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Experimental Study on Thermoacoustic Cooling System with Two Stacks in a Straight Resonator Tube

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It has been done an experimental study of the use of two stacks 1 and 2 in a straight resonance tube of a thermoacoustic cooling system. We used a half-wavelength straight resonance tube at which the one end is closed by a rigid plug and the other end is closed by a plastic diaphragm which can vibrate axially due to sound wave produced by a loudspeaker facing to it. The tube is PVC pipe and filled by free air at atmospheric pressure and has 112 cm of length so it gives a calculated operating frequency around 152 Hz. The stacks are parallel plates type, which have plates thickness of 0.3 mm, and the plates spacing of 0.85 mm which is around four times of the thermal penetration depth. The diameter of stack is the same as the inner diameter of the tube, i.e. 4.6 cm, while the length of stack is 10 cm. We varied the sound frequency in the range of 130 – 160 Hz, the input electric power of loudspeaker from 40 W until 160 W, and the location of the center of the each stack in the range of 8 – 25 cm measured from each end of the tube, to investigate the their influences to the temperature decrease which can be achieved. It is found that the temperature decreases of the two cooling points 1 and 2 reached maximum at sound frequency of 147 Hz and when the two stacks were placed near to the ends of the tube. It is also found that a higher electric power tends to produce a larger temperature decrease. At 90 W of the input electric power, the maximum temperature decrease around 9.8 °C was obtained at cooling point 1 when the center of the stack 1 was placed at 80 mm from the rigid closed end of the tube.

1 Introduction

Thermoacoustic refrigerator is an alternative cooling system which is environmentally friendly due to the use of non-chlorofluorocarbon or non-hydro-fluorocarbon gas as working medium, i.e. it uses air or noble gas. This system uses a high intensity sound wave to provide work for transferring heat from the cold to the hot regions through a stack in resonator tube of the system. The description on the basic principles of work of this apparatus has been discussed by Wheatley [1]. Wetzel and Herman [2] have described the guideline for design optimization of thermoacoustic refrigerator. Zoontjens e*t al* [3] have constructed a low-cost loudspeaker-driven thermoacoustic refrigerator.

Thermoacoustic refrigerator basically consists of an acoustic driver (loudspeaker) coupled with a resonator tube which is filled with a working gas. A standing sound wave with a high intensity can be established in the resonator tube by the loudspeaker. In the tube, a stack is installed near pressure antinode of the sound wave. This stack separates the cooling region in where the gas parcel expands, and the heating region in where the gas parcel compresses. The cooling and heating processes occur due to the heat exchange between the gas and the stack layers. The net effect is the heat flow takes place from the cool to the hot sides, i.e. in the direction to the pressure antinode.

Typically, the simplest resonator for thermoacoustic refrigerator is a straight tube with one end closed and the other is open to which the acoustic driver is coupled, forming a quarter-wavelength resonator tube. In this case, we have only one pressure antinode, and we put the one stack near it. Otherwise, if we use a half-wavelength resonator tube which both ends are closed, we will possess two pressure antinodes

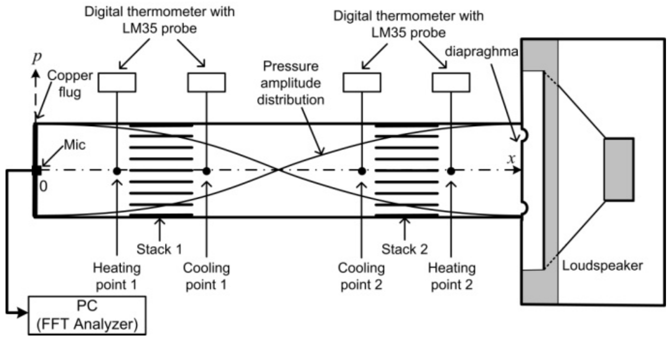

Fig.1 The schematic diagram of the thermoacoustic cooling system with two stacks in a half-wavelength resonator tube.

at the both closed end. If we then put two stacks near the pressure antinodes, we will have two cooling points and two heating point, the heat flows occur in opposite direction regarded to the stacks which basically give one cooling region in the middle of the resonator tube (Fig. 1). In this paper, we describe an experimental study of a thermoacoustic cooling sys-tem with two stacks in a straight resonator tube.

