conditions and geometry of the proposed test rig described below.

1.2 Thermoacoustic test rig

In an attempt to provide some empirical validation for these numerical results, a test rig is currently under construction which will allow a thermoacoustic stack to be mounted on a lead screw and moved axially in an acoustic wave by means of a stepper motor. Figure 5 shows a schematic of the test rig and figure 6 shows the pressure and velocity nodes in a standing wave (green representing areas of high pressure and blue, low pressure). In the initial study it is proposed that an acoustic standing wave be driven by means of a linear actuator, temperature sensors will be placed at either end of the stack to record the rate at which enthalpy is pumped by the stack at a range of different positions in the wave and at different hydraulic radii.

It is proposed that once this 'proof of concept' rig has been successfully evaluated, that hot and ambient heat exchangers be included at either end of the stack. This will allow the device to function as a prime-mover and equation 1 to be evaluated taking into account non-linear effects which are difficult to evaluate numerically.

2 Stack design and fabrication

The heart of any standing wave thermoacoustic device is the stack, consequently, the design and fabrication of thermoacoustic stacks is an important part of this project. Figure 7 shows a method of accurately spacing the plates which has been designed whereby spacer plates of low melting point alloy are accurately pierced and interleaved with the plate material (in this case a carbon fibre pre-preg) and placed in a mould. During the autoclaving process the excess resin from the pre-preg fills the voids in the spacer plates left from the piercings. When cured the assembly is heated and the molten alloy spun out centrifugally, leaving resin spacer posts between the layers as seen in figure 8. The process has been tested using a patternmaker's sheet wax in place of the alloy and a section of stack successfully produced giving confidence that the procedure is sound and offers a practical way to fabricate thermoacoustic stacks accurately.

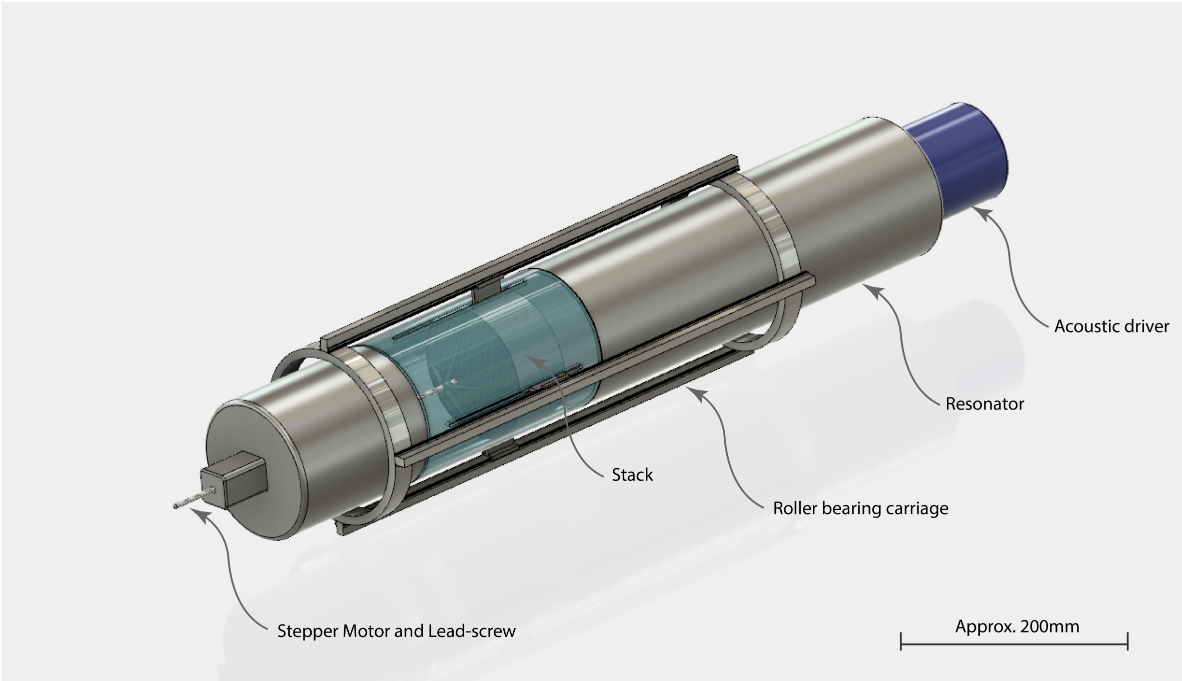

Figure 5: Test rig currently under construction to determine optimum stack position

