Experimental Study on Variation of Tilted Angles Toward Acoustic Power of Thermoacoustic Engine

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Abstract. Tilted angles have to be researched for determining the good position of thermoacoustic engine. The research aims to find the best acoustic power with a tilted angle of the position, therefore the performance of Standing-Wave Thermoacoustic Engine (SWTE) is going to be increased. The performance is affected by the tilted angles. The natural convection which occurs in the core of Thermoacoustic Engine will be different every tilted angle. The heat transfer characteristics within it were investigated under three tilted angles including, -90°, 0°, and 90°, with the resonator length 780 mm. This study was for getting the acoustic power which used the two sensors method with Data Acquisition (DAQ) NI-DAQmx 15.5 and two pressure transducers. It was calculated by Matlab R2013a. In this research is found that the acoustic power which is the best value is resulted on 90° of tilted angle, while the smallest value is found on 0°. Thes matter can be occured because phase difference of acoustic wave on the 90° is the biggest value, while the 0° is the smallest value. Further, have to study how phase difference has big effect toward the horizontal position which is resulted on the worse value compared the vertical position.

1. Introduction

In converting from heat energy to become another energy, acoustic power of thermoacoustic engines has been tried to contend with internal combustion engines for last several years ago. One of the examples is converting to electric energy. The four types of acoustic to electric conversions are such as electromagnetic devices, piezoelectric devices, magneto hydrodynamic devices, and bidirectional turbines [1]. Research has applied one of the types, piezoelectric devices in a study that is thermoacoustic piezo system called Rijke-Zhao system and has explained the energy conversion process and harvesting heat energy by the type [2]. Before converting heat energy to electric energy, heat energy first is converted to acoustic waves, then to be converted to electrical energy. For generating acoustic waves, thermoacoustic engine needs waste heat sources that contain abundant heat sources. Furthermore, the thermoacoustic engine has also been applied for cooling system. Research used the waste heat from the inside of microelectronic components to generate acoustic waves has been finished [3]. The sound was later used as a cooling driver of thermoacoustic to be cold the surface of the computer processor. The capability of cooling of the device could produce begin 0.1 up to 0.6 Watt per cm² in cross-sectional area of the resonator. The other study [4] of thermoacoustic refrigerator driven by reused heat from exhaust gases has applied to refrigeration system of vehicles. The system can substitute the conventional refrigeration system that has applied before.

The one of parameters which affect the acoustic power of Standing-Wave Thermoacoustic Engine (SWTE) is tilted angles of the device. Namely by varying position placement on SWTE device with
various angles, that is tilted angles such as horizontal position 0°, slope position -45°, and 45°, and vertical (-90°) and (90°). There was a research which was conducted by varying the tilted angles at range of -90° to 90°, and the result was comparing any others working fluid except air on some parameters analysis [5]. From now on, there have conducted same research [6], in the research, it was just explained about one parameter, onset temperature that was affected by tilted angles it was onset and also the damping behaviors of the onset temperature. When a position of the tilted angle called -90°, that the condition of the direction of the temperature gradient is similar as the direction of gravity, thus further it can be reinforcement the natural convection that can be occurring. So the onset temperature of SWTE, which was the greatest is when the device in (-90°) of this tilted angle. Furthermore, there is research that has conducted same research with variation with different aim [7] and any other research with the same variation also like tilted angles [8].

There have not been researches that published that have presented and have analyzed the connection of different tilted angles toward acoustic power of SWTE with common air as working fluid. This research aims for the acoustic power could be greater because it could be interpreted that the performance of SWTE is in good way. So in this research, it uses variations of tilted angles, there are three tilted angles including (-90°), (0°), and (90°). Therefore, research needs to be done with the variable of the variants that were mentioned above. The aim of this research is to investigate the effect of tilted angles with the working gas, which just uses air at 1 atm of pressure and 25°C until 27°C room temperature toward acoustic power. The results of the experiment are essential for an effective position based on tilted angles, then, this is obtained the best performance or describe and illustrate the scientific reason why this phenomenon occurs in SWTE.

2. Experimental Apparatus and Measurement

2.1. Component of Standing-Wave Thermoacoustic Engine (SWTE)

Fig. 1. below illustrates the components of SWTE. Names of each components are below the figure.

![FIGURE 1. Components of Standing-Wave Thermoacoustic Engine](image_url)

Information:
1. Hot Heat Exchanger (HHX)
2. Resonator
3. Thermal insulation
4. Glow plug
5. Wire mesh
6. Cold Heat Exchanger (CHX)

2.2. Positioning Thermoacoustic Engine Device with Variation of Tilted Angles

To get result of performance of SWTE with variation tilted angle, the apparatus of experimental research can be changed every different tilted angles. In process of experiment, the thermoacoustic engine was put on the floor, except on horizontal position, the device was propped up iron cantilever. The each experiment of thermoacoustic engine was conducted for each tilted angle. The angle was defined as a
positive value in case the HHX was above the CHX (tilted angle on 90º). It was defined as a negative value if the HHX was below the HHX (tilted angle on -90º) as shown as in Fig. 2.

