Final Report
FUNDAMENTAL STUDIES OF RADIAL WAVE THERMOACOUSTIC ENGINES

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by

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ABSTRACT

Our goal was to evaluate the influence of resonator geometry on thermoacoustic engine performance. Resonator geometry affects thermoacoustic heat transport and acoustic power generation, energy dissipation, and stack volume. Thermoacoustic engines placed in the first radial mode of a cylindrical resonator were studied in detail, and were compared with the more-developed plane wave resonator counterparts. A radial wave prime mover was constructed from use of our numerical model. Experimental results are that nonlinear generation of harmonics is considerably suppressed by the anharmonic radial wave resonator in comparison with a similar plane wave prime mover, and that the observed onset temperature for oscillation was in substantial agreement with model results. Short-stack-approximation results for radial and plane wave acoustic refrigerators indicate the plane wave geometry produces slightly better overall refrigerators when maximizing the coefficient of performance and cooling capacity together, though one radial geometry produces greater cooling capacity when coefficient of performance is not of central importance. The numerical model was used to evaluate a plane wave heat-driven sound source on a radial wave acoustic refrigerator. The optimized hybrid had an overall efficiency of 20%, and the refrigerator coefficient of performance was 25% Carnot.

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1. Project Description

This work has been on the influence of geometry on thermoacoustic engine and refrigerator performance (in close collaboration with Richard Raspet, Henry E. Bass, and students Jay Lightfoot and Jim Belcher, University of Mississippi). Earlier efforts indicated that proper choice of stack pore geometry could improve engine performance.[1,2] We now know that the improvement is due to an increase of the ratio of productive to dissipative volumes within a given pore.[2,3] The goal of this contract was to evaluate the influence of resonator geometry on the performance of thermoacoustic engines, and the accompanying influence on thermoacoustic heat transport, acoustic power generation from heat, energy dissipation, and stack volume. The first radial mode of a cylindrical resonator was studied in detail as it differs substantially from the more developed plane wave resonator.[4] Figure 1 shows a rather generic view of a resonator with sloping walls and with variable plate spacing in the thermoacoustic elements. The radial wave example (see Figure 2) is a special case of a general class of resonators and engines with arbitrary geometry.[5]

Variable stack plate spacing can ensure optimal thermal contact of the gas and solid, and can reduces losses due to kinetic energy dissipation. Likewise, the locations of maximum thermoacoustic power generation, and minimum potential and kinetic energy dissipation can be different in resonators with varying cross sectional area. Nonlinear generation of higher harmonics is generally not resonance enhanced since the modes are anharmonic. The price to be paid in performance of the variable plate spacing, variable resonator geometry is the possible reduction in resonator cross sectional area at the stack location since the magnitude of heat and work flow by the stack is directly proportional to cross sectional area.

Figure 1 depicts a rather generic view of a variable plate spacing, variable resonator geometry acoustic refrigerator. Stack plate spacing is wider at the hot end and narrower at the cold end to match the temperature dependence of the thermal boundary layer thickness to optimize refrigerator performance. A specific example of a variable resonator geometry is the radial mode of a cylindrical resonator. Figure 2 shows the likely arrangement for radial wave thermoacoustics. The largest portion of our efforts have been to evaluate the performance of parallel plate stacks in radial wave resonators, and to compare with plane wave resonator results.

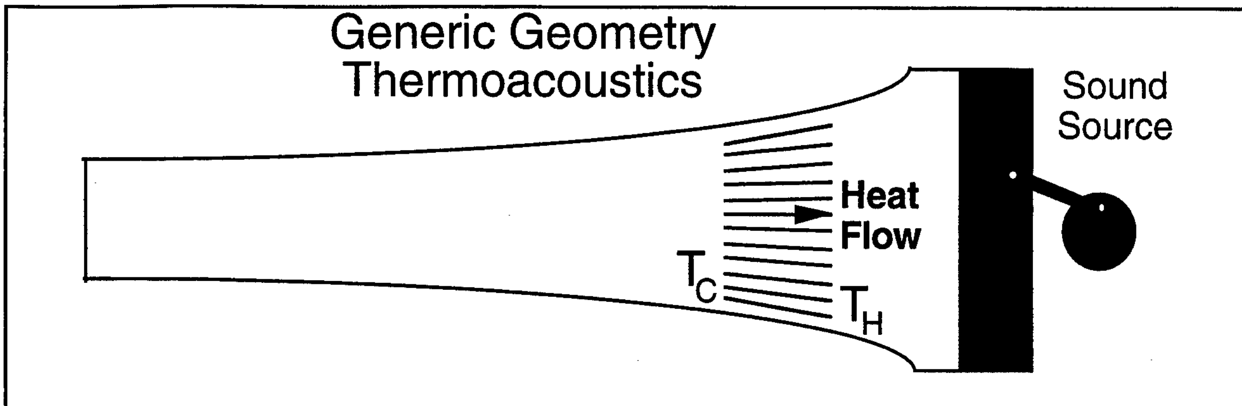

Figure 1. Generic geometry thermoacoustic engine.

