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Performance of a 3D-printed stack in a standing wave thermoacoustic refrigerator

Nor Atiqah Zolpakar^a, Normah Mohd-Ghazali^{a*}, Robiah Ahmad^b, Thierry Maré^c

^aFaculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

^bUTM Razak School of Engineering and Adv. Tech. UTM Kuala Lumpur, 54100 Jalan Semarak, Kuala Lumpur, Malaysia

^cLGCGM EA3913, Université de Rennes1, IUT Saint Malo, France

Abstract

Successful standing wave thermoacoustic refrigerators reported to date still have issues with the stack, the primary medium of the system. Being the core of the whole system, performance of the stack directly influences the refrigerator performance. Besides the lack of a comprehensive theory on thermoacoustic cooling in establishing a good temperature difference across the stack that is very much desired, stack fabrication is still an issue. Currently, stack fabrication involved ready-made celcor ceramic material cut to specification or hand-made spiral/parallel plate stack from Mylar, the most commonly used stack material. The former comes in fixed off-the-shelf cells per square inch while the latter is susceptible to error and inconsistencies depending on the fabricator. This paper presents performance results from a standing wave thermoacoustic stack fabricated using a 3D printer, not reported to date. The stack design parameters selected has been optimized with Multi-objective Genetic Algorithm (MOGA) to determine the optimum design parameters; stack length, center position and plate spacing. The results show that the 3D-printed stack has potential towards improvement of the temperature performance of the thermoacoustic refrigeration system although a more refined fabrication technology is still in need. 3D-printing of the stack minimizes the error, eliminates inconsistencies, and reduces the time for the production of the final product. Consistency in optimized stack production is crucial towards realizing high performance systems.

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Keywords : thermoacoustic refrigerator, 3D printing stack, MOGA

1. Introduction

Thermoacoustic refrigerator (TAR) system is an alternative environmentally friendly cooling system that has gained attention since the first cooler was successfully introduced by Hofler in 1986 [1]. The usage of inert gases as working fluid instead of hazardous refrigerants is an attractive aspect of the TAR system. The system operates based on the compression and expansion of gas parcels in a closed tube that creates a temperature difference at both extremities of a stack, a porous medium commonly made of parallel plates. Unfortunately, the low coefficient of performance (COP) limits the practical application of

* Corresponding author. Tel.: +6075534577; fax: +6075566159.

E-mail address: normah@fkm.utm.my.

the technology to date [2]. Being the core of the thermoacoustic system, the stack final product has been dependent on the fabrication mechanism. The system design generally begins with the designed temperature difference across the stack and performance is measured from the final temperature difference achieved or the temperature at the cold end of the stack. To date, even with an optimized stack design, the stack has been either hand-fabricated parallel or spiral geometry using Mylar material, or hand-cut of Corning Celcor ceramic ready made in terms of cells per square inch [3-7]. This paper reports experiments to measure the performance of the stack in terms of the temperature difference achievable, using a stack fabricated with a 3D printer, based on optimized design parameters. This rapid prototyping technology was first patented by Kodama in 1980 but a 3D printer only materialized six years later [8]. The 3D-printed stack has not been reported in relation with thermoacoustic experiments before. The results presented here indicate the importance of advanced fabrication technology that keeps up with the theory of thermoacoustic cooling.

2. Design parameters

The basic components of a standing wave thermoacoustic refrigerator are an acoustic driver, a stack, hot and cold heat exchangers, and the resonance tube. The performance of the system is very much dependent on the stack performance. This in turn depends on its length, L_s , centre position, x , and plates spacing, the last depending on the thermal boundary layer of the stack, δ_k [9]. The stack performance is defined by its COP which is the ratio of the cooling power to the acoustic work supplied to the stack. The normalized cooling power $Q_{cn} = Q_c/p_m aA$, and acoustic power, $W_n = W/p_m aA$, are given by Tijani et al. [10]:

$$Q_{cn} = \frac{\delta_{kn} D^2 \sin 2x_n}{8\gamma(1+\sigma)\Lambda} \times \left(\frac{\Delta T_{mn} \tan x_n}{(\gamma-1)BL_{sn}} \frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}} - 1 + \sqrt{\sigma} - \sqrt{\sigma}\delta_{kn} \right) \tag{1}$$

