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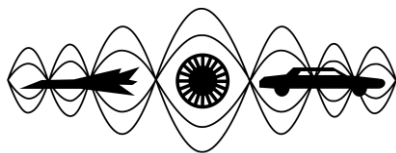
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MODULAR STACKS FOR ACOUSTIC REFRIGERATION: INVESTIGATING THE IMPACT OF SMALL AIR LAYERS IN A MODULAR STACK

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A key component in acoustic refrigerators and engines is the stack, a porous material strategically placed within a tube to harness the thermoacoustic effect. 3D printing technology for stack construction is promising due to its ability to provide accurate geometry control. One potential application is the construction of modular stacks, which could facilitate experimental studies on optimal stack length, integration of thermosensors along the stack, and printing time reduction. However, the construction of modular stacks introduces the potential for small air layers between the individual modules of the stack. This study explores the potential effects of those thin air layers between the parts of a modular stack. A numerical model of a thermoacoustic refrigerator, specifically a quarter-length resonator, was implemented based on the 1D thermoacoustic software DeltaEC. Our findings reveal that the presence of air gaps has a detrimental impact on the temperature difference achieved between the two ends of the stack. However, in the considered acoustic refrigerator configuration, small gaps below 1 mm result in a decrease below 1% of the temperature span. For the considered application and tolerances of the modular stack, the effect of the air layers could be negligible; this result opens the possibility of constructing these modular stacks. Further research is needed to corroborate these effects experimentally.

Keywords: thermoacoustic, alternative refrigeration, stack, thermoacoustic materials, 3D printing.

1. Introduction

Refrigeration is indispensable in various facets of modern life, serving not only for comfort but also to ensure the efficient preservation of foods, health, and safety. However, conventional refrigeration systems typically employ fluids with significant global warming potential, such as hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs), the last two being now almost globally phased out due to their ozone depletion potential. Aiming to the green transition and the

mitigation of escalating global warming, exploring environmentally friendly alternatives to conventional vapor-compression refrigeration technologies has become imperative.

One such alternative is the development of efficient thermoacoustic refrigerators (TARs), which can operate using non-polluting fluids (such as air, helium, argon, etc.). TAR technology offers additional advantages, including lower maintenance costs than conventional refrigeration systems, owing to reduced friction in moving parts. Notably, the sole moving component in TARs is the speaker, which sets the air in motion within the refrigeration system via traveling or standing sound waves.

Thermoacoustic refrigeration exploits temperature differences across a stack, exploiting the thermal effects of exchanging heat with sound waves [1], which is generally a porous material allowing sound propagation through its pores. The air is compressed and rarified during the process, and heat is exchanged with the stack, accomplishing a thermodynamic cycle. Effective design strategies often take advantage of linear thermoacoustic theory [2,3], wherein parameters such as thermal and viscous lengths, representing microscopic distances for heat and momentum diffusion, play pivotal roles.

While simple thermoacoustic refrigerators can be easily assembled using rigid tubes and plastic films for the stack [4], ensuring a consistent distance between stack walls, equivalent to a few thermal lengths, they can be cumbersome and imprecise. Literature showcases various economical, replicable, and robust prototypes [4,5,6,7]. Effective comparisons have been drawn between constructed TARs and numerical models implemented in softwares such as DeltaEC [8]. Notably, advancements in 3D printing technology have enabled the construction and optimization of stacks, although prior studies have not yet explored the construction of modular stacks.

The growing development of 3D printing technologies presents a promising approach for stack construction. By dividing the stack into modular components, printing time can be minimized while enhancing versatility for experimentation. Modular stacks offer the flexibility to insert temperature sensors between modules and alter stack lengths, facilitating comprehensive investigations. This study addresses part of this gap by examining the potential impact of thin air layers on the performance of a basic acoustic refrigerator, employing a numerical model based on linear thermoacoustic theory implemented in the DeltaEC software.

2. Methods

A numerical model was employed to investigate the impact of small air layers between the components constituting a modular stack in a simple thermoacoustic refrigerator. This model was developed using the DeltaEC software and designed to simulate one-dimensional thermoacoustic systems.

The case study involved a simple refrigerator configuration comprising a speaker at one end of a rigid tube, a stack subdivided into modules, and a closed end. Certain parameters were treated as constants throughout the analysis. A schematic representation of the model is depicted in Figure 1.