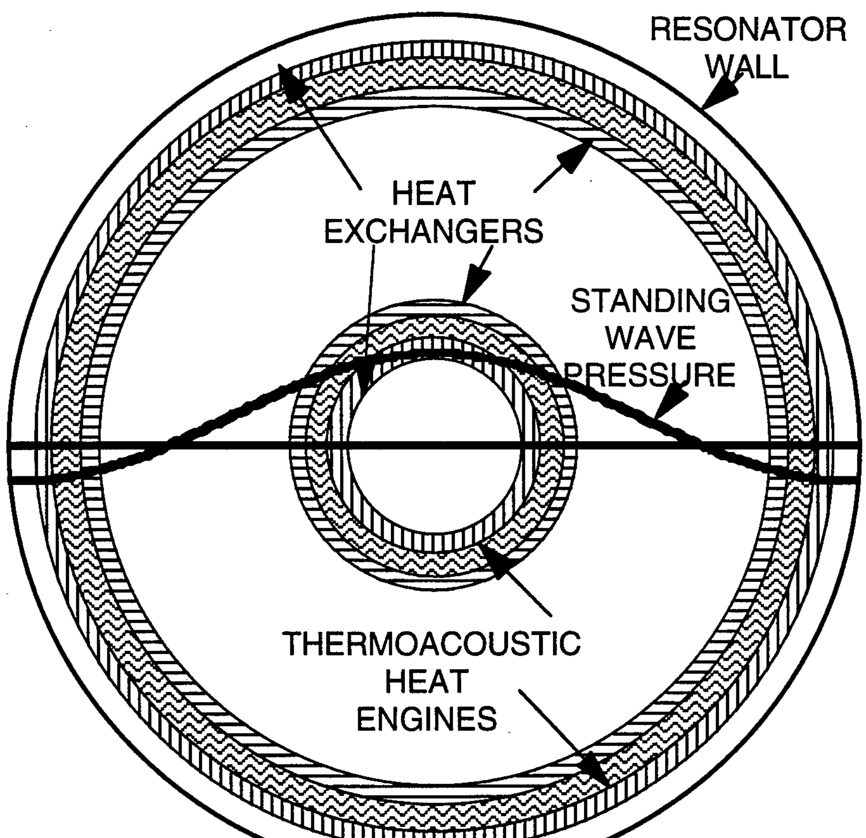

Figure 2. Geometry of the radial wave thermoacoustic engine. The inner and/or outer combination of heat exchangers and thermoacoustic engines may be used in an application.

An absolutely essential part of our work has been to compare thermoacoustic engine performance in radial and plane wave resonators. We devised comparison criteria[4] for this purpose. Figure 3 illustrates the plane and radial wave resonator geometry. The same resonator was considered for both geometries. The radial inner and outer stacks are considerably different due to the difference from the resonator center, though the plane wave stacks are identical. We found that the radial wave outer stack was similar to a plane wave stack though the radial inner stack was quite different, a result that is reasonable because cylindrical spreading of acoustic waves is most evident near the resonator center.

Let us consider why we might expect radial wave thermoacoustic engines to be different from their plane wave counterparts. A comparison of basic plane and radial resonator properties relevant to thermoacoustics are shown in Fig. 4. The horizontal axis indicates relative position in the resonator for the coordinates in Fig. 3. For example, the origin coincides with the resonator center for the radial case, and with the location $z=0$ in the plane wave case. Plane wave properties are dashed lines and radial are solid thick lines. A course qualitative assessment of the figure shows that the locations of maxima and minima are different for the two geometries. The upper panel shows the pressure modes. The second panel shows regions where prime mover or refrigerator operation are possible for an inviscid gas (the mean critical temperature gradient).[6] Both geometries have refrigerator operation when the stack temperature gradient and stack position in the resonator are in the refrigerator region. The Radial Refrig region corresponds to radial geometry refrigeration, and plane wave geometry prime mover. Likewise, the Plane Refrig region corresponds to radial prime mover. Both geometries have prime mover operation in the Prime Mover Region. The third panel is a figure of merit for the resonator, defined as the ratio of thermoacoustic gain divided by kinetic energy loss, (simply the product acoustic pressure and particle velocity divided by the square of particle velocity). The fourth panel is thermoacoustic gain as a function of position in the resonator. The relative maxima of thermoacoustic gain are reasonably close to the location one would place a refrigeration stack in the resonator(compare with Fig. 3); however, note that panel 3 shows this would not be desireable from the viewpoint of kinetic energy loss.