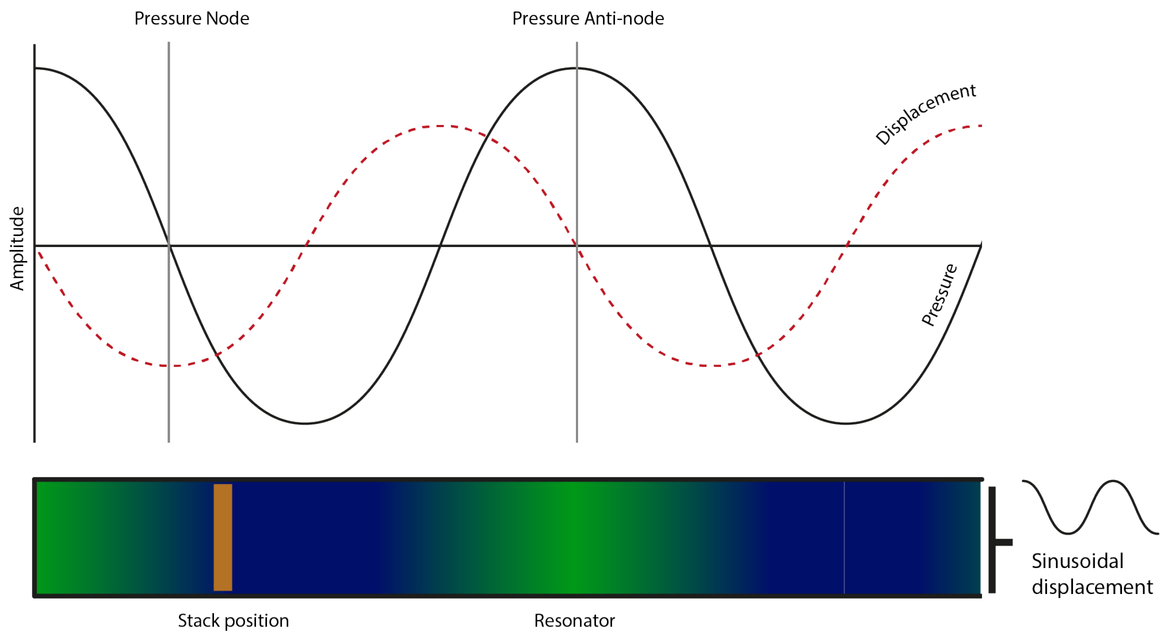

Figure 6: Pressure and velocity nodes in an ideal standing wave 2π out of phase.

The spacer plates are $250\mu m$ in thickness which corresponds to a r_h/δ_v ratio close to unity, near the ideal value predicted by the numerical analysis carried out by Yu and Jaworski [6].

A COMSOL model of a concentric stack is shown in figure 9 which evaluates the thermal stresses and potential subsequent deformation of the plates when subjected to a temperature gradient of 300K. Figure 9 shows the deformation of the outer 10 plates only when they are constrained by the support webs as a result of the disparity in the radial and circumferential strains. Far less deformation occurs in the parallel

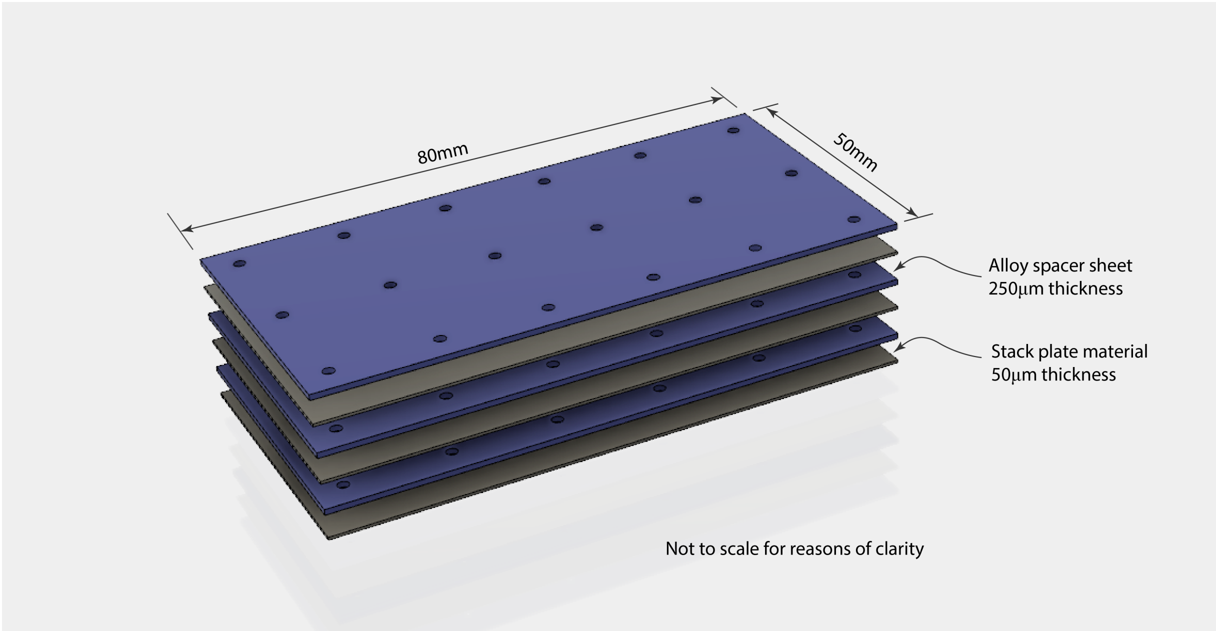

Figure 7: Low melting point alloy spacer plates pierced and interleaved with stack plate material.

