The Influence of the Length and Position of the Stack on the Performance of a Thermoacoustic Refrigerator

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Thermoacoustic refrigerator is a cooling device which uses sound wave to transfer heat. The heat transfer occurs in a stack, that is, occurs between working gas and stack plates. We used free air at the atmospheric pressure as working gas and the stack plates were made of mica sheet. It has been experimentally studied the influences of the stack's length and stack's position in a cylindrical resonator on the performance of a thermoacoustic refrigerator. The experimental result showed that each parameter has an optimum value at which the maximum cooling was obtained. In this case, the optimum length of the stack is 10 cm and the optimum position of the stack is 10 cm of the stack centre distance measured to the closed end of the resonator. This combination has given the maximum temperature decrease of the cold reservoir about 11 °C so that the air temperature in cold reservoir has reached down to 19 °C.

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I. INTRODUCTION

Thermoacoustic refrigerator is an environmentally friendly cooling system because it doesn't use freon but rather air or noble gases as working medium. It uses a high intensity sound wave to provide work for cooling process. Because of the abundance of the working medium and the relatively simple construction, thermoacoustic refrigerator could be an alternative cooler which has many advantages in the future compare to the conventional cooler.

The principles of the thermoacoustic refrigerator can be found in many papers.[1][2][3][4] Tijani *et al* have described not only the designing procedure of constructing a thermoacoustic refrigerator, but also its performance measurement.[5][6] A theoretical and experimental investigation of the frequency characteristic on a thermoacoustic refrigerator which is drived by a loudspeaker has been carried out.[7] A numeric modeling for integration of temperature gradient in stacks has been done.[8] The author and co-workers have investigated the effect of the length and the diameter of cylindrical resonator of thermoacoustic refrigerator on the cold reservoir temperature decrease.[9] The optimum position of a stack in a thermoacoustic heat pump has been examined, and it has been found that the most efficient heat transfer occured at the maximum position and the minimum position of the temperature change versus position curve at the resonance frequency.[10] In this paper, we describe the experimental study of the influence of stack length and stack position in cylindrical resonator of a thermoacoustic refrigerator respect to the temperature decrease which can be achieved.

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II. THEORETICAL BACKGROUND

Stack is a kind of heat exchanger which is placed in the resonator of thermo-acoustic refrigerator. Generally, stack consists of many surfaces or plates parallel to the axis of the resonator tube. When an acoustical standing wave with high intensity exists in the resonator, the heat transfer between stack plates and gas within resonator can occur. Because one end of the stack is in contact to the hot reservoir and another end is in contact to the cold reservoirs, then the net effect is a heat transfer from the cold reservoir to the hot reservoir. The requirement of this heat transfer is that the temperature gradient along the stack has to be greater than a critical longitudinal temperature gradient which is expressed by[4]

$$\nabla T_{crit} = \frac{p_0}{\xi \rho c_p} \tag{1}$$

where p_0 and ξ are pressure amplitude and acoustical displacement amplitude, respectively, ρ and c_p are gas density and isobaric specific heat of the gas within resonator. The heat transfer can occur when the peak to peak of the temperature variation caused by adiabatic compression of gas $(2p_0/\rho c_p)$ is greater than the temperature variation of local wall of the plate $(2\xi \nabla T_{crit})$ between the extremes of the gas particle motion.

Other important parameters for the stack in thermoacoustic refrigerator are thermal penetration depth (δ_κ) and viscous penetration depth (δ_v) which are respectively expressed by[1][3][4]

$$\delta_\kappa = \sqrt{\frac{\kappa}{\pi f \rho c_p}} \tag{2}$$

and

$$\delta_v = \sqrt{\frac{\eta}{\pi \rho f}} \tag{3}$$

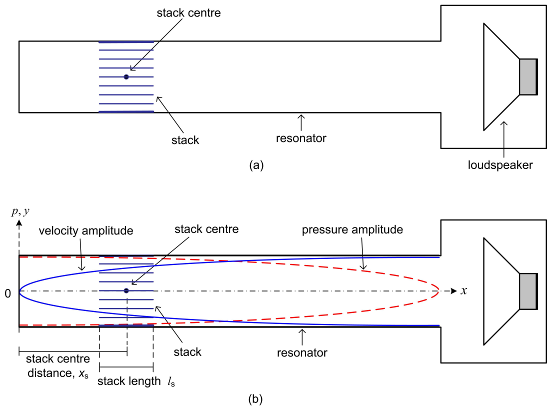

FIG. 1: (a) The schematic of main components of the thermoacoustic refrigerator. It consists of a loudspeaker in its housing box, a cylindrical resonator and a stack within the resonator. (b) Illustration that the stack center distance ($x_{\rm s}$) and stack length ($l_{\rm s}$) are related to the gas pressure amplitude and the molecular speed amplitude near to the both end of the stack.