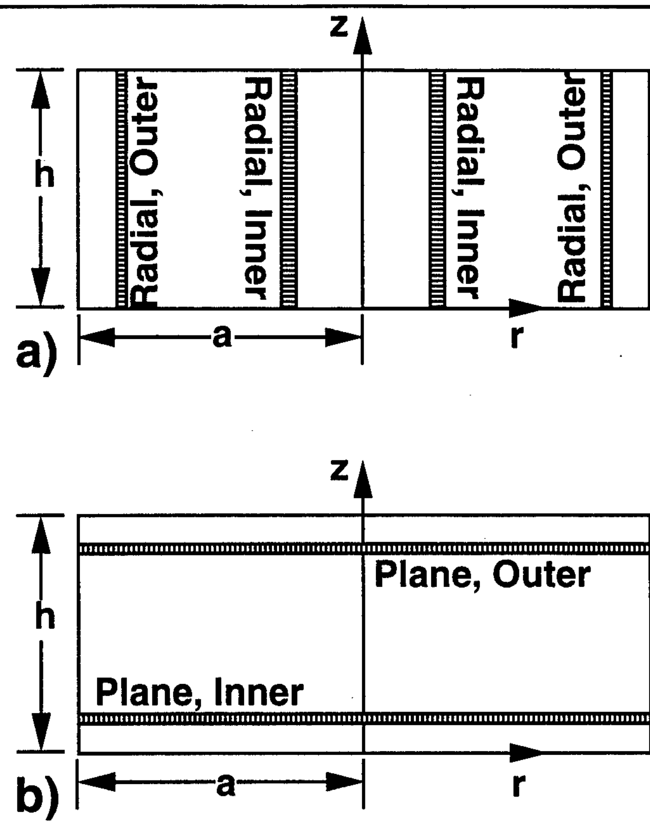

Figure 3. Coordinates and stack arrangments for comparison of thermoacoustic engine performance in radial and plane wave resonators. a) Radial wave stacks, b) plane wave stacks (redundant).

As we continue to evaluate why radial wave thermoacoustics might be different from plane wave thermoacoustics, let's consider operating points for acoustic refrigerators where all we care about is cooling capacity. Figure 5 illustrates such operating points. The vertical lines are stack locations in the resonators where thermoacoustic gain is maximized (i.e. cooling capacity). We follow up the vertical lines to their intersections with the figure of merit in panel 3 and note that radial inner, outer, and plane wave resonators all have very similar figures of merit. Continuing up to the second panel, note that radial resonators have higher critical temperature gradients than plane wave resonators by a factor of about 5/4. What can we say about the