$$W_n = \frac{\delta_{kn} L_{sn} D^2}{4\gamma} (\gamma - 1) B \cos^2 x_n \times \left(\frac{\Delta T_{mn} \tan x_n}{BL_{sn}(\gamma-1)(1+\sqrt{\sigma})\Lambda} - 1 \right) - \frac{\delta_{kn} L_{sn} D^2}{4\gamma} \frac{\sqrt{\sigma} \sin^2 x_n}{B\Lambda} \tag{2}$$

where Λ is defined as

$$\Lambda = 1 - \sqrt{\sigma}\delta_{kn} + 0.5\sigma\delta_{kn}^2 \tag{3}$$

The stack performance is generally experimentally measured in terms of the lowest temperature obtained at the cold end of the stack or the temperature difference across the stack, ΔT_m , the latter of which is being implemented here. The parameters used in this study are listed in Table 1. The working fluid used in the thermoacoustic refrigerator is air at atmospheric pressure. The system is designed for 100kPa with $\Delta T_m = 30$ K, mean temperature of 300 K and operating frequency, f , at 400 Hz

Table 1 Dimensionless parameters and fluid properties used

| | |
|--|---|
| <p>Dimensionless operating parameters Drive ratio: $D = p_0/p_m$ Cooling power: $Q_{cn} = Q_c/p_m aA$ Acoustic power: $W_n = W/p_m aA$ Temperature difference: $\Delta T_{mn} = \Delta T_m/T_m$</p> | <p>Fluid properties Speed of sound, $a = 347.2$ m/s Specific heat ratio, $\gamma = 1.4$ Prandtl number, $\sigma = 0.7$ Heat capacity, $c_p = 1005.5$ J/kg.K Thermal conductivity, $K = 26.3 \times 10^{-3}$ W/mK</p> |
| <p>Dimensionless tack geometry Stack length: $L_{sn} = kL_s$ Stack position: $x_n = kx$ Blockage ratio/porosity: $B = y_0/(y_0 + l)$</p> | <p>Gas parameters Prandtl number: σ Normalized thermal penetration depth: $\delta_{kn} = \delta_k/y_0$</p> |

The stack length and center position has been chosen based on the work of Zolpakar et al. [7], with the optimized outcomes of $L_s = 4\text{cm}$, $x_s = 4\text{ cm}$ and plate spacing, $2y_0 = 0.36\text{ mm}$. Details can be found in their report.

3. Experimental setup

Based on the optimized stack parameters of Zolpakar et al [7], the stack design has been selected; stack length, center position and plate separation gap. Experiments with hand fabricated stack from Mylar and that from ready-made Celcor ceramic structured stack had been completed and reported based on the optimized design parameters [7]. Recently, it has been discovered that a 3D printer is capable of producing a parallel plate stack when the drawing is completed in Solidworks and the specific dimensions are provided. However, due to the limitation of the capability of the current 3D printer available, the minimum spacing between the stack plates is set at 0.5 mm and the thickness at 0.5 mm with the material being VeroWhitePlus Rgd835 that has a thermal conductivity, $k = 0.23\text{ Wm}^{-1}\text{K}$ and specific heat of $1000\text{ Jkg}^{-1}\text{K}$. It has a higher conductivity than Mylar but lower than that of the Celcor Ceramic material. The 3D printer used here is Stratasys objet24 with the ink being polyjet photopolymer. Figure 1(a) shows a schematic of the 3D-printed stack and the experimental set-up.

The stack lengths tested are 3 cm, 4 cm (optimized length), and 5 cm. The center positions investigated are 3.5 cm, 4 cm (optimized center position), and 4.5 cm. The resonator is a quarter-wavelength resonator from Acrylic material having its fundamental resonance frequency at 400 Hz. The inner diameter of the resonator is 34 mm. At the end of the tube is a rigid end (reflector) and the other end was connected to a mid-range loudspeaker, PRIME R14X2, which constitutes the acoustic power source. Three K-type thermocouples were used to measure the temperatures. Each experiment was repeated three times for reliability of the data. The duration of each experiment is 500 s to achieve steady state.