2 Theory

The total rate of heat flux $\dot{Q}$ pumped acoustically along the stack is approximately (by neglecting viscous losses) given by [4]

$$\dot{Q} = -\frac{1}{4}\Pi\delta_\kappa T_m \beta p_1 u_1 (\Gamma - 1) \qquad (1)$$

where Π is the perimeter of the stack plate in the direction normal to the axis of the resonator, δ_κ is the thermal penetration depth of the gas, T_m is the mean of absolute temperature of the gas, β is the coefficient of thermal expansion of the gas, p_1 is the pressure amplitude, u_1 is particle velocity amplitude, and Γ is the ratio of the temperature gradient across the stack (∇T_m) to a critical mean-temperature gradient (∇T_{crit}). The critical mean-temperature gradient which is given by [4]

$$\nabla T_{crit} = \frac{T_m \beta \omega p_1}{\rho_m c_p u_1} \qquad (2)$$

where ω is the angular frequency of the acoustic wave, ρ_m is the mean density and c_p is the isobaric heat capacity per unit mass of the gas. While the thermal penetration depth is given by [5]

$$\delta_\kappa = \sqrt{\frac{\kappa}{\pi f \rho c_p}} \qquad (3)$$

where κ is thermal conductivity, ρ is density, c_p is iso-baric specific heat of the gas, and f is sound frequency.

3 Experimental Method

Our thermoacoustic cooling system is schematically depicted in Fig 1. We used a PVC pipe of 112 cm long and 4.6 cm of inner diameter, one end is closed by a copper rigid plug and the other end is closed by a thin plastic diaphragm. The "diaphragm end" is assembled on a loudspeaker box in where a 10 inches loudspeaker of 200 W 4 Ω is installed. The sound produced by the loud speaker will make the diaphragm vibrates axially and so create a half-wavelength of standing sound wave inside the resonator tube. The resonator was filled with free air at atmospheric pressure and has a calculated resonance frequency around 152 Hz (for a half-wavelength tube). The resonance frequency is usually used as the operating frequency.

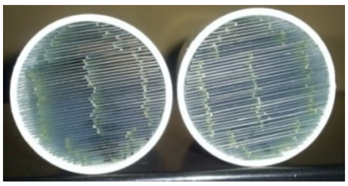

Figure 2. The cross section of the parallel plate stacks. The stack's housings are 2 in. PVC pipe.

We made two stacks of parallel plate type. The plate material is plastic which roughly has thermal conductivity in the range of 0.1 – 0.6 W/m·K and specific heat around 1.3 kJ/kg·K [6]. The plate thickness is 0.3 mm. To provide space between plates, we used nylon fishing lines of 0.85 mm in diameter which are glued to the plates. The stacks have length of 10 cm, diameter is the same as inner diameter of the resonator tube, i.e. 4.6 cm, and the cross sections are shown in Fig 2. In our condition for air at room temperature of 30 °C, the thermal penetration depth at frequency 152 Hz is around 0.215 mm, and our plate spacing is around $4\delta_\kappa$.

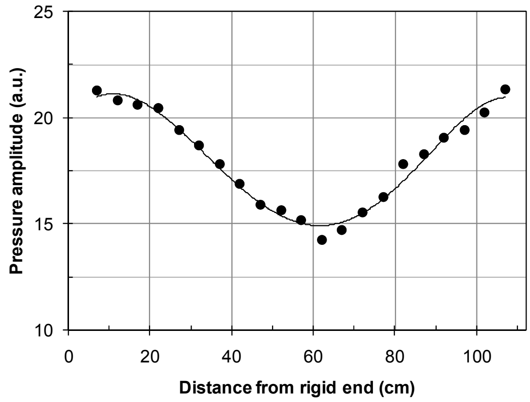

Figure 3. The relative pressure amplitude distribution in the resonator tube.

To ensure the presence of a half-wavelength of sound standing wave inside the resonator tube, we measured the relative amplitudes of pressure in the tube along the axis by using a small microphone and observed the FFT signal on a computer.

The temperature measurements were done by using four digital thermometers with LM35 temperature sensors, and carried out for various frequencies, input electric powers, and locations of the two stacks in the resonator tube.