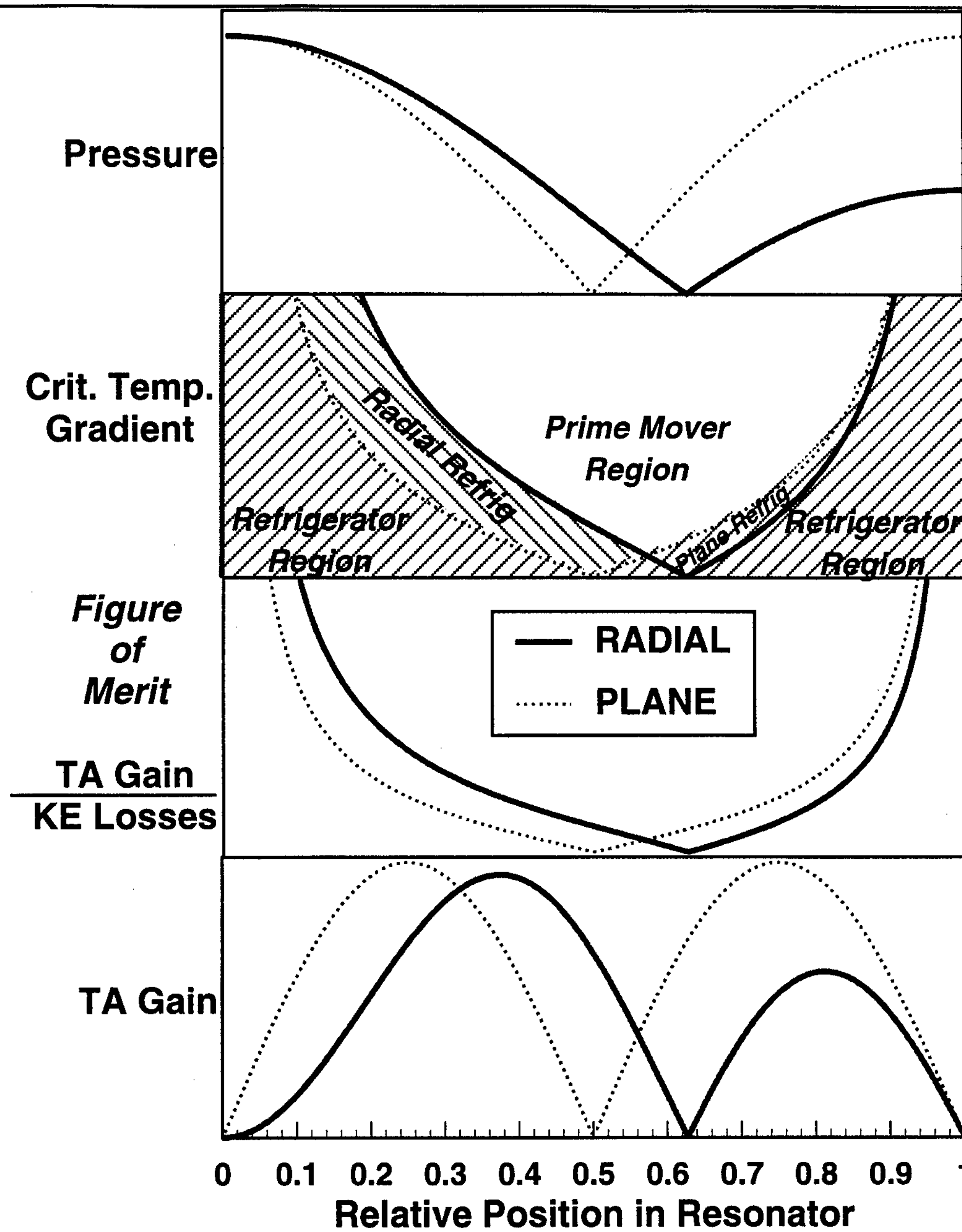

Figure 4. Radial and plane wave resonator properties. The solid thick lines are radial geometry results, and the dashes are plane results. The horizontal axis is either r/a for the radial case, or z/h for the plane case (see Fig. 3). The upper panel is the acoustic pressure magnitude, the second panel is a 'phase diagram' showing the critical temperature gradient that separates prime mover and refrigeration operation. The third panel displays a figure of merit given as the ratio of thermoacoustic gain to kinetic energy loss. The fourth panel is thermoacoustic gain. Likely stack locations would be near the relative maxima.

significance of this at our current level of rigor? Well, Swift defines a dimensionless ratio Γ as the actual stack temperature gradient to the critical temperature gradient. He shows that in the short stack approximation, cooling capacity is proportional to $(1 - \Gamma)$ and COP/COPc is proportional to Γ where COP is Coefficient of Performance and COPc is the Carnot (maximum) Coefficient of Performance. Thus for the same cooling capacity and COP/COPc, and hence the same Γ, a refrigerator stack would have a greater temperature gradient in the radial resonator.

One rarely would operate an acoustic refrigerator at the peak in the thermoacoustic gain because viscous losses significantly would reduce the COP. The short stack inviscid discussion in the previous paragraph completely left out gas viscosity and other realistic necessities for proper evaluation of thermoacoustic engines. Our research confirmed that radial and plane wave thermoacoustic engines are different and a summary of specific conclusions follow in the next section.

