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Design and Testing of Rapid Prototyped Stacks for Thermoacoustic Applications

Ryan Lampe
Mechanical Engineering
Milwaukee School of Engineering
1025 N. Broadway
Milwaukee, Wisconsin 53202 USA

Faculty Advisor: Dr. Subha Kumpaty

Abstract

The purpose of this research is to explore the use of rapid prototyping to create a host of thermoacoustic stacks and test their efficiency. Thermoacoustic devices can either use a temperature gradient to produce acoustic waves or use acoustic waves to produce a temperature gradient. The stack is the main component of thermoacoustic devices that enables this phenomenon. The efficiency of the stack can be affected by a variety of factors including its length, spacing, and general geometry. Due to the difficulty of making stacks by hand, prior research has not been able to explore the effects of these various factors in great detail. Using specific rapid prototyping technology called Selective Laser Sintering, several different stack arrays were attempted, including square tubes, parallel plates, and a pin array. The build layers in the rapid prototyping process corresponded well to the layers of the parallel plates. After a couple attempts, several pin stacks were also successfully fabricated. One square tube stack was attempted but was not successful, and because of the resolution of the rapid prototyping machine used, was not pursued further. In order to test and compare the successfully fabricated stacks, a heat pump consisting of a closed tube and a compression driver was constructed. Using two thermocouples the temperature on either end of the stack was then recorded. For a 12-W amplifier, with a 130mV peak-to-peak of the sine wave audio signal, a drop of 4.3 C was observed across a parallel plate stack which is significant for such devices. This work contributes to the optimum design of stacks for thermoacoustic applications using rapid prototyping as the viable means for fabrication.
Keywords: Thermoacoustic, Stack, Rapid Prototyping

1. Introduction

Just as the word implies, thermoacoustics is the combination of heat and sound. Thermoacoustic devices are capable of either taking a temperature gradient and producing acoustic waves or taking acoustic waves and producing a temperature gradient. When pressure waves are being created it is a thermoacoustic engine and when a temperature gradient is being created it is a thermoacoustic heat pump[1]. Thermoacoustics is very promising, and is currently being researched as a means of refrigeration, natural gas liquefaction, gas separation and a variety of other purposes. Although the analysis of a thermoacoustic device can be very involved the general makeup and parts used can be relatively simple and inexpensive. It is for this reason of simplicity that thermoacoustic devices are largely being pursued. Starting out, one of the biggest challenge thermoacoustic devices faced was efficiency. However, as more research is done and greater understanding of how thermoacoustics works is achieved, these devices have continued to become more efficient.

1.1. thermoacoustic heat pump

The three main components of a thermoacoustic heat pump are a closed tube, an acoustic wave source, and a stack. As seen in Figure 1, the acoustic waves will enter through the open end of the tube and interact with the stack resulting in a temperature gradient. In order to utilize the temperature gradient heat exchangers would be added to either end of the stack depending on the use of the device.

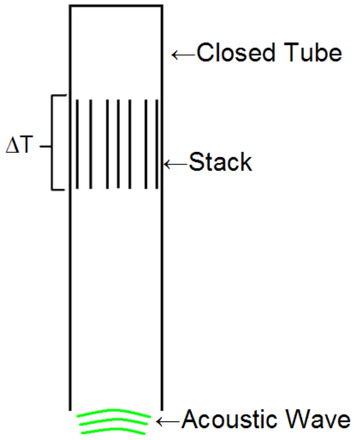

Figure 1. Thermoacoustic heat pump.

1.2. stack

The stack is the key component of the thermoacoustic device that enables this thermal gradient to occur. It is a porous structure that allows the acoustic waves to move through. An acoustic wave will cause pressure, temperature and position oscillations in a gas. When in a closed tube these oscillations will be such that when the gas is at one end of the stack it will have a higher temperature and the stack will absorb heat, when the gas is at the other end it will be cooler and the stack will give up heat resulting in a temperature gradient[2]. The efficiency of the stack is affected by a variety of factors including its length, spacing, location and general geometry.

2. Methodology

2.1. stack design

The general geometric structure of the stack has a significant effect on the efficiency of the stack. Two important factors are the viscous effects and the thermal penetration depth. Immediately surrounding the stack material there are viscous effects not allowing the gas to move back and forth. Adjacent to that is the thermoacoustic area which is doing the work. By changing the general geometry of the stack the ratio of viscous area to thermoacoustic area is changed[3]. Common designs include square tubes, parallel plates, spiral and pins, as seen in Figure 2.

