Experimental study on the influence of the porosity of parallel plate stack on the temperature decrease of a thermoacoustic refrigerator

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Abstract. Thermoacoustic refrigerators are cooling devices which are environmentally friendly because they don’t use hazardous gases like chlorofluorocarbons (CFCs) or hydrofluorocarbons (HFCs) but rather air or inert gases as working medium. They apply sound wave with high intensity to pump heat from the cold to hot the regions through a stack in a resonator tube. One of the important parameters of thermoacoustic refrigerators is the porosity (blockage ratio) of stack which is a fraction of cross sectional area of the resonator unblocked for the gas movement by the stack. This paper describes an experimental study on how the porosity of parallel plate stack affects the temperature decrease of a thermoacoustic refrigerator. The porosity of parallel plate stack is specified by the thickness of plates and the spacing between plates. We measured the maximum temperature decreases of thermoacoustic refrigerator using stacks with various porosities in the range of 0.5 - 0.85, with plate spacing from 0.5 mm to 1.5 mm and plate thicknesses 0.3 mm, 0.4 mm, and 0.5 mm. The measurements were done with two resonators with length of 0.8 m and 1.0 m, with air at atmospheric pressure and room temperature, correspond to thermal penetration depths (δₜ) of 0.26 mm and 0.29 mm, respectively. It was found that there is an optimum porosity which gives the largest temperature decreases, and there is a tendency that the optimum porosity shifts to a larger value and the temperature decrease become larger when we used a stack with thinner plates. On the other hand, the study on the dependence of the temperature decrease on the plate thickness and the plate spacing reveals more useful information than that on the stack porosity itself. We found that stack with thinner plates tends to give larger temperature decrease, and the plate spacing of around 4δₜ leads to the largest temperature decrease.

1. Introduction
Thermoacoustic refrigerators are environmentally friendly cooling devices since they use air or inert gases as working medium instead of chlorofluorocarbons (CFCs) and hydro-fluorocarbons (HFCs) as in conventional coolers. The relatively simple design with no or only a little moving parts and the abundance of the working gas make them can be built and maintained in a low cost budget and serve as an alternative and promising cooling technology in the future compared to the conventional systems.
Thermoacoustic refrigerators mainly consist of a sound driver (e.g. loudspeaker), a resonator tube, a stack (porous medium), and working gas. The sound driver provides a high power standing sound wave in the working gas inside the resonator tube. A stack is typically placed near the pressure anti-node of the standing wave. The interaction between the expanding and compressing gas with the stack material is resulting in heat transport axially in the stack in the direction from the pressure node to the pressure anti-node. More detail descriptions on the working principles of thermoacoustic refrigerators can be found elsewhere.[1][2][3]

One of the important parts of thermoacoustic refrigerator is stack which is a kind of heat exchanger and placed in a resonator tube. Generally, stack consists of a large number of closely spaced surfaces aligned parallel to the length of the resonator tube. Tijani et al [4] studied the optimal spacing of stack plates for thermoacoustic refrigeration. They found that a plate spacing of four times of the thermal penetration depth leads ($\delta_\kappa$) to the lowest temperature, while the best performance was given by a $3\delta_\kappa$ plate spacing. Kim et al [5] investigated the optimum position of a stack in a thermoacoustic heat pump with various operating frequency in the range of 150 Hz - 300 Hz. They concluded that the stack positions for the most efficient operation of the thermoacoustic heat pump are at the maximum position (up-stream pumping) and the minimum position (down-stream pumping) of the curve of the temperature different vs position at the resonance frequency. Setiawan et al [6] studied experimentally the effects of the length and location of stack on the temperature decrease of a thermoacoustic cooler. For their thermoacoustic apparatus, they found the optimum stack length was 10 cm and the optimum stack location was at 10 cm or 0.125 normalized distance of stack center to the closed end of resonator. The impact of gas blockage on the performance of a thermoacoustic refrigerator in the relation to the existence of heat exchanger in the both end of stack has been inspected by Akhavanbaza et al [7]. Their results show that the heat transfer decreases with an increase in the gas blockage, the relationship between gas blockage fraction and the temperature difference across the stack is linear, and a heat exchanger with larger thermal contact area (higher blockage fraction) increases the heat exchange between the heat exchanger fluid and the stack, but reduces the cooling power.