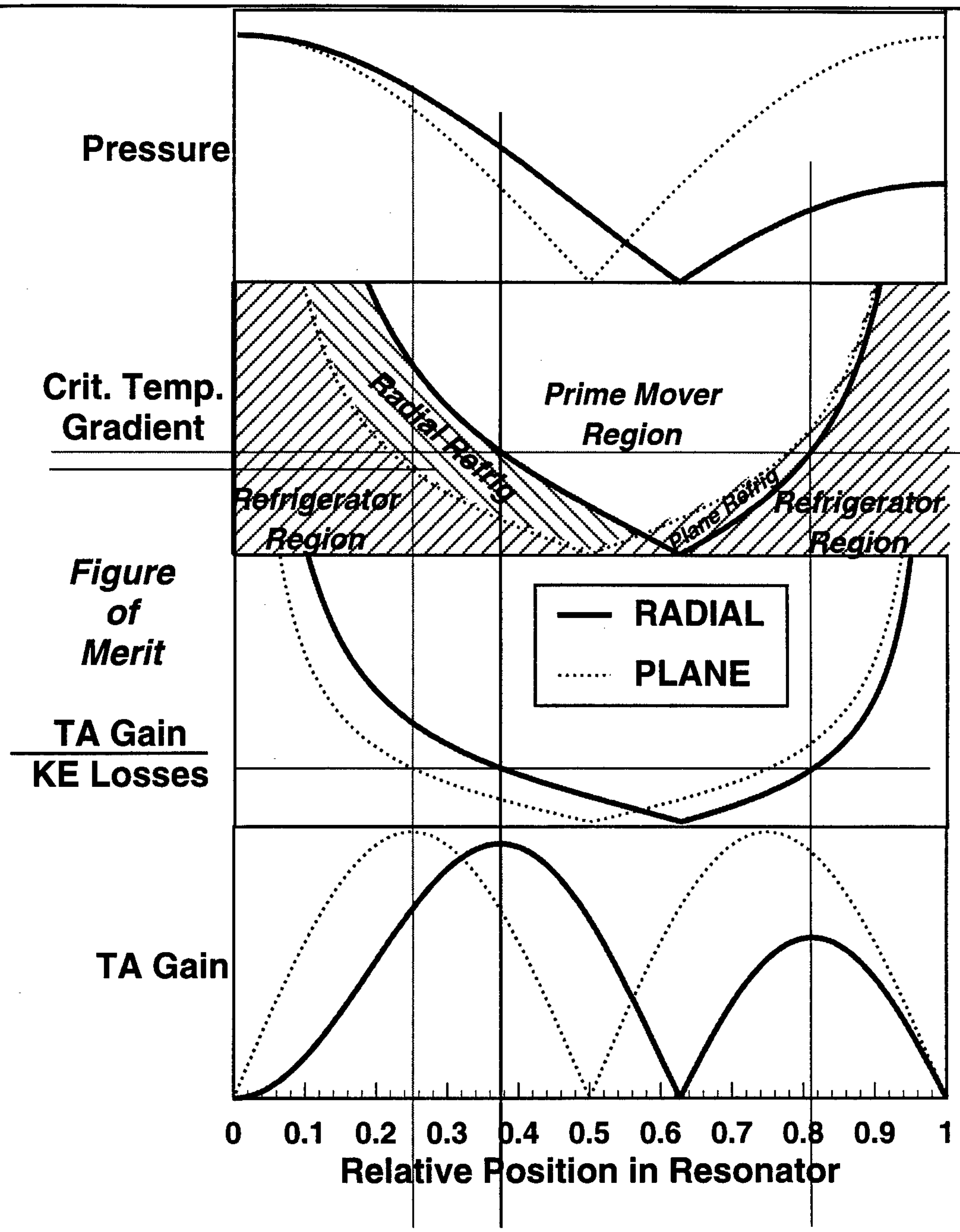

Figure 5. Same as Figure 4, though with lines indicating operating points at maximum thermoacoustic gain. For example, consider the vertical line through relative position 0.25. This corresponds to a relative maxima of thermacoustic gain for a plane wave engine. The critical temperature gradient for the plane wave resonator is less than that for the radial wave resonator as shown in the second panel, though the third panel shows that the merit ratio are very similar.

2. Approach taken.

Experience in both design and construction of thermoacoustic engines has indicated that models predict an upper limit for system performance. They are useful for considering many potential designs before the timely and costly process of construction begins, and they can enhance intuition about system performance when the model output is fully explored. A linear theoretical model was derived for predicting the first order acoustic and second order heat and work flow quantities for thermoacoustic heat engines, both for radial wave engines[4] and for rather arbitrary geometry engines and resonators.[5] The radial wave model was based on Swift's results[6] for this geometry, though we added generality to simplify numerical analysis.[4] The short stack analytical approximation was derived to compare engine performance in plane and radial wave resonators.[4] The numerical model predicts the performance of prime movers and refrigerators, and is useful for determining the complex eigenfrequency of prime movers below the onset of oscillation.[4] A key component of the model is a subroutine to stretch and shrink the physical lengths and plate spacings of the thermoacoustic elements to find designs that optimize the overall efficiency of heat-driven acoustic refrigerators.[7] Optimization of all thermoacoustic elements is an emerging concept that needs experimental verification, but looks promising.[8]

Modally enhanced nonlinear generation of harmonics has been observed in plane wave prime movers[9-11] and has been suppressed by insertion of large pencil-like elements into the resonator.[9] Radial modes are anharmonic in contrast to the nearly harmonic plane wave modes. The experimental effort at the University of Mississippi to develop a radial wave prime mover has been performed to evaluate the numerical model for radial wave thermoacoustic engines and to study nonlinear generation at high amplitude.

