Testing of a three-stage looped-tube thermoacoustic sound generator

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Abstract. Thermoacoustic sound generators are devices that produce sound waves by using thermal energy. The output acoustic oscillations can be used to drive a linear alternator to generate electricity. The devices are environmentally friendly because they do not produce any exhaust gases and they can utilize waste heat to generate the sound. This paper presents an experimental testing of a three-stage thermoacoustic sound generator of a looped-tube type. Each thermoacoustic core was composed of a regenerator, a hot heat exchanger and an ambient heat exchanger. The regenerators were made of a tight stack of 30-mesh stainless-steel screens, with a length of 35 mm. The looped-tube was made of stainless-steel pipes with inner diameter of 68 mm and total length of 4.3 m. Atmospheric air was used as working gas within the looped-tube. Three electric heaters, each with input power of around 394 W, were used as the heat sources and installed at the three hot heat exchangers. It was found that the device started to generate sound when the average temperature difference between the hot and ambient sides of the regenerators reached 255 °C. After 45 minutes operation, the average temperature difference was 538 °C, producing sound waves with a maximum pressure amplitude of 2.6 kPa and acoustic power of around 4.5 W. Additionally, it was observed a sound frequency jump during operation, that was 83 Hz until the temperature difference reached 526 °C and jumped to 339 Hz after that. During transition, both frequencies existed with relatively lower pressure amplitudes.

1. Introduction
Thermoacoustic sound generators (also called thermoacoustic prime movers) are devices that produce sound waves by using thermal energy. The sound waves are generated through thermal and hydrodynamic interactions between acoustically oscillating working gas and a porous solid material (stack or regenerator) having a large temperature gradient in the direction of sound propagation. The temperature gradient is created by external heat sources which supply thermal energy to the hot end of regenerator through a hot heat exchanger. The output sound waves can be used to drive a linear alternator to generate electricity or to power a thermoacoustic refrigerator [1].

Thermoacoustic technology becomes more attractive due to its simple construction with only a few moving components involved so that significantly reducing the need of lubrication and maintenance cost. Additionally, the thermoacoustic engines are environmentally friendly because they only use safe working gases such as air or noble gas, do not produce any exhaust gases, and can utilize waste heat as the thermal energy source in generating the sound [1][2]. However, thermoacoustic prime movers generally need high-temperature heat sources to be able to produce acoustic work. In the other words, they start to generate sound wave at a large onset
temperature difference between the both ends of regenerator. This condition inhibits utilization of low-grade heat source such as industrial waste heat or any other combustion heat in practical thermoacoustic applications.

To lower the onset temperature, multi-stage thermoacoustic engines have been proposed. Biwa et al [3] wanted to know to what extent the critical ratio of the hot and cold temperatures of the regenerator ends ($T_H/T_C$) can be lowered. They found that by using five regenerators which were differentially heated and installed at suitable locations in a looped-tube combined with a branched tube, the critical $T_H/T_C$ was decreased from 1.76 to 1.19. Since then, several multi-stage thermoacoustic systems (including prime mover, refrigerator, and electricity generator) have also been developed. For examples, two-stage thermoacoustic devices have been built and studied by Yahya et al [4], Kalid et al [5] and Kang et al [6], while Zhang et al [7] and Yang et al [8] have constructed and investigated three-stage thermoacoustic instruments.

This paper presents some results of a testing on a three-stage traveling-wave thermoacoustic sound generator of a looped-tube type with atmospheric air as working gas. The aim is to know the operational behavior of this thermoacoustic device. Compared to the previous results mentioned above, where the frequency of the generated sound was at a fundamental frequency, in this research it was found that the generated sound underwent a frequency jump during operation, from fundamental frequency jumped to became around four times the fundamental one. In this case, the discussion were made by considering the relative comparison among the regenerator hydraulic radius and the thermal- and viscous- penetration depths. In addition, the onset temperature difference, sound pressure amplitude, and acoustic power are also discussed in this paper.