![Image](a) ![Image](b)

**FIGURE 2.** The position of tilted angles of thermoacoustic engine
(a) -90º and (b) 90º

The research were performed for every 90º from -90º to 90º. The position of 0º is shown in Fig. 3. that the resonator lengths was defined 780 mm. Hence, three tilted angles including -90º, 0º and 90º have been tested in total. The thermoacoustic engine was arranged of two heat exchangers (hot heat exchanger and cold heat exchanger), thermoacoustic core, and resonator tube. The thermoacoustic core which is between two heat exchangers was the main component of thermoacoustic engine which is called stack.

![Image](a)

**FIGURE 3.** The position of tilted angle on 0º

The geometry of the component of thermoacoustic engine are presented by Table 1. There are sizes of components such as diameter of HHX, Stack, CHX, and Resonator Length. Also, the length for each components.

**Table 1.** Size of component of SWTE.

|                  | HHX | Stack | CHX | Resonator |
|------------------|-----|-------|-----|-----------|
| Diameter (mm)    | 52  | 52    | 52  | 52        |
| Length (mm)      | 40  | 30    | 40  | 780       |
2.3. Experimental Steps

In the research, the temperature of thermoacoustic core which consist of HHX, Stack, and CHX were measured every variation of tilted angles. The steps of experimental research were similar to each position of angle of tilted angles. The corresponding of experimental set up with several steps, there are:

1. HHX of thermoacoustic engine apply an electrical heater that is called Battery Charger Transformer (BCT) which the six glow plugs are stacked around a cylinder copper in the duct. A voltage regulator was used to control the heat temperature. The BCT was stabilized at 230 Watts. It would be heated until to maximum temperature at 320ºC in this experiment. The CHX was cooled by circulate common water which the temperature was steady at 25º – 28ºC. The temperature of HHX and CHX were measured by thermocouples which the type is K-type which were completed both of them. The thermocouples T1 and T2 which are the thermocouples in Fig. 4. were located between left and right side of the stack. The schematic diagram of this experimental research is shown at Fig. 4.

2. The data of parameter of acoustic wave were taken down and conjoint by Data Acquisition (DAQ) with series NI-DAQmx 15.5 and NI LabVIEW 2015 of the software program. This parameters of the acoustic wave such as pressure amplitude with time domain.

3. Result of raw data were times to pressure amplitude, then, the time domain was converted to become to frequency domain by Fast Fourier Transform (FFT) formula. Data Acquisition (DAQ) and software program, that is NI LabVIEW 2015 were used to record the process of taking raw data from pressure transducer to obtain the values such as frequency, pressure amplitude, and phase of acoustic wave with the FFT method. The values of them which were taken to caculate acoustic power by substitute them inside an equation were presented in the Equation (1) below. PT1 and PT2 are PA and PB in the equation which were pressure transducers with 50 mm of distance between them on the center of the resonator.

4. The stack was chosen with type of stack wire mesh screen with the material of stainless steel and onset temperatures were in interval 200ºC – 250ºC. Oscillation of acoustic wave in the resonator occurs in open end system.
The module in Data Acquisition (DAQ) National Instrument NI-DAQmx 15.5 which is presented in Fig. 5. with code NI9213 was connected to thermocouples. It was used to measure temperature in HHX and CHX. While the other one as code NI9234 was connected to pressure transducers for measure the pressure amplitude with domain of time and could be converted with FFT to domain of frequency.

**FIGURE 5.** Data Acquisition (DAQ) NI-DAQmx 15.5 with 2 module (NI9213 and NI9234)

Pressure transducer is presented in Fig. 6. below with type PCB 102 which accurately measured parameters of acoustic wave in resonator. There are two pressure transducers that could be used to measure pressure amplitudes based on two sensor method.

**FIGURE 6.** Pressure Transducer (PT) PCB 102 to measure pressure amplitude
The layout of LabVIEW when recording data in real-time condition is presented in Fig. 7. On the left side is the appearance of acoustic waves with time domain, while, right side is frequency domain.

![Image](image_url)

FIGURE 7. The Layout of LabVIEW in measurements pressure amplitude with FFT (Fast Fourier Transform)

Then, the magnitude of pressure amplitude was substituted in formulation to calculate acoustic intensity. Because it is the function of acoustic intensity, it can be resulted the data of acoustic power.

