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Investigation of a portable standing wave thermoacoustic heat engine

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Abstract

Increasing the efficiency and effectiveness of energy systems remains as one of the critical issues today with depleting energy resources and increasing energy demand. Utilization of alternative fuels and utilization of waste heat has also become a major research area. This study reports an investigation on a development of a portable thermoacoustic heat engine that converts energy from a combustion process into acoustic power. The prime mover operates with a temperature gradient imposed on a celcor ceramic stack which then induced pressure oscillations. The system consists of a 42-cm long stainless steel alloy 304 tube with a diameter of 50 mm open at one end. A propane torch is used to model a potential heat source from biomass combustion. No hot heat exchanger is required while copper plates are used as the ambient heat exchanger. At 500°C, thermoacoustic effects and pressure oscillations have been observed with a calculated power of 50 W at the stack. The system which operates at atmospheric pressure with air as the working fluid indicates the potential in utilizing the heat produced from biomass combustion that is widely applied in the rural areas.

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Keywords: Thermoacoustic heat engine; energy system, biomass combustion, acoustic power

Nomenclature

dB	decibel
L	length of resonator (cm)
T	temperature (°C)
K	type of thermocouple
K	thermal conductivity (W/m.K)
W	Power (watt)
Greek symbols	
μ	dynamic viscosity (Kg/m.s)
c_p	specific heat capacity (kJ/Kg.K)
σ	prandlt number
δ_k	thermal penetration depth (mm)
δ_v	viscous penetration depth (mm)

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Δx	stack length (cm)
ΔT	temperature difference along the stack (°C)

1. Introduction

The increasing demand for energy across the globe today has put a strain on fossil fuels, the main resources of energy. Despite intensive efforts in improving the efficiency and effectiveness of energy systems, energy issues remain the main concern of developed and developing nations. Thermoacoustic technology is a new technology being explored; a temperature gradient induced by acoustics and oscillations induced by a temperature gradient. A thermoacoustic heat engine converts thermal energy into acoustic power while a thermoacoustic refrigerator/heat pump generates acoustic power from an imposed temperature gradient. The working fluid is generally inert gases like Helium or mixtures of Helium and Xenon.

Since the first experiment by Byron Higgins in 1802 on oscillations produced by a hydrogen flame, investigations have been done to study the practical applications of thermoacoustic effects in heat engines and heat pumps/refrigerators. Feldman first reported a 27 W of acoustic power from 600 W of heat source in his Ph.D dissertation [1], with later researchers investigating the theory that could explain the phenomena, possible optimizations and operations of actual systems [2-10]. This study reports the experiments completed on a portable thermoacoustic heat engine that could possibly be utilized with a cook stove to generate power. Past reported works on a similar purpose system have used an electrically heated high temperature source which is manageable [11-13]. This study investigates the actual heat source that could come from a combustion process.

2. Theory

As fluid particles oscillate near a solid boundary, a temperature gradient is set-up in that wall, reaching a steady value as the fluid-solid heat transfer (thermoacoustics) at the ends balanced that of axial conduction within the solid. A low conductivity material is favorable for the stack to reduce the axial conduction. The thermal penetration depth, δ_k, is the distance through which the thermoacoustic effects take place but the viscous penetration depth, δ_v, attenuates the heat loss due to shear stresses. Thus, ideally a fluid with a low Prandtl number, σ, is desired for the working fluid [14],

$$\sigma = \frac{c_p \mu}{K} = \left(\frac{\delta_v}{\delta_k}\right)^2 \tag{1}$$

where c_p, μ, and K, are the specific heat capacity, viscosity, and conductivity of the fluid respectively. However, air is used in this study as it is easily available for the final use of the system. The stack length, Δx, as recommended by Swift [14] is

$$\Delta x = \frac{L}{10} \tag{2}$$

with L being the resonator length. Detailed design variables may be obtained in Swift, 2001 [15].

3. Methodology

A schematic of the thermoacoustic heat engine is shown in Fig 1. It is made of a 50-mm diameter stainless steel alloy 304 with a total length of 42 cm filled with air at atmospheric pressure. Although studies have shown that better efficiency has been obtained at high operating pressure (6-10 bars) with Helium or a mixture of the rare gases, this study focused on the practical application within a rural community. The objective is to model a heat source from a combustion process (i.e. biomass) to run a thermoacoustic heat engine generating power for local use. The stack is made from Celcor ceramic with 100 cells/in^2, cut into a diameter of 50 mm, shown in Fig 2a.