2. Experiment
The schematic diagram of the three-stage looped-tube thermoacoustic sound generator in this study is shown in figure 1. It is mainly made of 6.8 cm inner-diameter stainless-steel pipes with total length of 4.3 m. The looped-tube contains free air as working gas, that is having pressure of around 1 atm and temperature of about 26 °C in laboratory room. The sound speed in air at this condition is approximately 347 m/s. Assuming the looped-tube as one-wavelength resonator, the fundamental sound frequency within it is estimated around 81 Hz. Thermal penetration depth ($\delta_k$) and viscous penetration depth ($\delta_v$) in air at a frequency $f$ is calculated as $\delta_k = \sqrt{k/\pi f \rho c_p}$ and $\delta_v = \sqrt{\mu/\pi f \rho}$ where $k$ is thermal conductivity, $\rho$ is density, $c_p$ is isobaric specific heat, and $\mu$ is dynamic viscosity of air [9]. At a frequency of 81 Hz, this thermoacoustic device has $\delta_k = 0.290$ mm and $\delta_v = 0.248$ mm.

Three regenerators are made of tight stacks of 30-mesh stainless-steel screens ($n = 30$/inch) with wire diameter ($D$) of 0.18 mm. Each regenerator has a length of 35 mm. The porosity ($\phi$) and hydraulic radius ($r_h$) of the regenerators are estimated to be 0.83 and 0.224 mm, respectively, by using the equations of $\phi = 1 - \pi n D/4$ and $r_h = D \phi/4(1 - \phi)$ [9]. Therefore, the omega-tau ($\omega\tau$) parameter for the present thermoacoustic device is calculated to be around 0.60 by using a defined formula of $\omega\tau = (r_h/\delta_k)^2$ [10]. This $\omega\tau$ value ensures good thermal contacts between working gas and regenerator material which is required by traveling-wave type thermoacoustic devices which execute Stirling thermodynamic cycle [10].

The regenerator is sandwiched by a hot heat exchanger (HHX) and an ambient heat exchanger (AHX). The HHX consists of a copper block which has many small axial holes and is wrapped around with a flexible cable electric heater with 400-watt maximum input power. The AHX is composed of an ambient water flow system and a copper block with many small holes, as well. These heat exchangers create and maintain a temperature gradient along the regenerator which is needed to produce the sound waves. Other ambient water flow systems were installed on the looped-tube at a distance of 20 cm from each HHX, serve as additional ambient heat exchangers (AHX′) to cut off the heat flow from HHXs to the rest parts of looped-tube.
Figure 1. Schematic diagram of the three-stage looped-tube thermoacoustic sound generator. All dimensions are in millimeter (mm). P1, P2,..., P5 are installation location of five pressure transducers.

The experiment was done by heating the hot end of regenerators using the electric heaters with input power of 394 W. The temperatures at both ends of regenerators were measured by using type-K thermocouples (Sakaguchi E.H. VOC Corp.) (not shown here). After the thermoacoustic sound generator started to produce the sound waves within the looped tube, the dynamic pressures at five different locations P1, P2, ..., P5 along the tube (see figure 1) were measured by using PGM-10KH pressure transducers (Kyowa Electronic Instrument Co., Ltd). The data from thermocouples and pressure transducers were collected by a data logger, then displayed and saved by a computer.

3. Results and Discussion
After the electric heaters turned on, temperature difference between regenerator ends started to rise. Figure 2 shows the average temperature difference ($\Delta T$) history for the three regenerators in the present thermoacoustic sound generator. It was found that the device began to generate sound waves when the average temperature difference reached 255 $^\circ$C, as indicated in the figure. This onset temperture difference value was much lower than that of our previous thermoacoustic prime mover with only single-stage regenerator that was 417 $^\circ$C [11]. The average $\Delta T$ tended to be stable at a maximum value of around 538 $^\circ$C after 45 minutes operated. Furthermore, it was observed that the sound frequency inside the looped tube jumped from 83 Hz to 339 Hz after the average $\Delta T$ was larger than 526 $^\circ$C, as discussed in a more detail below.

