The Influence of the Density of Coconut Fiber as Stack in Thermo-Acoustics Refrigeration System

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Abstract. An experimental study of using coconut fiber as stack with varying density in thermo-acoustics refrigeration system has been done. Stack is a device which is described as the “heart” in thermo-acoustics refrigeration system. The length of stack is a fix parameter in this experiment. The performance of the coconut fiber was evaluated from the density of stack (varied from 30%, 50% and 70%), position of stack (varied from 0 to 34 cm from the sound generator), and frequency of sound generator (varied from 150 Hz, 200Hz, 250Hz and 300Hz). The inside, outside, and environment temperatures were collected every second using Data Acquisition (DAQ). The result showed that the increase of stack density will increase the performance of thermo-acoustics refrigeration system. The higher density produced temperature differences in cold side and hot side of 5.4°C. In addition, the position of stack and frequency of sound generator have an important role in the performance of thermo-acoustics refrigeration system for all variations of the density.

1. Introduction

Refrigeration system is generally used for air conditioning and cold storage, which is important to maintain the quality of agricultural products. Many refrigeration systems have been developed in many levels of temperature based on the application, such as vapor compression, absorption, thermoelectric, and pulse tube refrigeration. Recently, some researchers develop thermo-acoustics refrigeration (TAR) as alternative refrigeration system. TAR is purposed as an alternative refrigeration system, which is considered as environment-friendly, low energy consumption, and there is no moving part in the system [1,2,3].

TAR has been studied since several years ago. First observation of heat-induced acoustic oscillation was informed by Byron Higgins in 1777 and then basic theoretical for thermo-acoustic phenomena was established in 1969 until 1980 by Roth [4]. Actually, TAR is a system that uses thermoacoustic effect to achieve energy conversion between thermal and acoustic power. The thermoacoustic effect is either the energy transformation of acoustic work absorbed to transport heat (thermoacoustic refrigeration) or the energy conversion of the heat supplied to produce acoustic work (thermoacoustic engine) [5]. TAR system is consisting of resonator, loudspeaker and stack. Resonator is a part of TAR to resonance the process, in which the material should be compact, lightweight, and strong. The resonator tube should be chosen by considering the lowest energy loss [6,7]. The length of resonator in \( \lambda/4 \) has better energy dissipation than \( \lambda/2 \). Loudspeaker produces an acoustic standing wave at the fundamental frequency which interacts with a porous medium known as stack. The resonance frequency in thermo-acoustic refrigeration has a linear function; therefore the frequency is
the key in performance of TAR. Stack is part of TAR with a porous and this part known as the “heart” of the temperature gradient created in this part. The stack acts as a boundary for the compression and the expansion of the fluid (gas) [5].

The experiment in TAR system is divided into two main categories that are geometrical and operating parameters for each component of TAR and working fluid. The experiment to evaluate the influence of the length, diameter and the shape of resonator was done [8,9,10], concluding that the length and diameter of resonator is depend on the frequency. The shape of resonator consists of cylindrical, conical, tubular, Helmholtz, two sides tube and irreducible tube. The experiment for stack in TAR system is about the shape, material, length, porosity, position and acoustic frequency. The shape of stack has been studied by several researchers consist of parallel plates, honeycomb, corning celcor, spiral and pin array [5,6]. The material of stack has also been tested for stainless steel and cooper [11], random steel wool, copper scourers, carbon foam, mylar sheet [12], ceramic substrates [5], as well as organic ingredient such as drying squash [13,14], rice straw, pineapple fiber [14]. The experiment for working fluid, which is declared by researcher are using air, argon, helium, nitrogen [15].

Based on the explanation above, Indonesia as one of agricultural countries has a potency to develop a stack using agricultural waste. This paper will discuss about the use of coconut fiber as stack, which is potential to be used in Indonesia. The production of coconut in Indonesia reaches the number of 15.814 ton in 2015. Coconut fiber has also low thermal conductivity of 0.0488 W/m.K [16], smaller than that of mylar or PVC, which is about 0.2 W/m.K [17].

The objectives of this research are to identify the specific resonance of parallel stack from coconut fiber with random type which have acoustic effect, to measure temperature differences at steady state for all different frequency and position, as well as to describe the node and antinode region for stack from coconut fiber.