3. Method For Calculating Acoustic Power

In the beginning, calculating the acoustic intensity \( I \) before finding acoustic wave was determined to use the two pressure sensor method [9]:

\[
I = \frac{1}{8\omega \rho} \left[ \text{Im}[H](|p_A|^2 - |p_B|^2) + 2 \text{Re}[H]|p_A||p_B| \sin \theta^\circ \right]
\]  

(1)

Equation (1) calculates the acoustic intensity which is between the two sensors (in this research called pressure transducer) which is used to measure \( P_A \) and \( P_B \). Where \( P_A \) and \( P_B \) are the pressure amplitude of acoustic waves measured at two adjacent pressure sensor positions along the resonator, and \( \theta^\circ = \text{arg}[P_A/P_B] \) is the phase difference of pressure amplitude of acoustic wave \( P_A \) relative to \( P_B \). Then \( \rho \) is represented the density of the working gas, \( \text{Re}[\ ] \) and \( \text{Im}[\ ] \) represent the real and imaginary components.

Defining \( H \) with:

\[
H = \frac{kF}{\cos(k\Delta x/2) \sin(k\Delta x/2)}
\]

(2)

\( k \) constitutes the complex wave number and \( F \) constitutes a complex factor which are calculated by:

\[
F = 1 - \frac{2J_1(k^{3/4}\sqrt{2\rho_0/\delta_v})}{k^{3/2}(\sqrt{2\rho_0/\delta_v})J_0(k^{3/4}\sqrt{2\rho_0/\delta_v})}
\]

(3)
and
\begin{equation}
    k = -i k_0 \sqrt{\frac{J_0(\frac{3/2}{\sqrt{2}r_0/\delta_v})}{J_2(\frac{3/2}{\sqrt{2}r_0/\delta_v})}} \sqrt{\gamma + (\gamma - 1) \frac{J_0(\frac{3/2}{\sqrt{2}Pr_0/\delta_v})}{J_2(\frac{3/2}{\sqrt{2}Pr_0/\delta_v})}}
\end{equation}

where \( J_n \) is the \( n \)th order complex of Bessel function, and \( \sigma \) is the Prandtl number and \( \gamma \) is the specific heat ratio respectively.

So, acoustic power (\( \tilde{E} \)) is able to be calculated by dividing acoustic intensity (\( I \)) with cross-sectional area (\( A \)) of thermoacoustic core which is the same and connected by resonator.

\begin{equation}
    \tilde{E} = I \cdot A
\end{equation}

The calculating to acoustic power above was conducted with using software program as Matlab R2013a in order to be easier and fast to result end data, which is the acoustic power.

4. Result and Discussion

Effect of Different Tilted Angles toward Acoustic Power

The plotting data of acoustic power which are obtained from the experiments with variation of different tilted angles are presented in Fig. 8. We are able to know effect of different tilted angles toward Acoustic Power. The researcher found phenomenon that is the best position of this device at 90º of the tilted angle. The acoustic power at tilted angle of 90º was found of 10.7 Watts. While at 0º, it was found of 0.5 Watts. Besides, at -90º, it was found of 6.7 Watts. This is presented in Fig. 8 that can be inferred as we put a position of thermoacoustic engine with the core below the resonator on position (-90º). The data of acoustic power is on the best position because of natural convection occurring in the core. While the experimental investigation has been implemented at different tilted angles with range begin -90º to 90º. The more the tilted angle decreases, the more the working fluid (gas fluid) and stack of heat transfer coefficient of the natural convection are going to increase [10]. So that, this tilted angles affect it in using less energy than others positions. It is only appropriate for using heat energy sources. However, this statement is not consistent to acoustic power.

Beside the statements above, the phase of wave precisely affect a result in power. Because of the difference of two waves’ phase which is each measured by PT1 and PT2, it is called also phase difference become the function in calculating acoustic power. Table 1 presents the data of phase measured by PT1
Based on equation (1), phase difference \((\theta^o)\) which was found at 0º of tilted angle is the smallest value among the others, so that it cause the experiment result the smallest value of acoustic power. The best acoustic power is found at 90º same case with the best value of phase difference too. This research have not explained scientifically the phenomenon how it can be happening. So, it have to conduct the next research about the analysis of how phase difference can give big effect toward acoustic power, which causes the horizontal position has worse value compared vertical position.

Table 2. Phase and phase difference of each tilted angles

| Tilted Angles | phase measure by PT1 (\(\theta_1^o\)) | phase measure by PT2 (\(\theta_2^o\)) | phase difference (\(\theta^o\)) |
|---------------|------------------------------------|------------------------------------|-------------------------------|
| -90º          | -2.2479                            | -1.7334                            | 0.5145                        |
| 0º            | 0.4184                             | 0.3919                             | 0.0265                        |
| 90º           | -2.8473                            | -1.3577                            | 1.4896                        |

Conclusion

According to the result, it is able to be concluded that the acoustic power has the greatest position at 90º of tilted angle which the value is 10.7 Watts. Also, the smallest value of acoustic power found at 0º which the value is 0.5 Watts. It can be inferred that the big effect is caused by phase difference. The next researcher has to conduct the next research about the analysis of how phase difference has big effect toward the horizontal position which is resulted on the worse value compared the vertical position.

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