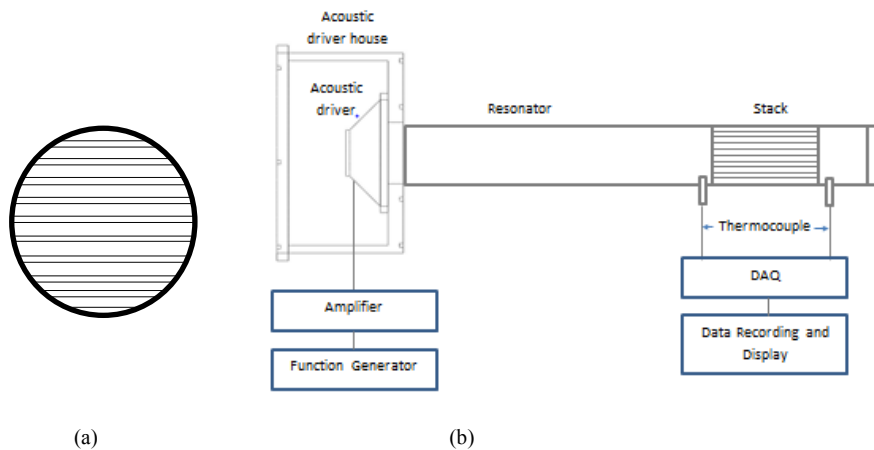


Figure 1 (a) 3D printed stack with parallel geometry (b) Experimental layout

4. Results and Discussion

Figure 2 shows the temperature recorded at both ends of the optimized stack center position, $x_s = 4$ cm at various stack length of 3 cm, 4 cm, and 5 cm. The maximum temperature difference is obtained with the optimized stack position at 4 cm, as predicted but not with the optimized length as reported by Zolpakar et al [7]. As shown in Figure 2, with the same center position, the temperature difference for the length of stack at 3 cm, 4 cm, and 5 cm are 16.8°C, 14°C, and 12.7°C, respectively. The temperature difference achieved is lower than the best that was reported by Zolpakar et al [7] for their optimized stack length (4 cm) and center position with the spiral Mylar stack, hand-made. The stack's length is actually constrained by i) increasing the stack length which increases the power density since more thermoacoustic interactions occur; ii) however, increasing the length increases the acoustic impedance and the pressure drop, particularly for dense stacks. The stack plate thickness affects the degree of conduction within the solid stack. Thus, having a combination of an optimum stack length, center position, and thickness is important for the thermoacoustic refrigerator to get an optimum performance.

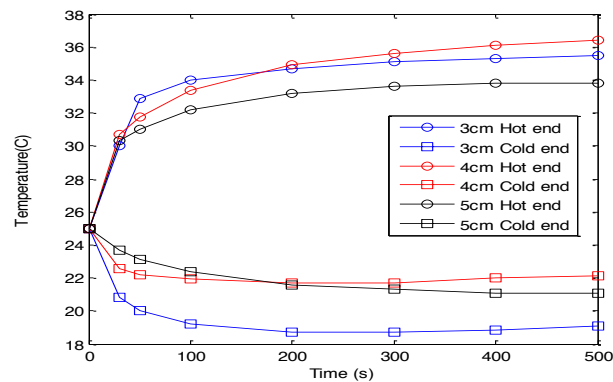
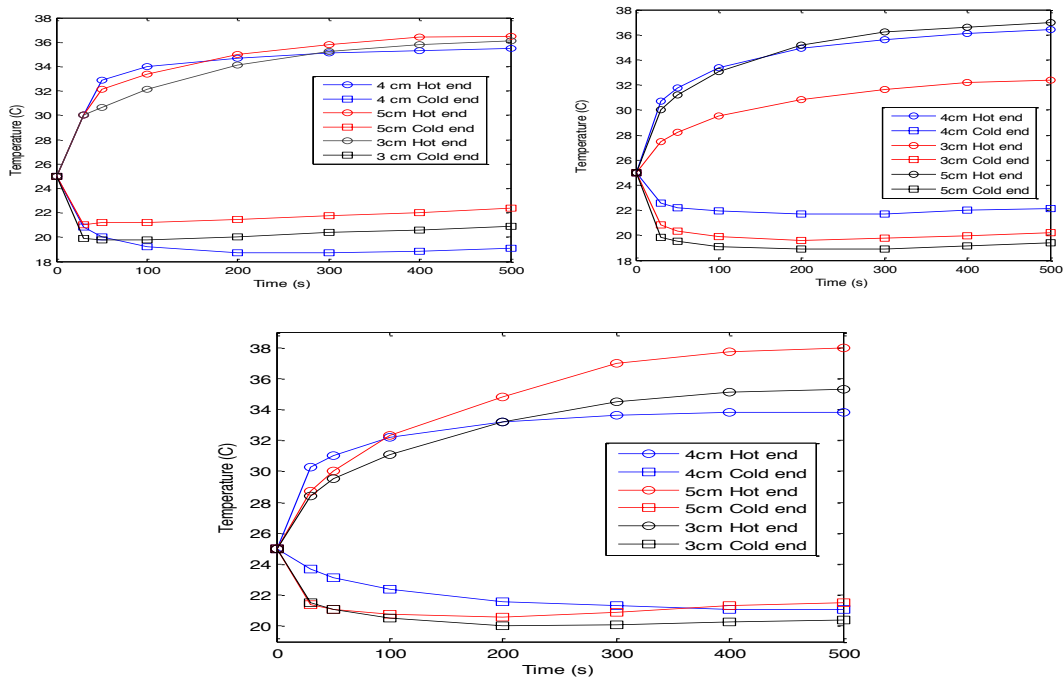