where κ is thermal conductivity of the gas, f is frequency of acoustical standing wave in resonator, and η is dynamic viscocity of gas. The thermal penetration depth determines the distance that heat can diffuse through a gas during time $1/\pi f$, and about four times thermal penetration depth is an optimum spacing between stack plates.[2][4] While the viscous penetration depth describes the gas layer thickness near the stack plates which the motion is resisted by viscous force which will give negative contribution to the thermoacoustic effect.

Figure 1(a) shows the schematic diagram of the main components set-up which consists of a resonator tube, a loudspeaker, and a stack. The resonator has one end opened and one end closed so that it would serve as a quarter-wavelength resonator. The loudspeaker can generate a sound with high intensity in the resonator so that the acoustical standing wave can exist there. The stack is placed near the closed end where the pressure antinode exists. In this case, the cold and hot reservoirs are in the right and the left of the stack, respectively. The gas displacement caused by the sound which is accompanied by expansion and compression of the gas in the stack channel causes the heat transfer from the cold reservoir to the hot reservoir. The result is the decreasing and the increasing of the temperature of the gas in the cold and the hot reservoirs, respectively.

Figure 1(b) shows the ilustration that stack center position (xs) and stack length (ls) are related to the pressure amplitude of the gas and the velocity amplitude of the gas particles near the both ends of the stack. The temperature gradient along the stack will be proporsional to the difference of the gas pressure amplitude near the both ends of the stack. This pressure difference is greater when the stack is longer as long as the stack is located between node and antinode of the pressure. However, the longer is the stack, the greater is the viscous loss occurs in the stack. Therefore, it could be expected that there is an optimal stack's length for this thermoacoustic device. On the other hand, the stack is should be located closed to the pressure antinode of the standing wave in order to minimize the viscous dissipation of acoustic power. However, standing wave systems produce acoustic power in rough proportional to the velocity amplitude.[11] This means that the stack need to be placed near to pressure node of the standing wave. Therefore, it could be expected that there is an optimal stack's position for this thermoacoustic cooler.

III. EXPERIMENTAL METHOD

The schematic diagram of the experimental set-up is shown in Figure 2. A PVC pipe with length of 80 cm and diameter of $1\frac{1}{4}$ in. is used as a quarter-wavelength resonator, so that it had 106 Hz of resonance frequency, for sound speed about 349 m/s in air with temperature of about 30 °C. We used free air at atmospheric pressure as working medium to fill in the resonator tube. The choice of 80 cm length of resonator is to provide 1 mm of four times thermal penetration depth, which will be used as value of stack plate spacing. (Thermal penetration depth was calculated by using Eq. (2) where, for air at 30 °C, κ = 0.026 W/m·K, ρ = 1.168 kg/m^3, and c_p = 1,005 J/kg·K).

We used parallel plates stack which were made of mica plastic as plates and nylon fishing lines for giving space between stack. Figure 3 shows the schematic illustration of parallel stack and the cross section of a stack which was used in this experiment. The plates have thickness of 0.5 mm. The nylon fishing lines, which have 1 mm in diameter, were glued on the mica plates with 1 cm spacing between plates. Stacks were made for 14 variations in length from 3 cm to 16 cm, each stack has diameter about $1\frac{1}{4}$ in. so that it can fit to the inner diameter of the resonator.

An audio signal generated by a digital audio function generator (AFG) model GFG 8016G is amplified by an audio amplifier, and then come into an 8 in. 8 Ω loudspeaker which has 150 W of maximum power to generate a high intensity of sound. The loudspeaker input

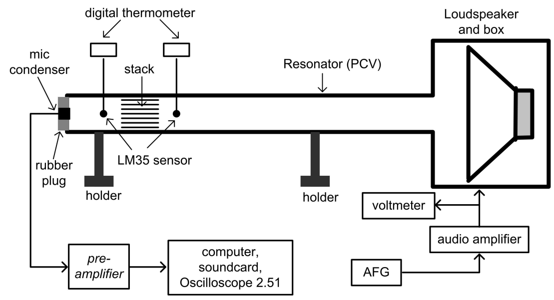

FIG. 2: The schematic of experimental set-up.

