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Thermoacoustic energy conversion in a square duct

Govind Harikumar[a,b], Ker Hin Ho[b], Kai Wang[c], Swapnil Dubey[a], Fei Duan[b,*]

[a]*Energy Research Institute @NTU, Interdisciplinary Graduate School, Nanyang Technological University, Singapore, 637141, Singapore*
[b]*School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798, Singapore*
[c]*Department of Chemical Engineering, Imperial College London, London, SW7 2AZ, United Kingdom*

Abstract

The present study aims to demonstrate the thermoacoustic energy conversion phenomenon in a standing wave resonator driven by a commercial loudspeaker with a stack made of plastic straws and atmospheric air as the working fluid. The system is driven at resonance frequency of 70 Hz with the stack kept in the middle section of the resonator and a temperature difference of 14.1°C was produced between the ends of the stack at a drive ratio of 3.57 %. The hot end reached a temperature of 36.5°C and the cold end reached a temperature of 22.4°C at the highest drive ratio. Moving the stack towards the end of the resonator reduces the temperature difference produced showing the influence of stack position. Thermoacoustic devices offer an environment-friendly solution to utilize waste heat or renewable energy sources, to upgrade low grade heat or generate cooling or produce electricity using acoustic-electric transducers. This study is done as a pre-cursor, to develop a relatively inexpensive prototype for studying non-linear effects at high drive ratios seen in thermoacoustic devices, which are known to reduce their performance.

Keywords: Thermoacoustics; stack; oscillating flow; resonator; temperature difference.

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1. Introduction

Thermoacoustics, as the name implies deals with the interconversion between thermal and acoustic energy [1]. Thermoacoustic processes involve the creation or amplification of an acoustic wave by virtue of a temperature difference or the generation of a temperature difference due to the propagation of an acoustic wave. A typical

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[*] Corresponding author. Tel.: +65-67905510; fax: +65-67924062.
E-mail address: feiduan@ntu.edu.sg

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thermoacoustic system consists of a stack or regenerator surrounded on either side by hot and cold heat exchangers constituting the 'thermoacoustic core' which is enclosed inside a resonator. The working fluids used are inert gases and they have no or very few moving parts, thereby making them reliable in the long run. They can be constructed with inexpensive materials and can be scaled according to energy requirements. Therefore, thermoacoustic systems can serve as an effective means of energy harvesting from renewable energy sources and waste heat with minimal environmental impact [2-6]. Our current understanding of thermoacoustics is based on the linear theory of thermoacoustics pioneered by Rott [1] and later reworked by Swift [7] for low amplitude oscillations by assuming sinusoidal time dependence for quantities like pressure, volume velocity, temperature and density. Using the linear theory, it is possible to predict the performance of thermoacoustic systems for steady-state low amplitude oscillations. However, in the case of practical thermoacoustic engines and refrigerators, high amplitude oscillations are present and the theory fails to make accurate predictions. At these higher amplitudes, several non-linear effects become prominent such as acoustic streaming, vortex generation and shedding, turbulence, harmonics and entrance effects [7]. These effects can degrade the performance of thermoacoustic engines and refrigerators in the real world. Therefore, in order to design thermoacoustic systems with higher power densities, there is a need to understand these non-linear effects and make proper design recommendations. In this preliminary study of thermoacoustic systems, a thermoacoustic device driven by a commercial loudspeaker, producing standing waves inside a resonator has been constructed using relatively inexpensive materials. The resonant frequency is determined and the variation of drive ratio (which is the ratio of magnitude of oscillating pressure or pressure amplitude to the mean pressure) with voltage has been observed. Also, a stack made from plastic straws has been introduced into the flow to demonstrate the generation of a temperature difference between the ends of the stack. This study serves as a pre-cursor to understanding the thermoacoustic phenomenon in the non-linear regime.