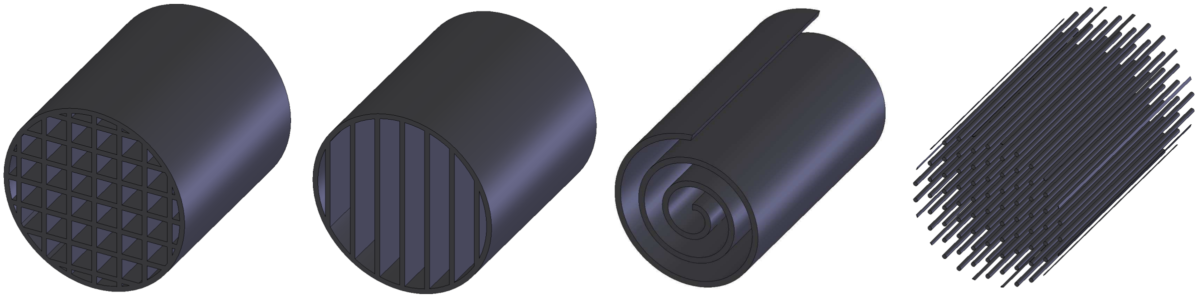
Square Tubes Parallel Plates Spiral Pins

Figure 2. Common stack designs.

2.1.1. common methods for fabricating stacks

One common way of making a stack is to simply adapt an already existing material. These materials generally have tube geometry with openings on the order of 1.00 mm. One example is the ceramic material inside catalytic converters[4]. Another example is commercially available metal honey comb[5].

A more labor intensive method is to fabricate them by hand. This is often done by rolling up a thin material to make a spiral stack. Using spacers or radial ribs at the ends, the desired spacing is maintained[6]. This method generally results in more efficient stacks because the stacks can be custom tailored to the device it is being used in.

2.1.2. optimal spacing

For any particular stack design there will be an optimal spacing of the material. Just as with the general design the optimal spacing is dependent on viscous effects and thermal penetration depth. If the material is too close together, viscous effects hamper the motion of the gas. If the material is too far apart, then there is an excess amount of gas between the stack material that is not able to transfer heat to and from the stack. For a simple parallel plate design the optimal spacing should be 3 thermal penetration depths[7]. The thermal penetration depth, δ_k, as defined in equation (1), is dependent on the frequency, f, of the standing wave and the thermal conductivity, κ, density, ρ, and the isobaric specific heat per unit mass, c_p, of the gas[8].

$$\delta_k = \sqrt{\frac{\kappa}{\pi f \rho c_p}} \tag{1}$$

With no stack in place the resonant frequency for the experimental setup was found to be close to 300 Hz. Assuming this does not greatly change with the stack in place, using equation (1) and 3 thermal penetration depths the optimal parallel plate spacing for this setup should be 0.44 mm. This was calculated using air properties at 300K.

2.2. rapid prototyping

Rapid prototyping is a method of fabrication that is able to construct complex geometries by building them in layers. The various rapid prototyping machines use a variety of methods and materials but the general process of building it in layers is the same. However, there is significant difference in the strengths and limitations of the different rapid prototyping machines. This is a result of the different materials used, the method used, and the limitations of the machine, on the size of the parts made and the detail it can achieve.

2.2.1. selective laser sintering

The rapid prototyping machine used in this research was the Selective Laser Sintering (SLS) Sinterstation 2500Plus. In SLS a thin layer of powder is fused together using a CO_2 laser, as seen in Figure 3. That layer is on a platform which then lowers. Another layer of powder is then spread over the previous and the next part area is fused together. Then the platform lowers again and gradually the desired part is built. The SLS was chosen for the strength of the parts it makes along with the nylon powder that can be used. The machine used builds in 0.1 mm thick layers using a 0.25 mm diameter laser[9]

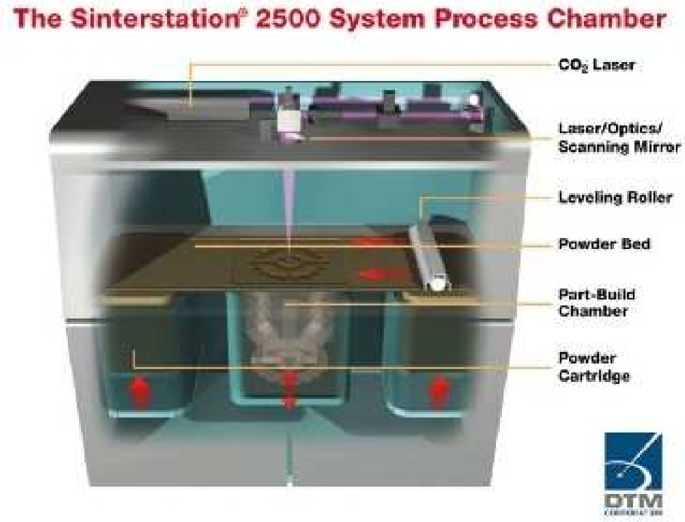

Figure 3. SLS machine[10].