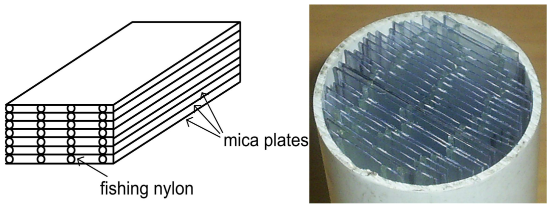

FIG. 3: Left: The schematic of parallel plat stack which is made of mica plat and fishing nylon. Right: A typical cross section of the parallel plat stack which was used in this experiment.

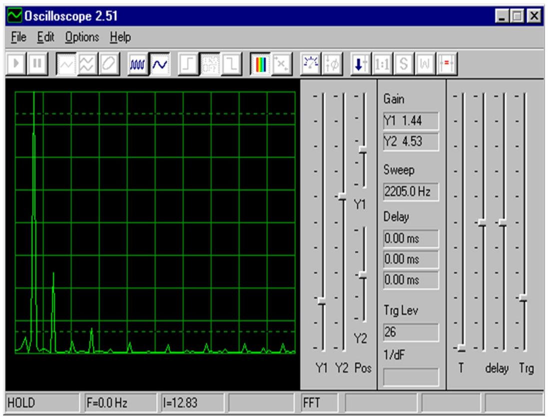

FIG. 4: The spectrum of sound in the resonator in the resonance condition at frequency around 106 Hz.

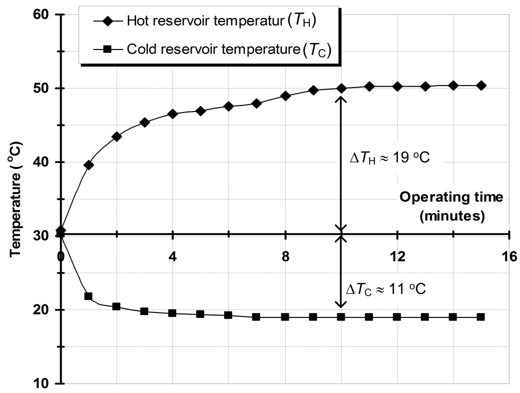

FIG. 5: Temperatures change of hot and cold reservoirs as a function of operating time of the thermoacoustic refrigerator where l_s =10 cm and x_s = 10 cm

voltage was measured by a voltmeter. The sound frequency was set at resonance about 106 Hz, so that an acoustical standing wave existed in the resonator. The resonance condition can be determined from the spectrum of sound in the resonator which was displayed in a real time on a computer monitor by using Oscilloscope 2.51 software.[12] With the standing sound wave within the resonator, the heat transfer can occur from the cold reservoir to the hot reservoir. The temperature of each reservoir was measured by using a digital thermometer with LM35 probe. For simplicity, the performance of this thermoacoustic cooler would simply be seen from the maximum temperature decrease of the cold reservoir. The measurements of air temperatures in the reservoirs were accomplished for different stack length and position in the resonator of the thermoacoustic device.

IV. RESULTS AND DISCUSSION

Figure 4 shows the spectrum of sound wave in the resonator when resonance condition occurred at frequency about 106 Hz. It can be seen that the first order component is a predominant frequency component in the resonator. The existence of stack in resonator caused a little shift of resonance frequency from its theoretical value for a quarter wavelength resonator. Therefore, for each time we changed the stack length and position in resonator, we needed to find a new resonance frequency.

A typical result of measurement of reservoirs temperatures as a function of operating time is depicted by Figure 5. In this case, we have used stack with 10 cm in length, and the distance of stack centre position from closed end is about 10 cm. This result confirmed the occurrence of heat transfer from cold reservoir to hot reservoir so that the air temperature in the cold reservoir decreased, while it increased in the hot reservoir. Initially, the reservoirs have same temperature of 30 °C. After 10 minutes of operating time, it has been observed that the temperature decrease (ΔT_C) of the cold reservoir is about 11 °C and the temperature increase (ΔT_H) of hot reservoir is around 19 °C. After that, air temperatures in the reservoirs were roughly constant. This indicated that thermal equilibrium of the system has been achieved. In addition, the increase of hot reservoir temperature was greater than the decrease of cold reservoir temperature because the volume of hot reservoir is smaller than that of cold reservoir.