3. Specific work accomplished, 1 Oct 93 through 14 September 96.

Accomplishments are given in separate theory and experiment sections below. A brief summary will be given to introduce these sections. A numerical model was developed to evaluate radial wave refrigerators and prime movers. This model is similar in rigor to the Los Alamos model, DELTAE. The primary application was to evaluate a radial refrigerator driven by a plane wave prime mover. Boundary conditions were developed to connect the plane wave and radial wave resonators. An optimization routine was developed to assist in evaluation of many system configurations. This routine took an intuitively-designed heat-driven refrigerator and significantly improved the performance of the prime mover and refrigerator. The system designed by the routine was thoroughly evaluated as a reality check of the routine and as a means to improve on intuition for thermoacoustics. One particularly interesting result of the optimization routine was the prediction that the prime mover stack plate spacing should be narrower than the short stack approximation would suggest, because the dynamical temperature gradient that generates sound is considerably increased by narrowing the plate spacing.[7] This result was for a relatively low thermal conductivity stack (compared with a stainless steel stack) that had the temperature distribution strongly influenced by the acoustic wave and less influenced by stack thermal conductivity.

The radial wave prime mover at the University of Mississippi finally has gone into oscillation after considerable effort by Jay Lightfoot! We designed and built a hot end heat exchanger at DRI for the prime mover. Work is currently underway to compare prime mover performance predictions with measurements. The onset temperature for initial prime mover operation was measured and was 10 C above the theoretical estimate performed using the numerical model. This result is consistent with our previous work on plane wave prime movers. The measured onset temperature difference across the stack was 114 C.

3a. Theory

Only one key theoretical finding will be emphasized here. Others can be found in Secs. 4 and 5 below. The short stack approximation for radial waves was developed and was used along with the plane wave version to compare the theoretical performance of refrigerators in these geometries. Many assumptions were necessary to make the comparison.[6] Briefly, the acoustic refrigerator stacks were placed in the same resonator. An optimization routine was used to maximize Coefficient of Performance (COP) and cooling capacity together. Stack plate spacing, location in the resonator, and stack length were all free parameters in the optimization. A parameter, m, was used to signify the relative importance of COP. Large m indicates high emphasis on COP. The results of optimization are shown in Fig. 6. They indicate the plane wave geometry produces better overall refrigerators when maximizing the coefficient of performance and cooling capacity together, though one radial geometry produces greater cooling capacity when coefficient of performance is not of central importance. The cooling capacity of the radial inner stack was somewhat greater than that of the radial outer stack and the plane wave stack, though the COP of the radial inner stack was notably worse than either of the others.

As mentioned earlier, the radial outer stack is qualitatively similar to a plane wave stack. The radial inner stack performance seems to be limited by the need to make its radius large enough so that a reasonable amount of heat can be handled. Decreasing the stack radius moves the stack to a region of lower kinetic energy dissipation and thus improves the COP; however, cooling capacity is compromised.