In this paper, we describe an experimental study on the influence of the porosity of parallel plate stack on the temperature decrease of a thermoacoustic cooler. The porosity, also called as blockage ratio ($B$), is the fraction of the cross sectional area of the resonator unblocked for the gas movement by the stack. For parallel plate stack, the porosity depends on the plates thickness and plate spacing, and expressed by [8]

$$B = \frac{d}{d + t}$$

where $d$ is the plate spacing and $t$ is the plate thickness as depicted in Fig. 1. When the plate spacing is too wide, then it could make the heat transport between gas and plates don’t effectively occur, whereas when the plates spacing is too narrow, then the gas particles motion...
will be more hampered by viscous effect. The optimal plate spacing usually compare to the thermal penetration depth ($\delta_\kappa$) of the gas in the stack. The thermal penetration depth is a measure of the distance that heat can diffuse in through a substance during time $1/\pi f$, and can be expressed by \[\delta_\kappa = \sqrt{\frac{\kappa}{\pi f \rho c_p}} \]  

where $\kappa$ is the thermal conductivity, $\rho$ is the density, $c_p$ is the isobaric specific heat of the gas, and $f$ is the resonance frequency of sound in the resonator. On the other hand, the plate thickness determines not only the cross sectional blockage area of the stack, which blocks gas for moving back and forth, but also the thermal contact surface area between the gas and stack plates involved in the heat exchange process.

2. Experiment

Fig. 2 shows the schematic diagram of the experimental set-up. The thermoacoustic cooler in this experiment is a standing wave type and mainly consists of a loudspeaker, a resonator tube, a stack, and air as the working gas. A digital function generator (model GFG 8016G) was used to generate an audio sinusoidal signal. This signal was then amplified by a 350 W audio amplifier before fed into a 12” 400 W loudspeaker. The input voltage and current of the loudspeaker were measured by a digital voltmeter (V) and an ampere-meter (A), respectively. The loudspeaker together with its box is coupled to the resonator tube, so that they serve as a quarter-wavelength resonator system. We used free air at the atmospheric pressure and room temperature as the working gas that fills the resonator tube. In this experiment, we used two resonator tubes with different length ($L$), i.e. 80 cm and 100 cm, for which the estimated resonance frequencies were around 107 Hz and 86 Hz, respectively. A stack is placed near the closed end of the resonator so that the center of stack is located at a distance of around $L/5$ from the closed end of resonators. Both resonator tube and the stack housing are made of 1-1/4” PVC pipes.

In order to study the impact of the porosity of stack on the temperature decrease of the thermoacoustic refrigerator, we prepared fifteen plate parallel stacks with various porosities. The plates were made of mica plastic sheets with three kinds of thickness ($t$), i.e. 0.3 mm, 0.4 mm, and 0.5 mm. To provide gap (plate spacing, $d$) between the plates, we used nylon fishing lines which are glued onto the plates along the stack axis with distances of 1 cm. We used five different diameters of the nylon fishing lines, i.e. 0.5 mm, 0.85 mm, 1.0 mm, 1.2 mm, and 1.5 mm. This nylon fishing lines are ignored in the calculation of the stack porosities. The length

![Figure 2. The schematic diagram of the experimental set-up.](image-url)
of stacks are 10 cm chosen based on our previous result [8] and the diameter is 3.5 cm. Figure 3 shows the cross section of one of the stacks we used in this experiment, in which the plate thickness is 0.5 mm and plate spacing is 1.0 mm. The stacks are not so good built that the plates are slightly curved.

Experiments were done by operating the thermoacoustic cooler at its resonance frequencies. A small microphone is attached at the closed end of resonator to catch the sound and send the signal to a computer via a sound card. The resonance condition was recognized from the real time spectrum of the sound displayed by Oscilloscope 2.51 software on the computer’s monitor. The high intensity sound from the loudspeaker provides work to pump heat from the cold region to the hot region (from right side to left side of the stack in Fig. 2). To study the influence of stack porosity on the temperature decrease and temperature difference of the thermoacoustic cooler, we measured the temperatures at the cooling point and the heating point the both ends of the stack (see Fig. 2) for various stacks with different porosities, with various combination of plate thicknesses and plate spacings of the stacks. We used two digital thermometers with LM35 sensors to measure the temperatures at the heating and cooling points.

3. Results and Discussion

Figure 4 shows one of measurement results of the temperatures of the heating and cooling points for the the first 15 minutes operation of the thermoacoustic refrigerator. In this case, we used resonator with 80 cm in length and the stack with 0.3 mm plate thickness and 1.0 mm plate spacing. The temperatures of both measurement points after 15 minutes were relatively constant (not shown in the figure). The initial temperatures of both measurement points were 30.2°C, and then we can see that the temperature of heating point was rising up to 43°C and that of cooling point was decreasing down to 21.5°C after the first 15 minutes. It means that the temperature increase ($\Delta T_H$) was 12.8°C, the temperature decrease ($\Delta T_C$) was 8.7°C, and the

![Figure 3. The cross section of a stack inside a 1-1/4 inches PVC pipe which is used in this experiment. The plate thickness $t = 0.5$ mm and the nylon diameter (plate spacing) of $d = 1.0$ mm.](image)

![Figure 4. Temperatures of the heating and cooling points for the the first 15 minutes operation of the thermoacoustic refrigerator. In this case, $L = 80$ cm, $t = 0.3$ mm, and $d = 1.0$ mm. The dash lines are to guide the eye.](image)
temperature difference of 21.5°C between the both ends of stack was established after that time period.