Figure 2 Temperature at optimized stack center position, $x_s = 4$ cm

Figure 3 shows the evolution of temperature with time at different stack center positions. The lowest temperature recorded is $T_c = 18.9^\circ\text{C}$ and the temperature difference is 18.1°C when the $x_s = 5$ cm with $L_s = 4$ cm. Due to the limitations of the 3D printer machine, the spacing of the 3D printer stack had changed from the identified optimized stack separation of 0.36 mm to 0.5 mm. Although Wheatley et al [11] stated that the ideal spacing in a stack is $2\delta_k$ to $4\delta_k$ which should give a gap from 0.266 mm to 0.532 mm, optimization outcomes from Zolpakar et al [7] have shown that 0.36 should be the best separation distance. However, the parameters in the stack are inter-related to one another. Therefore, changing the spacing of the stack will affect the optimum center position of the stack. This explains the slightly greater cooling observed with the 5 cm center location and not at the expected optimized length of 4 cm. The effect of the center position can also be observed from Figure 3(a). When $L_s = 3.5$ cm, the lowest temperature recorded is at $x_s = 4$ cm which is 18.9°C , then by changing to 3 cm and 5 cm, the lowest temperature is 21°C and 19.8°C , respectively. Figure 3(c) shows a similar pattern but the lowest temperature recorded is 20°C when $x_s = 3$ cm. Locating the stack nearer to the end of the resonator means that it is nearer to the pressure antinode and velocity node. Thus, lower velocity (node) reduces the losses in the stack and hence increases the performance of the stack.

The overall performance of the 3D-printed stack is found to be better than that obtained with the optimized stack parameters reported in Zolpakar et al [7] with almost the same set-up and operating conditions. Despite having followed the optimized stack length, center position and drive ratio, the spiral

stack hand-fabricated from Mylar and the ready-made Celcor Ceramic produced a smaller temperature difference. Compared with these two stacks, the 3D-printed stack still shows the best performance measured by the lowest temperature achieved and temperature difference with the thickness being thicker by almost 40%. These results can be explained in terms of the fabrication technique. Inconsistencies might have developed during the setting up of the stack plates caused by the lengthy and tedious steps. The Celcor Ceramic ready-made stack previously used had a separation of 1 mm with a higher thermal conductivity than that of Mylar. This thermal property induced higher conduction within the stack and thus lowered the temperature difference achieved across the stack.



(c)

Figure 3 Temperature for (a) $L_s = 3.5\text{cm}$, (b) $L_s = 4\text{ cm}$, (c) $L_s = 4.5\text{ cm}$ for different center position

5. Conclusion

The new method of stack fabrication using rapid prototyping technology has been introduced, based on a previous optimized stack design. Based on the designed temperature difference across the stack, results have shown the superior performance obtained in terms of the higher temperature difference achievable with the 3D-printed stack compared to previous ones under the same design and operating conditions. Combination of the optimized parameters with the more precise fabrication technique has produced the desired outcome expected by engineers. With 3-D printing, the error from drawing board to fabrication has been minimized, inconsistencies eliminated, and the time for fabrication of the stack has been reduced. It is expected that the performance of the thermoacoustic refrigerator can be further improved if the fabrication technology can keep up with the optimization theory.

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Normah Mohd-Ghazali was born in 1961 in Malaysia. She graduated with a B.Sc. in Nuclear Engineering in 1984 from the University of Wisconsin-Madison, Wisconsin, U.S.A. She then obtained her M.Sc. from the University of Malaya, Kuala Lumpur, in 1991. She completed her Ph.D. in Mechanical Engineering from the University of New Hampshire at Durham, U.S.A. in 2001. She is currently an Associate Professor in the Faculty of Mechanical Engineering at Universiti Teknologi Malaysia (UTM), Johor Bahru. Her research interest include thermal management of microchannel heat sinks and thermoacoustics.