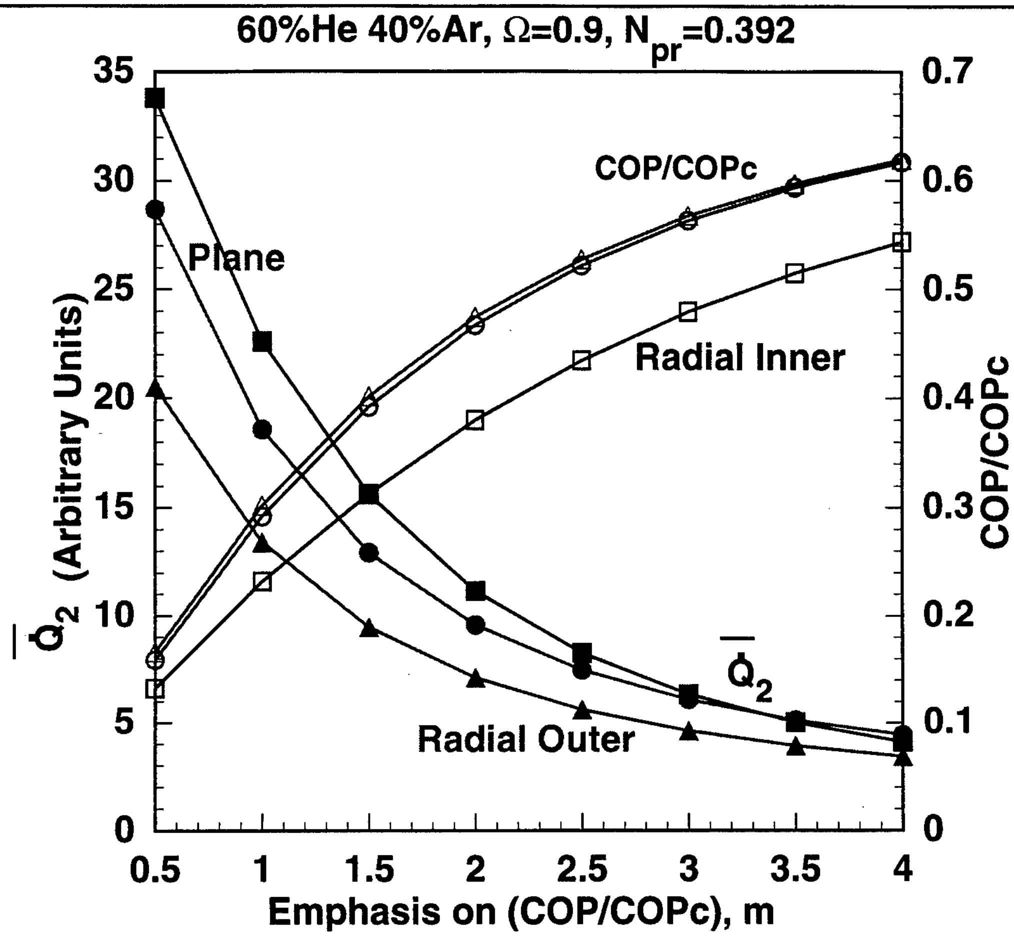

Figure 6. Cooling capacities and Coefficient of Performance ratios as a function of the emphasis, m, on Coefficient of Performance. Calculation points are shown by the symbols and the lines connect these points for viewing ease. Solid symbols are cooling capacity, squares refer to radial inner stacks, triangles to radial outer, and circles to plane stacks. *COP /COPc* nearly overlap for plane and radial outer. [From Fig. 7 of Ref. 4].

3b. Experiment

A radial wave prime mover was constructed from use of the developed theory and numerical model. Experimental results are that nonlinear generation of harmonics are considerably suppressed by the anharmonic radial wave resonator in comparison with a similar plane wave prime mover, and that the observed onset temperature for oscillation was in substantial agreement with model results.