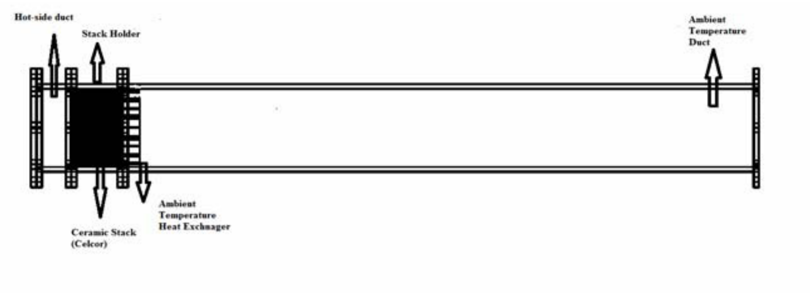

Fig. 1 A schematic of the heat engine.

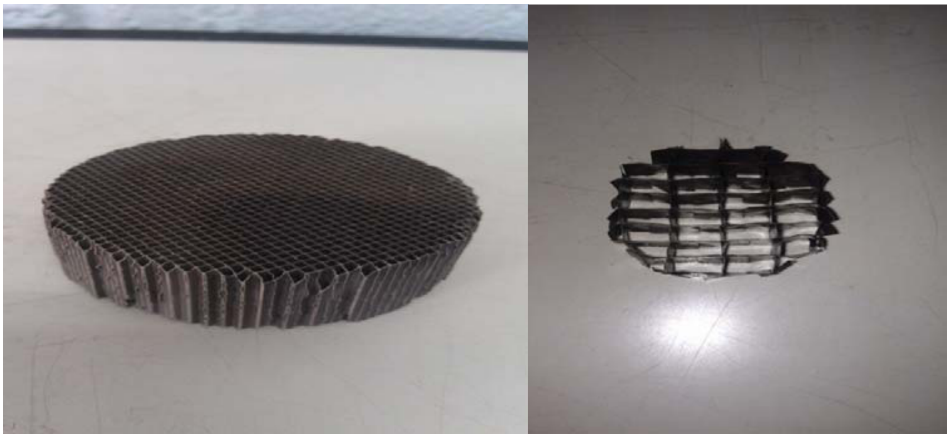

Fig 2. (a) The celcor stack (b) The ambient heat exchanger.

A 2-cm and 3-cm stack length has been studied to look at the acoustics generated from a heat source generated by a propane torch. The source is placed before the opening of the hot-side duct of Fig 1. No hot heat exchanger is used with the heat being directed straight to the stack [13]. The ambient heat exchanger was fabricated from thin copper plates, the dimensions of which are 10 mm by 50 mm with a thickness of 1mm (Fig 2b). The heat exchanger was cut into a 50-mm diameter and positioned next to the Celcor stack within the duct. Four K-type thermocouples are used to measure the temperatures at the mouth of the resonator (T_1), before (T_2) and after the stack (T_3), and the end of the resonator (T_4). A type 26AH microphone amplifier is located at the closed end for measuring the local pressure deviation from the ambient.

4. Results and discussion

The recorded temperatures over time for the 3-cm stack are listed in Table 1 with the graph presented in Fig 3.

Table 1. Temperature recorded for the 3-cm stack

Time, *t* (min)	T_1 (°C)	T_2 (°C)	ΔT
0	28.0	28.0	0
5	249.2	40.5	208.7
10	409.0	51.2	357.8
15	468.8	63.5	405.3
20	504.8	66.3	438.5
25	503.0	69.3	433.7
30	511.0	76.5	434.5

A temperature gradient is established along the stack soon after the heat is supplied. This temperature difference induced across the stack indicates that thermoacoustic effects have occurred. The temperature difference for the 3-cm stack seems to stabilize at approximately 20 minutes after the torch was fired, at $\Delta T = 430°C$, which is slightly lower than the maximum temperature difference achieved. Since the celcor ceramic stack in this study was taken from a used catalytic converter of a Proton Perdana V6, a local car, the temperature gradient could have been higher if a new celcor stack had been used. The maximum temperature difference for the 2-cm stack achieved after 10 minutes is 50% lower than that from the 3 cm stack, dropping soon after, shown here in Fig 4. The higher temperature observed at the cold side of the 2-cm stack can be attributed to the axial conduction heat transfer from the hot side thus causing a lower temperature difference across the stack. Although thermoacoustic analysis always assume a short stack approximation such that its presence does not interfere with the acoustic oscillations, an optimum length comparable to the resonator length is required for a stable temperature gradient as seen here.