Figure 3 presents spectrums that confirmed the frequency jump which occurred when the temperature difference increased. Figure 3(a) is the frequency spectrum when $\Delta T = 526$ $^\circ$C (at $t = 26$ minutes), showing that the dominant sound frequency is 83 Hz. This spectrum was
Figure 2. Average temperature difference ($\Delta T$) history for the three regenerators in the present thermo-acoustic sound generator.

obtained by applying the fast fourier transformation on the time domain dynamic pressure signal detected by the pressure transducer at P5 location (see figure 1), giving pressure amplitude ($p_0$) of 1.32 kPa. All sound spectrum for $\Delta T < 526 ^\circ C$ (before $t = 26$ minutes) revealed that the dominant frequency was around 83 Hz (not presented here, but see figure 4 as a summary). This frequency was not so different from the estimated fundamental frequency of 81 Hz which was mentioned in previous section by assuming the looped tube as one-wavelength resonator. A minute later (at $t = 27$ minutes), the temperature difference decreased to 524 $^\circ C$, and it was found at this situation that the sound waves inside the looped tube consisted of two dominant frequencies, those were 83 Hz and 339 Hz, as indicated by the spectrum in figure 3(b). In this case, the pressure amplitudes of the dominant sound waves were much lower than before, those were 0.57 kPa and 0.63 kPa. It is understood as a transition situation, and most of the sound energy at this period was shared to the waves whose those two dominant frequencies. The temperature difference ($\Delta T$) was slightly reduced because the additional dominant sound wave with different frequency triggered a mass streaming [9] of air from ambient side to hot side of regenerators. This resulted in a temperature decrease at each regenerator hot side and in turn reduced the temperature difference between the both ends of regenerators. Next, a minute after that (at $t = 28$ minutes), the dominant sound frequency was fully at 339 Hz, as can be seen in figure 3(c). In this case, the pressure amplitude was 1.03 kPa. All sound spectrum after this time revealed that the dominant frequency varied slightly from 339 until 341 Hz (not presented here, but see figure 4 as a summary). The frequencies within this range was roughly four times the fundamental frequency found before the frequency jump occurred.

The occurrence of frequency jump has significant impacts on the values of thermal penetration depth ($\delta_k$), viscous penetration depth ($\delta_v$), and $\omega\tau$ parameter. If we write the new frequency as $f' \approx 4f_0$ where $f_0$ is fundamental frequency, then the new thermal- and viscous- penetration depths become a half of the old values ($\delta'_k = \frac{1}{2}\delta_k$ and $\delta'_v = \frac{1}{2}\delta_v$), and the new $\omega\tau$ becomes four times the old one, that is $(\omega\tau)' = 4\omega\tau$. For the present thermoacoustic device with $r_h = 0.224$ mm and frequency $f_0 = 83$ Hz, $\delta_k$ is 0.286 mm and $\delta_v$ is 0.244 mm. Therefore, with a new frequency $f' \approx 4f_0$, the new thermal- and viscous- penetrations depth are $\delta'_k \approx 0.143$ mm and $\delta'_v \approx 0.122$ mm, respectively. Figure 5 depicts a graphical comparison among $r_h$, $\delta_k$, $\delta'_k$, $\delta_v$, and $\delta'_v$. It points out that at a low frequency ($f_0 = 83$ Hz), the viscous boundary layer ($\delta_v$) was larger than the hydraulic radius ($r_h$) of the regenerator pores. This situation led to high acoustic
Figure 3. Sound spectrum (a) before frequency change (at $t = 26$ minutes or and $\Delta T = 526^\circ C$), (b) at transition (at $t = 27$ minutes or $\Delta T = 524^\circ C$), (c) after frequency change (at $t = 28$ minutes or $\Delta T = 523^\circ C$).

Figure 4. The sound frequency experience a jump after $\Delta T$ reached $526^\circ C$.