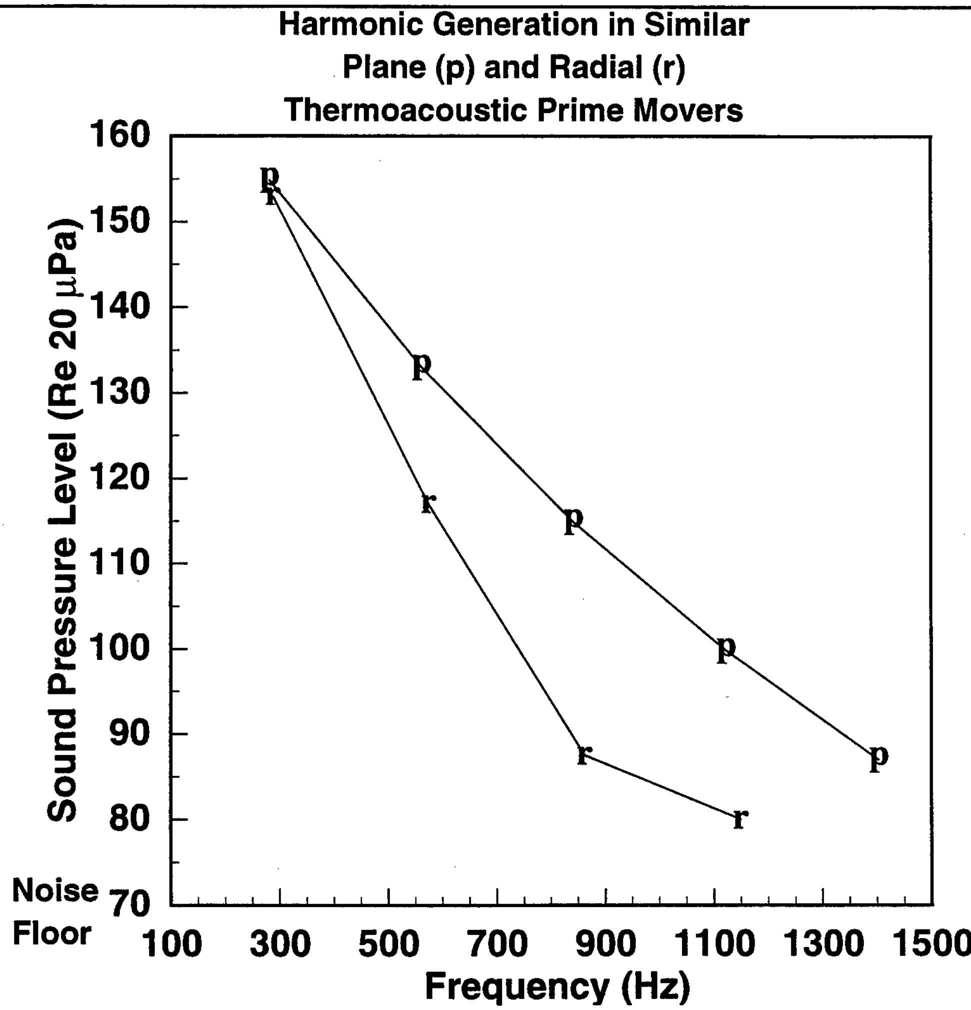

Figure 7. Harmonic generation in similar plane and radial wave prime movers. Sound pressure level denoted by the symbol 'r' for radial and 'p' for plane. Lines are only a guide to the eye.

The radial wave prime mover has the following features:

- Resonator mass = 2900 Lbs, 1316 kg.
- Resonator top and bottom are 1" carbon steel, 61.5" o.d. and 14" i.d.
- Resonator wall is carbon steel, 1.5" thick (radial direction) and 4" tall.
- Center caps (top and bottom) are stainless steel to decrease thermal conduction across stack
- Stack is mica paper, 1.25 cm long (radial direction), 6 mil thick, spaced by mica washers (15 mil) and teflon thread.
- Heat exchangers are copper vertical flaring fins, 0.4" wide, 4" tall, and 30 mil thick. Each fin has 3 holes. 1/8" copper tubing fills the holes. Cooling fluid is used on the cold side. Nickel chromium wire with ceramic bead insulatures were threaded through the copper tubing on the hot side to provide heat. The heat exchangers were manufactured at DRI.

The main resonator was constructed at the University of Mississippi.

The peaks in the frequency spectrum of the radial wave prime mover is shown in Fig. 7 along with those of a similar plane wave prime mover. Both prime movers had similar onset temperature and resonant frequencies. Note that harmonic generation in the radial wave prime mover is considerably suppressed below that of the plane wave prime mover. Work on the radial wave prime mover continues to progress.

4. Specific Conclusions

- Use of the radial resonator geometry does not significantly improve upon the capabilities of plane wave thermoacoustic engines.[4]
- The choice of radial or plane resonator geometry should be made on pragmatic terms.
- Radial wave prime movers do seem to have significantly lower nonlinear generation of harmonics than plane wave prime movers. This could be important for very strongly driven refrigerators.
- Optimization of thermoacoustic engines by adjusting many design parameters appears to significantly improve performance. Thorough interpretation of optimization predictions for parameters like stack position, stack temperature gradient, etc, helps build a new intuitive model for thermoacoustics that goes beyond the short stack approximation.[7,8]

5. Tentative Conclusions and Open Questions

- In the past, we found significant differences in thermoacoustic engine performance as a function of stack pore geometry. It seems that efforts to improve thermoacoustic engine performance should concentrate most on the thermoacoustic elements (stack, heat exchangers, sound sources).
- It is still possible that other geometries such as exponential or cone shaped resonators could have a significant effect on thermoacoustic engine performance.
- Variable plate spacing in the stack seems to improve refrigerator COP by approximately 10% when compared with constant plate spacing stacks.
- For prime movers, variable plate spacing in the stack to approximately match the temperature dependent thermal penetration depth significantly improves the performance of heavily loaded engines.
- Open question: Can we improve acoustic refrigeration by using a gas that undergoes liquid-vapor or solid-vapor and vica-versa phase transitions driven by density changes in the acoustic wave.

- Open question: Would flattening out the stack temperature gradient with a carefully designed inhomogeneous stack improve upon acoustic refrigerator performance?

6. Specific theoretical, computational, and experimental tools that were developed.

- Theory to ease analysis of radial wave thermoacoustic engines.[4]
- Short stack approximation for the radial geometry.
- Numerical model for radial and plane wave prime movers below onset and working as sound sources, and for acoustic refrigerators, both driven by prime movers and by massive drivers. Code can be used to model the quality factor of resonators as a function of stack temperature gradient. Code is similar in scope and accuracy to the Los Alamos National Lab DELTAE model.
- Heat exchangers for radial wave thermoacoustic engines.

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