2.2.2. sls limit

After attempting to construct the first three stacks, it was decided to determine the resolution limit of the SLS machine before attempting more stacks. In order to find the minimal spacing possible a simple cube was constructed with two sides open. Parallel plates were then constructed that went from 0.5 mm apart to 2.0 mm apart, increasing by 0.1 mm increments. Since the part is built in layers the direction of the rapid prototyping layers relative to the parallel plates was also tested by having the cube orientated several different ways during the building.

Figure 4. Left and center, solidworks images of test cube; right, photo of one test cube.

The best result was with the plates oriented parallel to the layers used in the rapid prototyping process. In this orientation the plates were open all the way down to the 0.5 mm spacing. In all the other orientations the plates could not be closer then 1.0 mm without fusing.

2.3. experimental setup

A thermoacoustic heat pump was constructed in order to test the functionality and efficiency of the different stacks. As seen in Figure 5 the heat pump consisted of a 1 inch diameter acrylic tube 12 inches long, an aluminum plug, a compression driver (usually used in public address systems), and the stack being tested[11]. In order to take measurements, two type T thermocouples and a voltmeter were used. The voltmeter was used to find the resonant frequency of the setup. In order to find the temperature gradient produced one thermocouple was located above the stack and the other was located below. For ease it was decided to use air as the working gas.

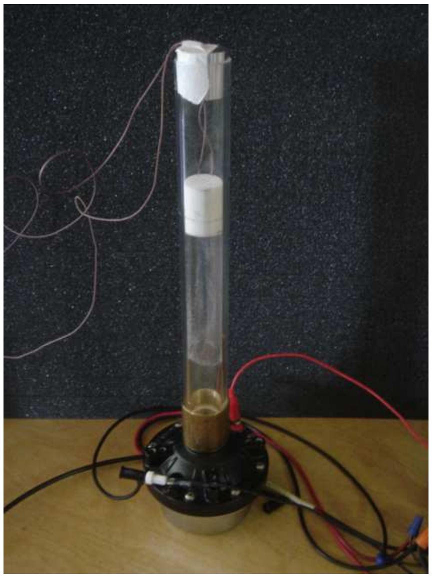

Figure 5. Thermoacoustic heat pump.

Seen in Figure 6, the equipment used from left to right was a Hewlett Packard 34970A Data Acquisition/Switch Unit, a Hewlett Packard 33120A 15 MHz Function/Arbitrary Waveform Generator, the heat pump, a Hewlett Packard 54607A Oscilloscope, a Kemo 12W amplifier (small black box in front of Oscilloscope), and a Lodestar 8207 power supply. Also used was a computer (not pictured).

Figure 6. Experimental setup.

3. Results

3.1 stack fabrication

The three stack designs this research focused on were the square tubes, parallel plates, and pin stack. Using the optimal spacing of 0.44 for parallel plates as a reference point, it was decided to try and achieve a spacing of 0.5 mm in the stacks.

3.1.1. parallel plates stack

The parallel plate geometry lent itself very well to the SLS. The first parallel plate stack, designed with 0.5 mm spacing, attempted failed because the orientation of the stack during the build resulted in fused plates. After building the test cube, the subsequent stack, still designed with 0.5 mm spacing, were orientated properly and did not fuse.

After noticing slight warping in the plates a third parallel plate stack was designed with one cross plate to maintain the desired spacing. The cross plate did just what was intended and limited the warping.

3.1.2. pin stack

Several pin stacks were attempted. The first one was oriented with the pins going perpendicular to the build layers. This resulted in none of the pins holding together.

When oriented with the pins parallel to the build layers similarly to the parallel plates, the second two parallel pin stacks were partially successful. One pin stack was designed with the pins parallel to the direction of the stack. About half of the pins held together in this stack. The other was designed with the pins going across the stack. There were still some broken pins in this stack but far fewer.

Two last parallel pin stacks were designed with extra supports and slightly thicker pins. These stacks came out very successful, with almost all the pins intact. Additionally it would seem there are still improvements that could be made to the design of the pin stack. The pins that where missing in these final two stacks did not seem to be missing because they had broke, but that the machine had almost skipped them completely. This is likely a result of a pin layer not lining up well with any of the build layers. So, by very slightly changing some of the stack dimensions these pins might not have been lost.

3.1.2. square tubes stack

Prior to making the SLS test cube, one square tube stack was attempted. With the tubes oriented perpendicular to the build layers, the stack fused into one solid piece and was not tested in the heat pump. Because of its geometry and the limit of the SLS, this design could not have been fabricated with tubes smaller then 1.0 mm and was not pursued further.