The measurements like above was then carried out for different distance of stack centre position from closed end of resonator. The result is shown by Figure 6 where we have used stack with 10 cm length. It can be seen that there is an optimum stack distance which give the maximum temperature decrease of cold reservoir of about 11 °C, the maximum temperature increase of hot reservoir of about 19 °C, and the maximum temperature difference (ΔT) between hot and cold reservoirs, i.e. of 30 °C. In this case, the optimum distance is around 10 cm where the pressure and velocity effects, as described in previous section, have compromised to give an optimal performance for the thermoacoustic device.

The air temperatures in the reservoirs have also been measured for various length of stack we used. The result is depicted by Figure 7, where we have set 10 cm of stack centre distance from closed end of resonator. It can be seen that there is an optimum value of stack length

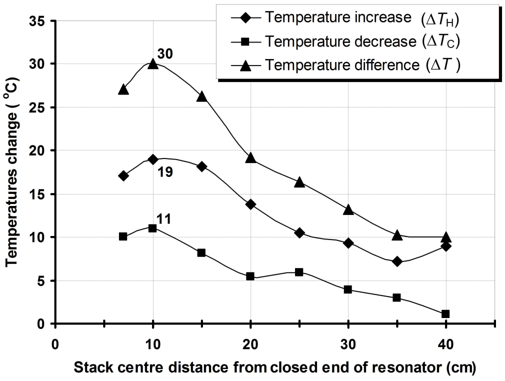

FIG. 6: The influence of stack centre position (distance from closed end of reso-nator) on the maximum temperatures change of reservoirs and the maximum temperature difference between reservoirs.

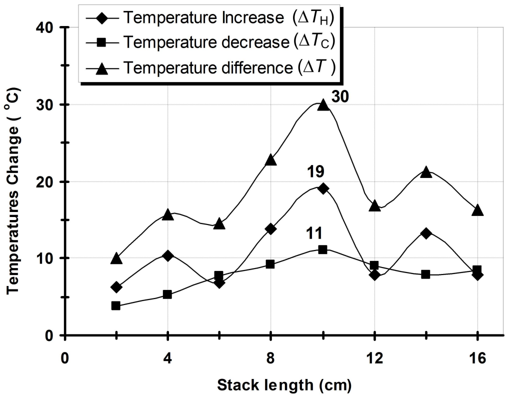

FIG. 7: The influence of stack length on the maximum temperatures change of reservoirs and the maximum temperature difference between reservoirs.

which give a maximum temperature changes of the cold and the hot reservoirs, and therefore a maximum temperature difference between the two reservoirs which can be achieved by this device. In this case, the optimum length of the stack is 10 cm which give temperature decrease of 11 °C, temperature increase of 19 °C, and temperature difference of 30 °C. When the stack length is less than its optimum value, the longer stack gives the greater difference of gas pressure amplitudes near to the both end of the stack which gives the greater temperature gradient along stack and therefore the greater temperature changes of the hot and cold reservoirs. When the stack length is more than its optimum value, the longer stack means that one end of the stack is closer to the pressure antinode (velocity node) and the other end is closer to the velocity antinode, where the first produces only a small acoustic power in standing wave system, and the second causes a greater viscous loss in the stack because of greater velocity.[11] In addition, the longer stack also contributes to the greater viscous loss because of the longer contact surface between gas and stack channels. These effects, therefore, make the heat transfer from cold to hot reservoirs was not effective enough so that the temperatures change of reservoirs were smaller.

V. CONCLUSION

From the description above, it can be concluded that there is an optimum value of each of stack length and stack position in thermoacoustic refrigeration system which give maximum temperature decrease of cold reservoir. In this case, the optimum stack length is 10 cm and the optimum stack position in resonator is 10 cm of the distance of the stack centre distance from resonator closed end. This optimum combination has given a temperature decrease of 11 °C so that the air temperature in cold reservoir, which was initially at 30 °C, has decreased down to 19 °C.

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