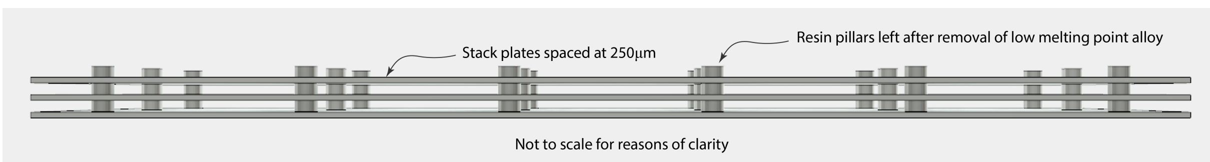

Figure 8: Resin pillars act as spacers following removal of the low melting point alloy.

plate stack proposed (shown in figure 10) provided the support structure surrounding the plates is of the same material so that there is no disparity between the various thermal expansions. Unfortunately this arrangement does not benefit from the pre-stressing of the plates that the coiling of the foils in the coiled stack, this increases the stiffness required of these thin foils ($50\mu m$). The thermal and structural analysis of various stack configurations is a key focus since in attempting to optimise the stack for a particular hydraulic radius for a low onset temperature gradient and blockage ratio (maximising the free passage of the wave through the stack) the plates must also exhibit sufficient stiffness and thermal capacity for a given thickness.

Anisotropy of thermal properties in the plates.

It is hoped that the analyses presented above will underpin a successful stack design; one in which a measure of anisotropy of the thermal properties can be introduced through the innovative use of materials which favour heat transfer into the plates (in the y direction), hindering leakage of heat axially through the plate (in the x direction). Defining the thermal properties of the plates as tensors represented by vectors in COMSOL will allow parametric sweeps to be made of a range of values. The most promising candidates for such materials appear to be fibre composites in which tow orientations can significantly influence the materials' thermal properties. Other possibilities are being explored such as etched films and nano-structures.

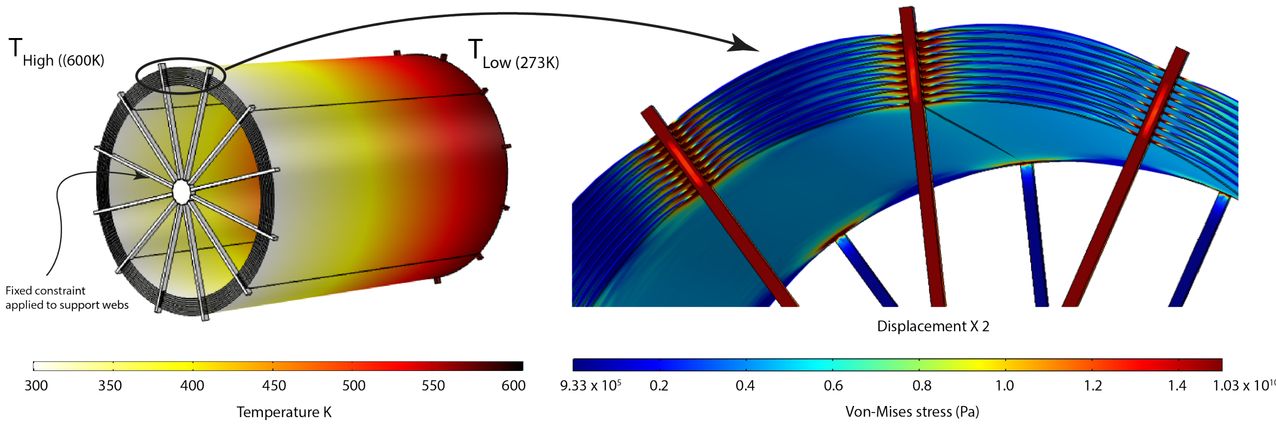

Figure 9: Finite element analysis of a concentric stack showing deformation of the plates (X2)