The measurement results of the maximum temperature decrease for various porosities of the stack are shown in Fig. 5 for $L = 80$ cm (A) and $L = 100$ cm (B). It can be seen in each figure that, for a given plate thickness, there is an optimum porosity which gives the largest temperature decreases. Moreover, there is a tendency that the optimum porosity shifts to a larger value and the temperature decrease become larger when we used a stack with thinner plates.

In order to have further analysis, we look the experimental data in a different way as shown in Fig. 6 in where the temperature decreases are plotted versus the plate spacing of the stacks instead of versus the stack porosity as in Fig. 5. We can see clearly that for a given plate thickness there is an optimum plate spacing which gives the largest temperature decrease, and the optimum values of plate spacing are the same for the same resonators length ($L$), regardless of the plate thickness. In this case, the optimum plate spacings are 1.0 mm for $L = 80$ cm and 1.2 mm for $L = 100$ cm. In addition, it can more clearly be seen in Fig. 6 that, for a given plate spacing, the stack with thinner plate yields a larger temperature decrease.

The dependence of temperature decrease on the plate thickness can be understood as follows.

**Figure 5.** The dependence of temperature decrease on the stack porosity for (A) $L = 80$ cm and (B) $L = 100$ cm. The lines are to guide the eye.

**Figure 6.** The dependence of temperature decrease on the plate spacing for (A) $L = 80$ cm and (B) $L = 100$ cm. The lines are to guide the eye.
The stack with thinner plate has not only more gas channels and hence larger thermal contact surface area between gas and stack material, but also smaller cross sectional blockage area. These conditions make the stack has more effective heat transport from the cold end to the hot end of the stack which in turn is resulting in a larger temperature decrease at the cooling point. On the other hand, the influence of plate spacing on the temperature decrease is related to both the viscous effect which is suffered by the moving gas and the thermal penetration depth ($\delta_e$) of the gas in the stack as has been described in the the previous section. By using Eq. (2) and the values of air properties at the experimental conditions (1 atm, 303 K), the thermal penetration depths were calculated approximately 0.26 mm and 0.29 mm for resonators with length of 80 cm and 100 cm, respectively. When we compare the optimum plate spacings to these thermal penetration depths, we can find that the optimum plate spacings are $3.8\delta_e$ and $4.1\delta_e$, respectively. These facts agree with the previous results obtained by Tijani et al [4] that plate spacing of 4 leads to the lowest temperature in a thermoacoustic refrigerator.

By comparing the data presentation in Figs 5 and 6 and the analysis, it can be said that the data presentation in Fig.6 reveals more useful information than those in Fig. 5. This is natural because the porosity of a plate parallel stack is specified by the plate thickness and plate spacing of the stack. Therefore, we should consider the two parameters i.e plate thickness and plate spacing rather than the stack porosity only to characterize a plate parallel stack more properly. In addition, the result of this study suggests us to use thinner plate and around 4$\delta_e$ plate spacing for plate parallel stack to obtain a lower temperature decrease in thermoacoustic coolers.

4. Conclusion
An experimental study on the influence of the porosity of parallel plate stack on the temperature decrease of a thermoacoustic refrigerator has been successfully done. The range of porosity was 0.5 - 0.85, with plate spacing from 0.5 mm to 1.5 mm and plate thicknesses of 0.3 mm, 0.4 mm, and 0.5 mm. Two resonators with length of 0.8 m and 1.0 m were used, with air at atmospheric pressure and room temperature, correspond to thermal penetration depths ($\delta_e$) of 0.26 mm and 0.29 mm, respectively. It was found that there is an optimum porosity which gives the largest temperature decrease, and there is a tendency that the optimum porosity shifts to a larger value and the temperature decrease become larger when we use a stack with thinner plates.

Because the porosity of a plate parallel stack is specified by the plate thickness and plate spacing, the study on the dependence of the temperature decrease on the plate thickness and the plate spacing reveals more useful information than that on the stack porosity itself. It was found that the use of stack with thinner plate tends to result in larger temperature decrease, and the plate spacing around 4$\delta_e$ leads the largest temperature decrease, regardless of the plate thickness.

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