2. Description of apparatus

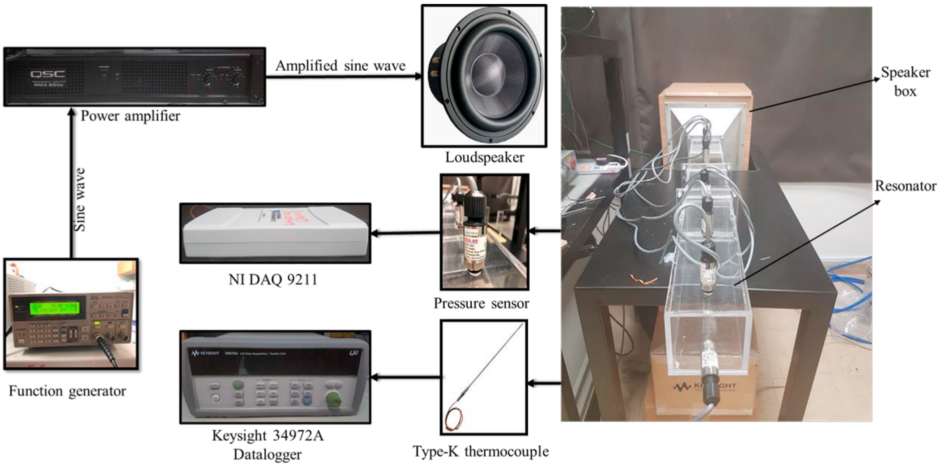


Fig. 1. Layout of experimental setup

The layout of the experimental setup being used is shown in Fig. 1. It consists of a 0.96 m long square duct with internal cross-section 100 mm x 100 mm and made of Perspex that functions as the resonator. The oscillating flow is driven by 200 W loudspeaker (Visaton TW 250 XS – 8 Ω) which is mounted inside a loudspeaker box. The resonator is attached to the loudspeaker box by means of a conical section to account for the change in cross-section. A function generator (Tektronix AFG320) is used to generate sine waves of different frequency and amplitude. The output from the function generator is sent through an amplifier (QSC RMX 850a) that outputs 200 W/channel at 8 Ω which drives the loudspeaker. The resonator is divided into three sections which are connected by means of flanges and has a number of openings which can be used to mount various sensors or can be plugged when not in use. Pressure sensors with range 0-2.5 bar (HUBA-511) are mounted at seven locations to measure the pressure amplitude. The signal from the pressure sensors are sent to a data acquisition system by NI (NI-USB 6211) and recorded using a MATLAB script. The RMS value of voltage supplied to the ends of the loudspeaker are measured using a multimeter. A basic stack with same cross-section as of the resonator is made using plastic straws glued together. Type-K thermocouples from Omega (TJ36) are attached at the ends of the stack to measure the temperature difference. The thermocouples are connected to another data logger (Keysight 34972A) which records the temperature. The working fluid in this thermoacoustic system is atmospheric air. The accuracies of measuring instruments are listed in Table 1.

Table 1 : Accuracy of measuring instruments

Instrument	Parameter	Accuracy
Tektronix AF320 function generator	Frequency (sine wave)	±50 ppm
	Voltage (sine wave)	±(1% of amplitude + 5 mV)
Fluke 111 True RMS multimeter	AC voltage	±(1% of reading + 3 counts)
HUBA-511 Pressure transducer	Absolute Pressure	±0.3% full scale
Omega TJ36 Type-K thermocouple	Temperature	2.2ºC or 0.75 % error limit

3. Experimental procedure

Measurements are done for the following three cases of loudspeaker driven oscillating flow inside the resonator as shown in Fig. 2.

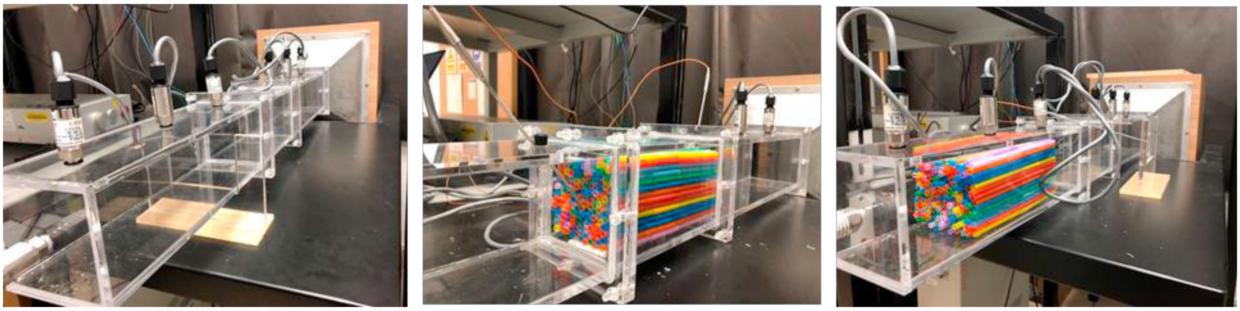
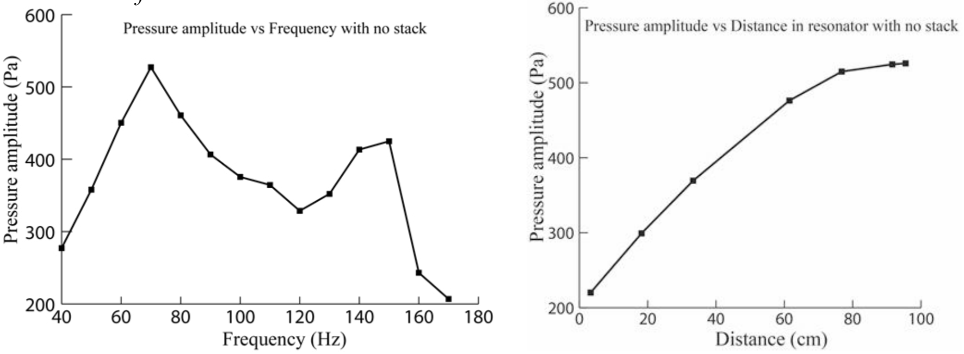