Figure 5. Graphical comparison among $r_h$, $\delta_k$, $\delta'_k$, $\delta_v$, and $\delta'_v$ in this experiment.

losses due to viscous effects in the working gas within the regenerator pores. In contrast, at a higher frequency ($\approx 4f_0$), the viscous boundary layer was smaller enough than the hydraulic radius ($\delta'_v \approx 0.56r_h$), resulting in lower acoustic losses. Hence, the present thermoacoustic device tended to set itself up to working at a high frequency to reduce the acoustic losses while still had a good enough thermal contact between working gas and regenerator material ($\delta'_K \approx 0.67r_h$).
Figure 6. Pressure amplitude variation: (a) versus time $t$, and (b) versus average temperature difference $\Delta T$ between regenerators ends.

This condition is then considered as the effective and efficient situation for thermoacoustic energy conversion (thermoacoustic effects) to occur, as can be deduced from the next figure. Figure 6 shows the sound pressure amplitude variation versus time (a) and versus average temperature difference between the regenerators ends (b). Two data points within dashed circles corresponded to the two pressure amplitudes of the dominant sound waves with frequencies of 83 Hz and 339 Hz which appeared simultaneously at transition period, as have been indicated in figure 3(b). Before transition, with sound frequency of 83 Hz, the pressure amplitude tended to slowly increase along with time and the rise of temperature difference. Since the transition, with sound frequency of around 339 Hz, the pressure amplitude rapidly increased along with time and the accretion of temperature difference. The increase of temperature difference as big as 186 $^\circ$C before transition gave only 0.52 kPa (65%) pressure amplitude increment, whereas the increase of temperature difference of just 15 $^\circ$C since transition resulted in enhancement of 1.97 kPa (312%) pressure amplitude. These results support the notion that thermoacoustic effects work more effective and efficient at higher frequency in the present thermoacoustic device, due to smaller viscous boundary layer in regenerator, as has been discussed above. Further research is needed to know the reason why a frequency jump occur at a certain high temperature in regenerator.

Figure 7. Acoustic power at points A and B (see figure1) for various temperature difference.
It has been known that the direction of acoustic energy flow is running around the loop through the regenerator from AHX to HHX [10][12]. Hence, the acoustic energy was flowing clockwise in the present thermoacoustic device if we referred to figure 1. The acoustic power ($W_{ac}$) at two points A and B (see figure 1) have been measured by using two-sensor method which used the equation of $W_{ac} \approx \frac{A}{2\rho \omega \Delta x} |p_1| |p_2| \sin \theta$ [9][13]. In this equation, $p_1$ and $p_2$ are pressure amplitudes measured by two pressure transducers at points 1 and 2, respectively, which are separated by a distance of $\Delta x$, $\theta$ is phase difference by which $p_1$ leads $p_2$, $A$ is area of the tube cross-section, and $\omega$ is angular frequency of the sound wave. Figure 7 shows that the acoustic power at points A and B increased markedly from around 1 watt to about 4.5 watt when the average temperature difference between both ends of regenerators rose from 528 °C up to 538 °C. In addition, the acoustic power at point A was always higher than that at point B. This is because the acoustic power at point A was a result of sound amplification from two regenerators 1 and 2 (minus acoustic losses in the pipe from HHX-2 until point A), while the acoustic power at point B was a result of amplification from regenerator 3 only (minus acoustic losses in the pipe from HHX-3 until point B).

In the future, the present device can be improved by installing the fourth regenerator, beside the third one, for example. Moreover, the sound pressure amplitude can be increased by using pressurized working gas. Afterward, by installing a linear alternator (e.g. loudspeaker) at location where the pressure amplitude is high makes this device become a heat-powered electricity generator.

4. Conclusions
A three-stage looped-tube thermoacoustic sound generator has been experimentally tested. By using three electric heaters as the heat sources with input power of around 394 W for each heater, the findings are as follows. The average onset temperature difference was 255 °C. A frequency jump occurred during operation. In this case, it was jumping from 83 Hz to 339 Hz after the temperature difference reached 526 °C, and the higher frequency was more favorable due to smaller viscous losses. The average temperature difference tended to be stable at around 538 °C, producing sound waves with a maximum pressure amplitude of 2.6 kPa and acoustic power of around 4.5 watt.

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