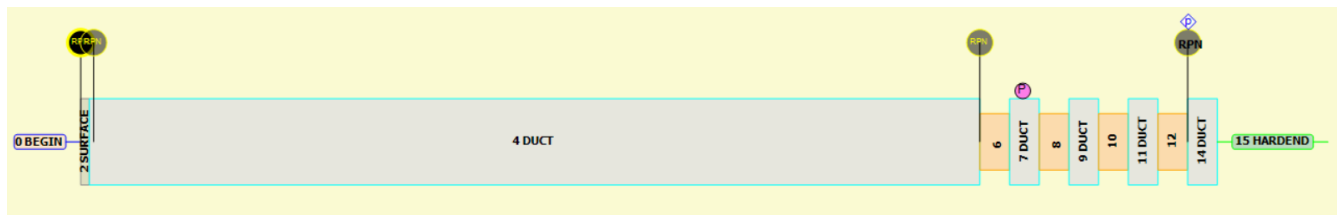


Figure 1: Schematic representation of the numerical model in DeltaEC.

The stack, with a total length of $L_{\text{stack}} = 4$ cm, was assumed to consist of four components, each with an equal length of $L_{\text{modulus}} = L_{\text{stack}}/4$. Air layers between the four modules were presumed to have

equal lengths, denoted as d , and were systematically varied within the range of 0 to 1 cm. The thermal penetration depth, δ_k , was utilized to determine the pore dimensions of the stack, as described by Equation 1. Here, κ represents the thermal conductivity, f denotes the frequency, ρ signifies the gas density, and c_p stands for the specific heat at constant pressure.

$$\delta_k = \sqrt{\frac{\kappa}{\pi f \rho c_p}} \quad (1)$$

The main output is the temperature span across the stack, ΔT_{stack} , see Eq. 2.

$$\Delta T_{\text{stack}} = T_{\text{hot}} - T_{\text{cold}} \quad (2)$$

The resonance frequency was determined through a simple numerical procedure and held constant throughout the analysis, see Fig. 2. Other parameters, such as tube diameter D , total resonator length L , and stack position relative to the hard end L_0 , remained constant. Material properties of a 3D printer resin were experimentally determined and utilized as parameters for the stack material. Before the present study, the model was calibrated to replicate the outcomes of the experimental setup described in detail in reference [6].

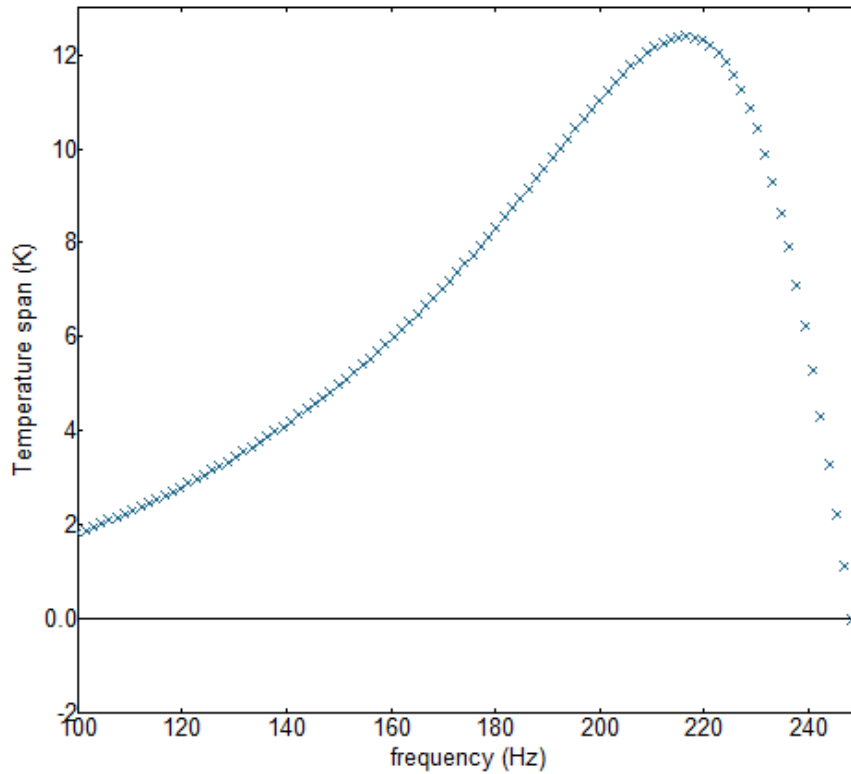


Figure 2: Resonance frequency of the refrigerator, $d = 0$.