(a) (b) (c)

Fig. 2. Thermoacoustic system with (a) No stack (b) Stack in the middle section (c) Stack at the end section (opposite side of loudspeaker)

The function generator is used to generate sine waves of required frequency, which are then amplified and sent to the loudspeaker. The loudspeaker vibrates producing oscillating air flow inside the resonator at the set frequency. The voltage supplied to the loudspeaker can be adjusted either using the function generator or at the amplifier. For a given frequency, the ratio of the pressure amplitude (measured at pressure antinode) to the mean pressure gives the drive ratio of the system. The frequency at which the pressure amplitude is the highest is the resonant frequency of the system. Now driving the system at the resonant frequency, the voltage is varied and the corresponding values of drive ratio are also calculated. Using the data from the pressure sensors at different locations, we can also observe the variation of pressure amplitude with respect to position from the end of the conical section. Now, the stack is introduced at the middle section inside the resonator. The resonant frequency is again determined and the variation of the drive ratio at the pressure antinode with voltage is noted. To measure the temperature at the ends of the stack, two pressure sensors located near the stack ends are replaced with the type-K thermocouples and kept in contact with the stack ends. Both the hot end and cold end temperatures are recorded at different values of voltage and corresponding drive ratio. The temperature difference between the stack ends is also plotted against the drive ratio. The above steps are again repeated for the third case with the stack situated at the end section instead. Comparisons are made to determine the effect of presence of stack in loudspeaker driven oscillating flow and also to understand the influence of stack position in thermoacoustic energy conversion. The measurements can provide a qualitative understanding of the process.

4. Results and discussions

4.1. Flow in the absence of stack



(a) (b)

Fig. 3. Variation of (a) maximum pressure amplitude with frequency (b) pressure amplitude with distance from end of conical section

From Fig. 3(a) it can be seen that there are two peaks corresponding to the first and second resonance frequencies. The maximum pressure amplitude at the pressure antinode is seen at 70 Hz when the voltage is kept constant at 4 V. Fig. 3(b) shows the pressure amplitude measured by seven sensors at different sections in the resonator and the maximum is seen at the end section which is the pressure antinode. By driving the system at resonance frequency and varying the voltage applied to the loudspeaker, we see that the drive ratio increases almost linearly with the voltage as shown in Fig. 4. This is because as the loudspeaker voltage increases, the cone displacement also increases resulting in larger pressure levels and thereby stronger oscillations. The maximum recorded drive ratio is 3.7 % at 40 V to prevent damage to the loudspeaker.

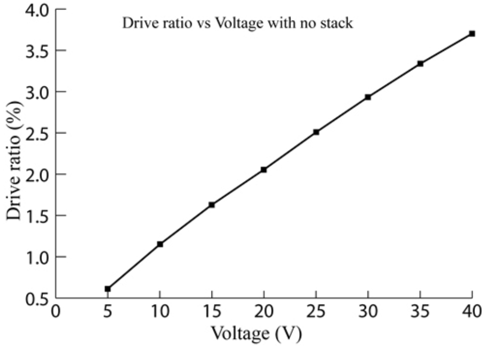


Fig. 4. Variation of drive ratio with loudspeaker voltage at resonance frequency

4.2. Flow with stack at the middle section

When the stack is placed at the middle section of the resonator (at 48 cm from the end), the resonance frequency remains unchanged at 70 Hz. However, the drive ratios corresponding to the same voltage variations as that in the flow with no stack are slightly lower as shown in Fig. 5. This may be due to minor losses encountered due to change in cross sectional area of flow channel, entrance effects and discontinuity at the stack region.

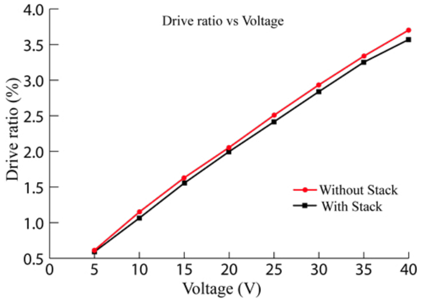


Fig. 5. Comparison of variation of drive ratio against loudspeaker voltage with and without stack

The presence of a stack leads to the creation of a temperature difference between its ends caused by the thermoacoustic heat pumping effect. The pressure and volume of gas inside the resonator varies sinusoidally. The gas absorbs heat from one end of the stack walls during compression and rejects heat at the other end during expansion. This means that one side of the stack becomes cooler while the other heats up similar to a refrigerator by consuming some work in the form of acoustic energy supplied by the loudspeaker. The temperature difference increases gradually and reaches a steady value for a fixed voltage. With increase in voltage and consequently the drive ratio, the cold end temperature begins to decrease further and the hot end temperature begins to increase as shown in Fig. 6. As the drive ratio increases, the oscillations are stronger and more acoustic power enters the system pumping more heat. The stack at the middle section is able to produce a temperature difference of 14.1°C at a drive ratio of 3.57 % when 40 V is applied to the loudspeaker.