4 Results and Discussion

The measurement results of the relative pressure amplitude distribution in the resonator tube at a driving frequency of 152 Hz is shown in Fig. 3. This confirmed that a half-wavelength of sound standing wave was present in the resonator tube. It can be seen that the pressure node was not exactly at the middle of the length of the tube and somewhat shifted toward to the diaphragm end due to the use of this diaphragm.

Based on this result, then we put stack 1 and stack 2 inside the tube each near the pressure antinodes, and it is expected that the heat will flow through the stacks to the middle of the the tube.

Fig. 4 depicts the typical result of the temperature measurements at the cooling and the heating points. In this case, the temperature decrease at the cooling point 1 (near rigid end) is greater than that of the cooling point 2 (near diaphragm), and conversely the temperature increase at the heating point 1 was smaller than that of the heating point 2, so that the temperature difference after 15 minutes, between heating and cooling points for each stack, are not so different.

The measurements of the temperature decrease at the cooling points for various sound frequencies give a result as shown in Fig 5. It shows that, in this case, the temperature decrease at the cooling point 1 is always greater than that of at the cooling point 2. In addition, it can be inferred from the figure that the operating sound frequencies are roughly in the range of 140 - 150 Hz which gives maximum temperature decrease. This operating frequency range is slightly below the calculated resonance frequency of 152 Hz for a half-wavelength resonator tube of 112 cm length. The presence of the stack in the tube and the use of diaphragm at one end of the tube were suspected to be the causes of the shift in operating frequency from the expected value.

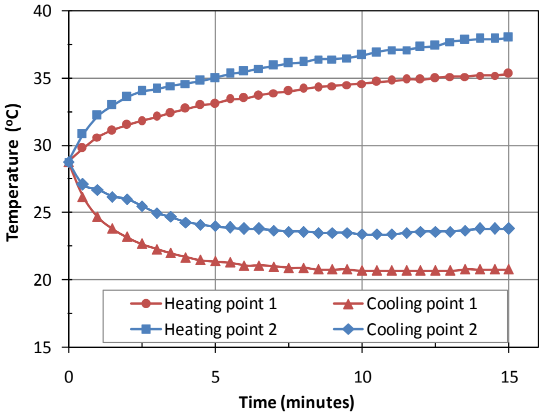

Figure 4. Temperature changes in time of the cooling and heating points 1 and 2 at frequency of 147 Hz and input power of 90 W.

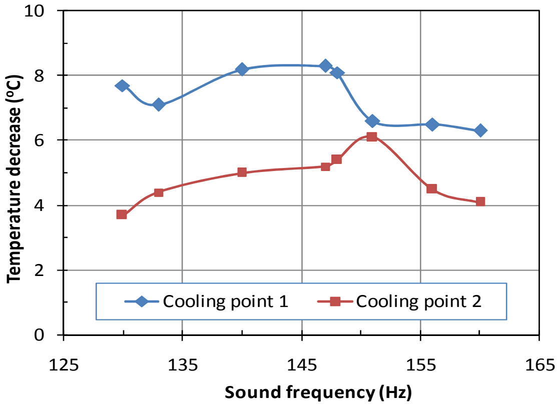

Figure 5. The temperature decreases for various sound frequencies.

The dependency of temperature decrease on the input electric power of loudspeaker can be seen on the Fig 6. It points out the tendency that the temperature decrease will be greater when we used the higher power input. Because this cooling system did not use any heat exchangers, the higher power input gave a greater heating in the hot side, and did not significantly enhance the temperature decrease due to the heat conduction through the stack.

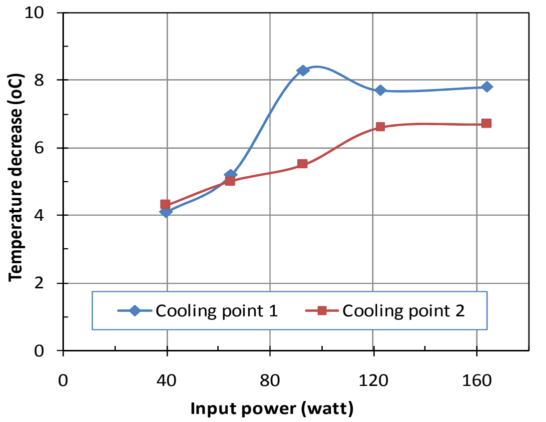

Figure 6. The temperature decrease for various input electric power.