3.2. functional stacks data

As seen in Table 1, of the stacks tested, the best results where obtained using the first parallel plate stack. Although the cross plate maintained the spacing and limited warping, it did not achieve the same temperature gradient. It is unclear if this is a result in the differences in the stacks themselves or in the setup, such as the thermocouple locations during testing.

The two partially successful pin stacks produced mild temperature gradients. The improved pin stack that remained almost entirely intact was able to produce a temperature gradient close to that of the parallel plate with the cross plate.

Table 1. comparison of the temperature gradient achieved by the different stacks using 130 mVPP output through a 12 W amplifier.

Stack	∆T (C)
Parallel Plate I	4.3
Parallel Plate II (Cross Plate)	3.9
Parallel Rods (Extra Supports)	3.7

Seen in Figure 7 is the graph from testing the first parallel plate stack. This particular data was taken using 275 Hz sine wave and 130 mV peak to peak output from the wave generator. After going through the amplifier the signal to the compression driver is on the order of 9 V peak to peak.

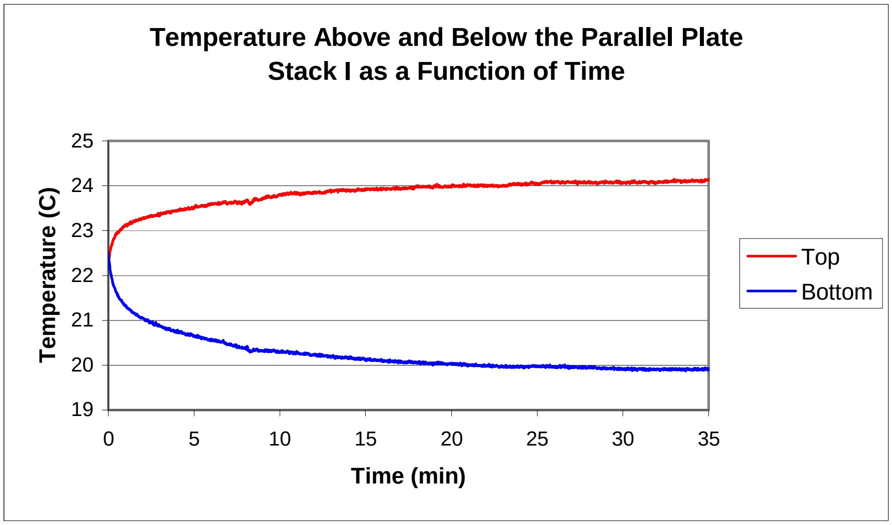

Figure 7. Temperature above and below the first parallel plate stack as a function of time.

3.2.1. increasing temperature gradient

The power input to the compression driver for these experiments was kept minimal. This was done for several reasons. First, the main goal in testing the stacks was to make sure they functioned and to get a baseline as to how their performance compared. Secondly, a very snug fit was provided at the top and bottom of the acrylic tube by the aluminum plug and the connector but, in order to ease the process of changing between stacks, neither end was sealed air tight. Lastly, at higher amplitudes different parts of the device would begin to resonate relatively loudly. If the device had been sealed air tight and held down, instead of being simply placed on the table, increasing power input would not have been an issue.

A larger temperature gradient for this particular setup could have easily been achieved by increasing the power input. For example, for the parallel plate stack that maintained a 4.3^{o}C temperature difference using a 130 mVPP output from the wave generator, a 5.4^{o}C temperature difference was obtained using a 170 mVPP output. Provided the compression driver can handle it, a larger amplifier could have simply been used. If the device was sealed air tight different working gases such as helium could have also been used.

4. Conclusion

Using rapid prototyping several functional thermoacoustic stacks were fabricated. Of the stack designs tested the parallel plate was best suited to being fabricated with the SLS, able to achieve 0.5 mm spacing, and provided the largest temperature gradients. Pin stacks were also able to be fabricated and were able to achieve a temperature gradient slightly lower then that of the parallel plates. Square tube stacks can be fabricated but to keep from fusing the tubes would have to be larger then 1.0 mm.

The 0.5 mm spacing was the smallest attempted using the SLS, so it is not known at this point if the SLS can achieve closer spacing. Further research can be done to determine the closest possible spacing with the SLS for parallel plate stacks. There may also still be some very slight changes made to the pin stack that would ensure no pins are lost. Research can also be done into using the other rapid prototyping machines or techniques such as stereolithography which may have higher resolution.

Using rapid prototyping stacks could easily be fabricated varying in length, spacing, and either parallel plate or pin geometries. These stacks could then be systematically tested to compare experimental and theoretical results.

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