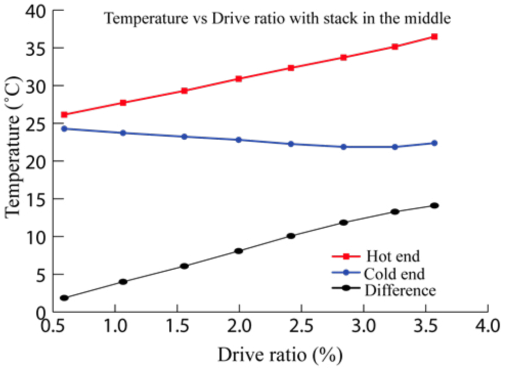
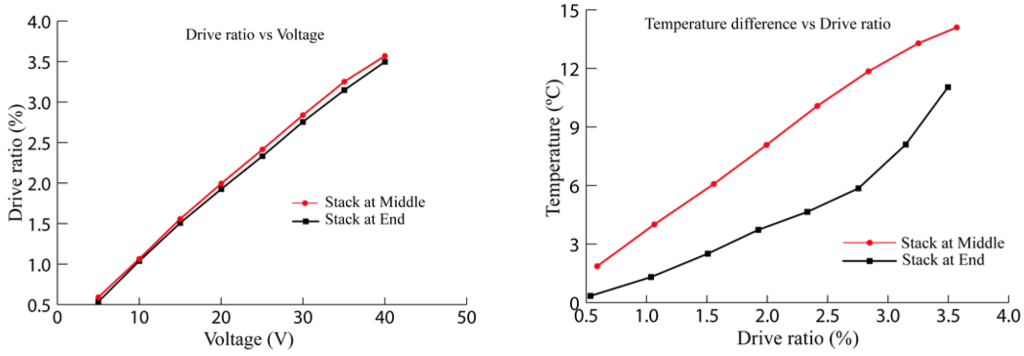


Fig. 6. Variation of hot and cold end temperatures and their difference against the drive ratio

4.3. Flow with stack at the end section



(a) (b)

Fig. 7. Comparison of (a) drive ratio against loudspeaker voltage and (b) temperature difference produced, for two stack positions

When the stack is moved nearer to the end section (19 cm from end), we can see that the drive ratio corresponding to different voltages is slightly lower than that with the stack at the middle as seen in Fig. 7(a) indicating more losses. Also the temperature difference recorded between the ends of the stack is lower than the case with the stack at the middle as shown in Fig. 7(b). This is may be attributed to the heat flow being proportional to the product of competing factors namely, pressure amplitude and flow velocity [7]. Therefore heat flow varies with position of the stack inside the resonator and there is an optimal position for maximum performance. The maximum temperature difference obtained is 11°C at a drive ratio of 3.5 % when 40 V is applied to the loudspeaker.

5. Conclusions

An experimental study of the thermoacoustic effect was conducted in a loudspeaker driven thermoacoustic device. The resonant frequency of the system was determined to be 70 Hz and the pressure amplitude was maximum at the end of the resonator. A linear relationship was established between drive ratio and loudspeaker voltage up to 40 V. A stack made of plastic straws was introduced into the system which results in heat flow from one end to the other demonstrating thermoacoustic energy conversion. With the increase in voltage and drive ratio, the pressure oscillations becomes stronger, heat flow increases and the temperature at the hot end of the stack rises and the temperature at the cold end decreases. We have obtained a hot end temperature of 36.5ºC and a cold end temperature of 22.4ºC at the maximum drive ratio of 3.57 % with the stack in the middle. When the stack was moved to end section, the values of hot and cold end temperatures as well as the temperature difference produced were lower. Therefore there is an optimum position of the stack inside the resonator for maximum thermoacoustic energy conversion.

The present study demonstrated that using a plastic straw stack, a significant temperature difference can be obtained by thermoacoustic energy conversion and provides a qualitative understanding of the phenomenon. Therefore, the study can be extended further by improving the design of the stack based on the material used, dimensions, geometry and position to improve the performance and develop devices for relatively inexpensive, environmentally-friendly refrigeration. Furthermore, the measurements of other flow parameters like velocity, vorticity and a more comprehensive temperature profile can be included in the future to better understand the thermoacoustic process in the non-linear regime at high drive ratios (>3 %). This would prove beneficial to develop better designs for thermoacoustic devices which operate at high amplitudes.

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