The pressure measured by the microphone for the 3-cm stack is shown in Figure 5, the increase from ambient fluctuating after 20 minutes. The sound pressure level observed without the background noise is equivalent to 53 dB. Further experiments need to be done to identify if the fluctuating behavior repeats itself to indicate a standing wave profile. No significant sound level was recorded, however, for the 2-cm stack.

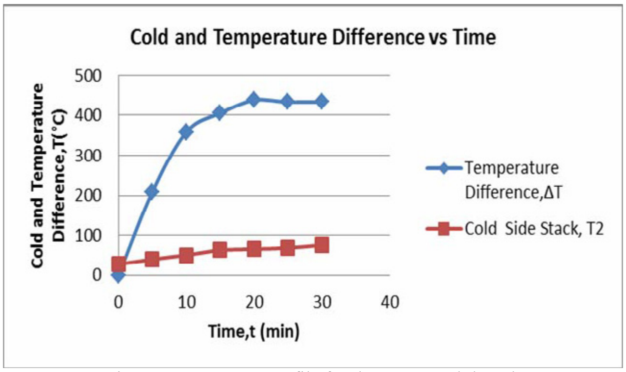

Fig. 3: Temperature profile for the 3-cm stack length

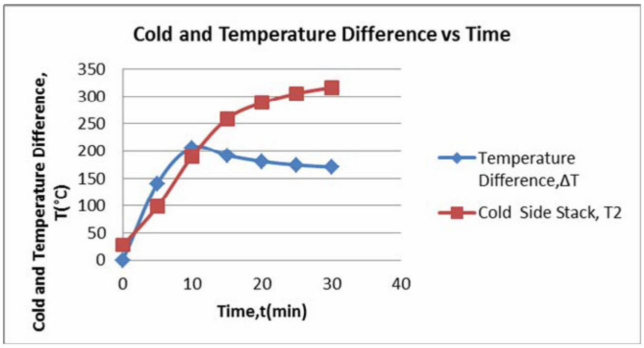

Fig. 4: Temperature profile for the 2-cm stack length

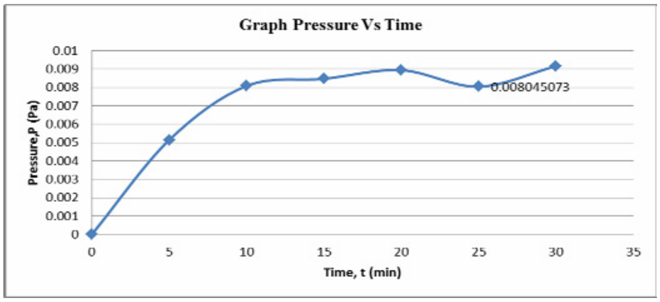

Fig 5 Pressure profile of engine

The overall results from the thermoacoustic heat engine are given in Table 2. The frequency obtained is calculated to be equivalent to a half-wavelength. Although the acoustics obtained may be low, the estimated power generated from the study may be adequate for specific rural household use. The potential application of the thermoacoustic heat engine for remote areas – where biomass combustion in cook stoves is wide spread – can be realized with further studies into the development of the interface between the acoustics generated and power conversion capability. However, the cost of conversion to electricity should be uppermost if the target user is the rural community. Thus, the utilization of waste heat from cook stoves for electricity can be made prevalent.

Table 2. Measured and calculated parameters

Resonator length, L	42.0 cm
Measured parameters:	
Temperature difference across stack, ΔT	433°C
Frequency, f	400Hz
Calculated parameters:	
Acoustic pressure amplitude in the engine, P_A	101kPa
Acoustic power generated in the stack, W	50.67W
Rate of heat supply to the stack, Q_{in}	2952.97W
Thermoacoustic efficiency, $\eta = W/Q_{in}$	1.72%

Conclusion

A portable and simple thermoacoustic heat engine has been developed and results showed the potential application with the heat source possibly coming from biomass combustion. Operating at 1 atmospheric pressure with just air as the working fluid, the low technology prime mover produced up to 50 W of acoustic power at the stack with a heat source at 500°C. Future work should explore the actual heat from a cook stove as well as the interface for power generation at the closed end of the thermoacoustic heat engine.

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