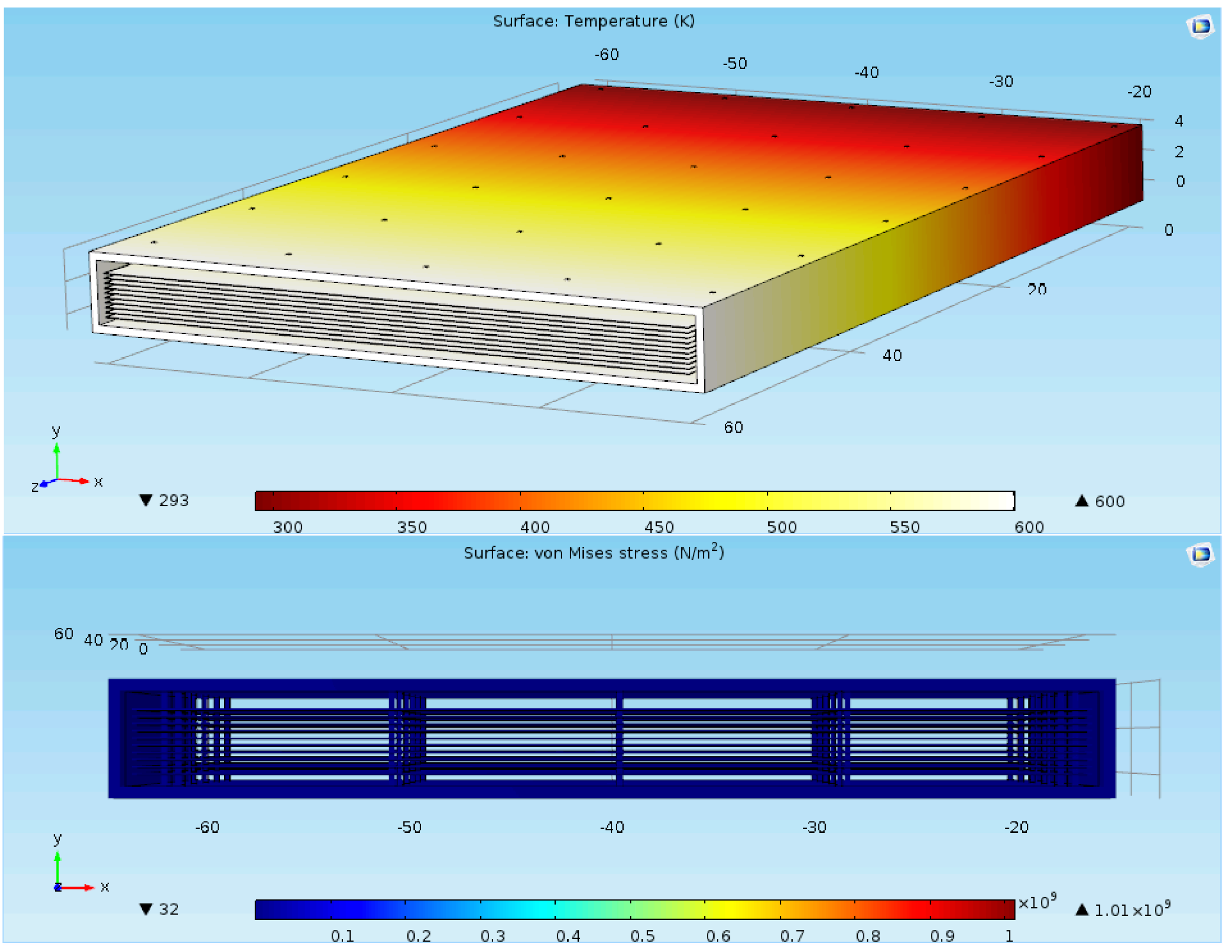

Figure 10: Finite element analysis of a parallel plate stack

Summary

This paper has provided an overview of thermoacoustic research being undertaken for energy harvesting applications. The rationale behind the proposed thermoacoustic test rig has been explained as a way of validating the theoretical 'sweet spot' for positioning the thermoacoustic stack in the wave (as predicted by the numerical evaluation of the equation for critical onset temperature gradient). Initial efforts will measure the rate of change in temperature difference across the stack as the result of an applied standing wave and the research will progress to producing a standing wave by introducing heat exchangers to the apparatus. An innovative method for accurately fabricating parallel plate thermoacoustic stacks has been presented and the potential of this method in tailoring the thermal properties of the stack. Aspects to be considered are the potential for introducing a degree of anisotropy to the thermal properties which may lead to limiting leakage of heat along the temperature gradient in the stack and enhancing efficiency. A finite element analysis of the thermal stresses in two stack arrangements were discussed to examine the thermal distortion of the stack and how it may be mitigated in a real device. Future work will explore the development of a fully functioning thermoacoustic device that is capable of harvesting low-grade waste heat and producing electrical energy using piezoelectric a transducer.

Acknowledgements

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