2. Materials and methods

2.1. Material and Apparatus
The discussion on this paper will focus on the performance of coconut fiber as stack with constant dimension but different position and frequency, therefore no heat exchanger was used. The geometry of stack is described as in table 1 below:

| Parameter                        | Value            |
|----------------------------------|------------------|
| Geometry                         | Thermal penetration depth ($\delta_k$) |
|                                  | 0.18 mm          |
|                                  | Length ($L_s$)   |
|                                  | 6 cm             |
| Thermal Properties               | Thermal conductivity(K) |
|                                  | 0.0488 W/mK      |

The density of stack varied from 30%, 50% and 70% with the form as shown in figure 1 and table 2 below:

Figure 1. Stack from coconut fiber with (a) 30% density, (b) 70% density
Many researchers have noted that the performance of TAR depends on the material and geometrical of stack. Random shape of material was selected because it is easy to create from waste material, low cost, and it is not possible to control all stack parameters.

| Condition of stack (%) | Mass of stack (g) | Density (kg/m\(^3\)) |
|------------------------|------------------|------------------------|
| 30                     | 2.58             | 18.79                  |
| 50                     | 4.25             | 30.94                  |
| 70                     | 5.91             | 43.03                  |

The experiment apparatus is shown in figure 2. The apparatus consists of acoustic driven, resonator and stack. The acoustic driven is connected to amplifier and function generator. The resonator was made from acrylic and has tube length of 40 cm, diameter of 5.4 cm and thickness of 3 mm. The acrylic was used due to its strength, lightweight and transparent so that the placement of stack was easier to visualize. Stack was made from coconut fiber. The temperature was measured by thermocouple type K and collected every second by Data Acquisition (DAQ) connected to computer. Acoustic driven placed in a box was also made from acrylic. The position of stack varied from 0 until 32 cm and the frequency varied from 150, 200, 250 and 300 Hz.

![Figure 2: The apparatus for TAR system with stack from coconut fiber](image)

2.2. *Thermo-acoustic Refrigeration Analysis*

An optimized \( \lambda/4 \) length parameter was used for resonator design [17], and then introduced using the equation below:

\[
f_n = \frac{nv}{4(L + \frac{4D}{2\pi})}
\]

Where \( f_n \) is frequency (Hz), \( v \) is velocity (m/s), \( L \) is length (m), and \( D \) is diameter (m). The thermo-acoustic effect generated in stack is an important component in TAR system. Stack length, porosity, position and acoustic frequency are all variables which influence the efficiency or the performance of
the TAR. The COP is used in this experiment analysis to evaluate the performance of TAR system. The maximum of relative coefficient of performance refrigeration (COP_R) [18] is given by:

$$COP_R = \frac{COP}{COP_{\text{carnot}}}$$

(2)

And the COP can be calculated by:

$$COP = \frac{Q_L}{W}$$

(3)

The cooling load [19] can be obtained from:

$$Q_L = A_{\text{stack}} K \frac{\Delta T}{L_{\text{stack}}} = (1 - \Omega) A_{\text{pipe}} K \frac{T_H - T_L}{L_{\text{stack}}}$$

(4)

The theoretical maximum coefficient of performance named Carnot [18] can be written as:

$$COP_{\text{carnot}} = \frac{T_H - T_C}{T_C}$$

(5)

Where Q_L is cooling load (kJ/s), A is Area of stack (m²), ΔT is temperature difference (°C), is porosity of stack (m), W is work of acoustic generation (kJ/s), T_C is temperature at the cooling side (°C), and T_H is temperature at the hot side (°C).

3. Result and discussion

3.1. The Profile of Node (N) and Antinode (AN) Region

Figure 3 until 5 describe the profile of Node (N) and Anti Node (AN) region made from temperature differences between cold and hot sides of stack using coconut fiber and plastics on the different frequency. The high temperature differences between cold and hot side is about 5°C occurred in coconut fiber stack with 70% density at AN region with frequency of 200 Hz and stack position of 27 cm. The lower achievement of about 1.8°C occurred in coconut fiber stack with 30% density at the same condition of frequency of 200 Hz and stack position of 27 cm. The phenomenon of Node (N) and Anti Node (AN) was noted to be occurred in all research in TAR system for some material which is used for stack (plastic, mylar, PVC) [6,7,20]. The optimum result of temperature differences for AN region in this experiment which occurred at stack position of 27 cm (coconut fiber with density 70%) was different from stainless steel wool, copper scourers, carbon foam, and mylar stack, where the AN region occurs at 1.1 m [12]. The different of AN region depended on the length and diameter of tube resonator and frequency. The experiment using stack from stainless steel wire-mesh mentioned that the different position of AN and N region occurs due to the pressure amplitude [21].
Figure 3 Profile of N and AN region of coconut fiber with density 30%