3. Results

Figure 3 illustrates the relationship between the temperature span across the stack (ΔT_{stack}) and the distance between the modules (d) forming the air gap. As depicted in the figure, an increase in the air gap results in a degradation of the thermoacoustic effect. However, this effect is relatively minor. For instance, considering an air gap of $d = 1$ mm, the temperature span ΔT_{stack} experiences a decrease of less than 1%. Furthermore, the dependency is quasi-linear. This finding suggests that while precise stack construction is crucial for optimizing thermoacoustic performance, minor deviations in module spacing

may not significantly compromise system efficiency. However, it is important to acknowledge the potential limitations of the numerical model, such as simplifications in the representation of physical phenomena and assumptions regarding material properties. Further experimental validation and refinement of the model parameters are warranted to enhance the robustness and applicability of the findings to real-world scenarios.

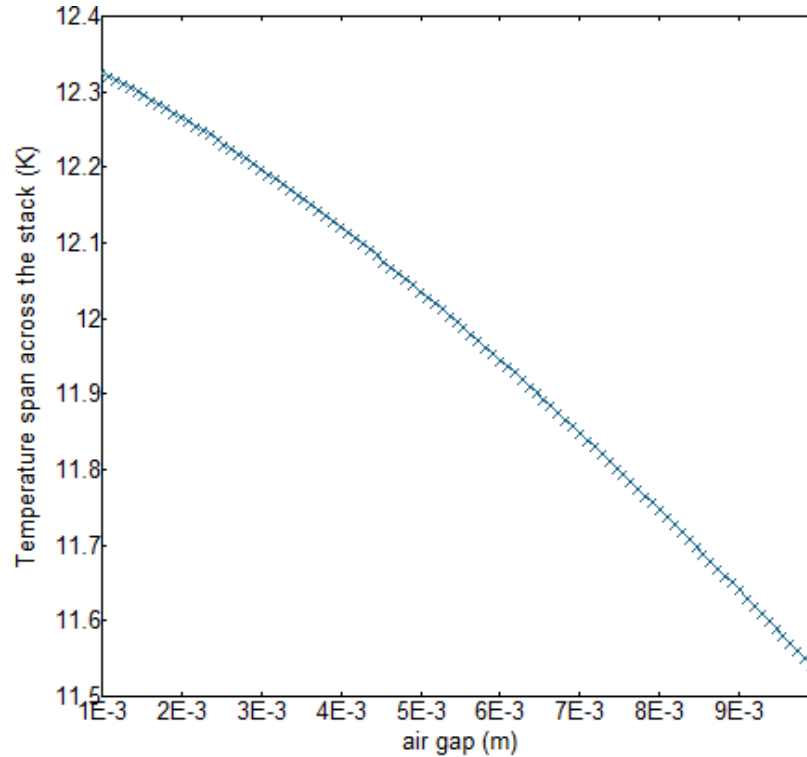


Figure 3: Temperature span across the stack, ΔT_{stack} , vs. air gap distance between the modulus d .

4. Conclusions

This study investigated the impact of incorporating air layers between the components of a modular stack in a thermoacoustic refrigerator. Through the implementation of a one-dimensional numerical model, several key observations were made:

- introducing air layers within the stack detrimentally affects the refrigerator's performance, reducing the temperature span across the stack;
- despite this negative influence, the effect of thin air layers (below 1 mm) was negligible, with a temperature span decrease of less than 1% observed;
- the findings support the idea of building modular stacks, utilizing multiple modules while maintaining minimal gap thickness. It is anticipated that experimental validation could confirm the numerical results presented herein.

Furthermore, the influence of the number of modules composing the stack remains an area suitable for future investigation. While it is reasonable to expect that increasing the number of modules may diminish the obtained thermal effect, further research is warranted to explore this aspect comprehensively. Future research should aim to validate these findings experimentally and explore additional factors influencing system performance for a more comprehensive understanding of thermoacoustic refrigeration technology.

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