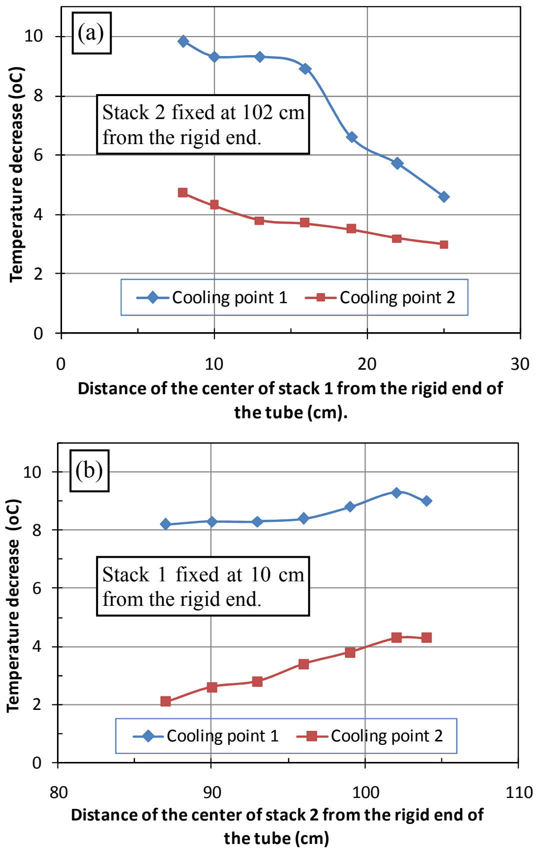

Figure 7. The temperature decrease: (a) for various location of stack 1 (stack 2 fixed at 102 cm from rigid end), and (b) for various location of stack 2 (stack 1 fixed at 10 cm from rigid end).

Fig. 7 shows the influence of stacks location in the tube on the temperature decrease at the cooling points 1 and 2. In Fig. 7(a), the location of the center of stack 1 was varied from 8 cm until 25 cm measured from the rigid end of the tube, while the center of stack 2 was fixed at 102 cm. Whereas in Fig. 7(b), the center of stack 1 was fixed at 10 cm, and the center of stack 2 was varied from 86 until 104 cm measured from the rigid end of the tube. It is clearly seen that the temperature decrease are greater when the stacks are each nearer to the ends of the tube, i.e. nearer to pressure antinodes. According to Eq.(2), the rate of the heat transfer is proportional to the product $p_1 u_1$. So when the stack is nearer to the closed end of the tube then it means a greater p_1 and a smaller u_1; and a smaller u_1 gives a lesser viscous loss. As a result, in this case, the cooling process is greater when the stack is located nearer to the both closed ends of the resonator tube.

The other fact which is shown by Fig. 7 is, again, the temperature decrease of the cooling point 1 is always greater then that of the cooling point 2. This shows that, in this case, the use of our diaphragm did not give a good cooling process in the stack near the diaphragm end. We sure that if we could make a better diaphragm, or we modify the loudspeaker so that its coupling with the tube make a closed end (pressure antinode), then the cooling at cooling point 2 would be better.

5 Conclusion

It has been built a thermoacoustic cooling system with two stacks in a straight resonance tube. The tube is a half-wavelength resonator with one end is closed by a rigid plug and the other end is closed by a plastic diaphragm. It was found a range of operating frequency of sound which give a maximum temperature decrease. This operating frequency was slightly below the calculated resonance frequency for a half-wavelength tube. The magnitude of temperature decrease was roughly proportional to the input electric power of the loudspeaker. The temperature decrease of the cooling point near the diaphragm is smaller than that of the cooling point near the rigid end. It is suggested to make a better diaphragm, or modify the loudspeaker so that it can give a better cooling at cooling point near the diaphragm. The investigation on the influence of stack location yield that the temperature decrease of the cooling points 1 and 2 tend to be greater when each of the stacks are placed nearer to each end of the tube.

Acknowledgement

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