Figure 4 Profile of N and AN region of coconut fiber with density 50%

Figure 5 Profile of N and AN region of coconut fiber with density 70%
3.2. Profile of Temperature at Node (N) and Anti Node (AN)

Figure 6 to 8 show the outside and inside temperature position at AN and N region for coconut fiber stack with density of 30%, 50% and 70%. Profile of temperature at figure 6 for both Node (N) and Anti Node (AN) occurred at the position of 27 cm from loudspeaker with the 30% density of coconut fiber stack. The result showed that the higher acoustic effect occurred at the frequency of 200 Hz at AN region and the lower acoustic effect occurred at the frequency of 150 Hz at N region. The acoustic effect at AN region for frequency of 200 Hz and position of stack 27 cm produced outside temperature (cold side) of 25.8°C and inside temperature (cold side) of 27.6°C. Different phenomenon occurred at N region, which showed no acoustic effect because there is no differences between inside and outside temperature. The higher acoustic was achieved for coconut fiber with density of 70%. At AN region in frequency of 200 Hz and stack position of 27 cm and density of coconut fiber of 70% produced outside temperature (cold side) of 29.3°C and inside temperature (hot side) of 32.7°C. All profile of temperature showed that there was no acoustic effect at N region. The AN region produced temperature at hot side of 33°C and the cold side of 28°C. The N region showed different result; where the cold and hot side produced the same temperature of about 31.1°C until 31.6°C. There was no temperature difference in N region due to the high amplitude pressure differences at AN region [6]. Compared to the other stack materials, such as pineapple fiber, squash, and rice straw [14] the temperature difference of using coconut fiber stack is smaller, due to the different power inserted to the system [22,23].

![Figure 6](image1.png)

**Figure 6** Profile of temperature at (a). N region, (b) AN region of coconut fiber with density 30%

![Figure 7](image2.png)

**Figure 7** Profile of temperature at (a). N region, (b) AN region of coconut fiber with density 50%
3.3. Performance of TAR system

The performance of TAR system in this experiment is evaluated by COP, COPC, and COPR. Table 3 shows the calculation result of coconut fiber performance varied from density of 30%, 50%, and 70%. The COP, COPC, COPR were calculated based on equation 1, 2, 3 and 4. The maximum COP reached using coconut fiber stack was 0.00115, whereas using plastic was 0.00882. These values are very small in comparison with conventional refrigeration technology such as vapor compression, absorption refrigeration, thermoelectric, and pulse-tube refrigeration. The COP will increase if the temperature differences between hot and cold side increased and the other researcher also mentions that the value of COP will increase linearly with the cooling load [12].

| Density of Coconut Fiber (%) | Frequency (Hz) | COP   | COPC  | COPR   |
|-----------------------------|----------------|-------|-------|--------|
| 30                          | 150            | 0.00020 | 16,1875 | 1,24E-05 |
|                             | 200            | 0.00029 | 10,96  | 2,68E-05 |
|                             | 250            | 0.00030 | 9,357143 | 3,19E-05 |
|                             | 300            | 0.00027 | 9,769231 | 2,78E-05 |
| 50                          | 150            | 0.00021 | 30,5  | 6,87E-06 |
|                             | 200            | 0.00045 | 12,30435 | 3,66E-05 |
|                             | 250            | 0.00032 | 16,77778 | 1,91E-05 |
|                             | 300            | 0.00049 | 11,25  | 4,33E-05 |
| 70                          | 150            | 0.00050 | 15,76471 | 3,16E-05 |
|                             | 200            | 0.00148 | 5,555556 | 2,66E-04 |
|                             | 250            | 0.00062 | 10,48  | 5,94E-05 |
|                             | 300            | 0.00066 | 9,481481 | 6,93E-05 |

4. Conclusions

The stack from coconut fiber had been built and tested with varying density. Increasing the density will increase the temperature differences between hot and cold side. The Node (N) and Anti Node (AN) have an important role for temperature achievement. AN region will produce higher temperature differences. The use of coconut fiber as stack in this experiment has low COP compared to other refrigeration systems. Therefore it needs further development to use coconut fiber as stack in TAR System.
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