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# Temperature Measurement of Stored Biomass Using Low-frequency Acoustic Waves and Correlation Signal Processing Techniques

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## Abstract

As a substitute of traditional fossil fuels, biomass is widely used to generate electricity and heat. The temperature of stored biomass needs to be monitored continuously to prevent the biomass from self-ignition. This paper proposes a non-intrusive method for the temperature measurement of stored biomass based on acoustic sensing techniques. A characteristic factor is introduced to obtain the sound speed in free space from the measured time of flight of acoustic waves in stored biomass. After analysing the relationship between the defined characteristic factor and air temperature, an updating procedure on the characteristic factor is proposed to reduce the influence of air temperature. By measuring the sound speed in free space air temperature is determined which is the same as biomass temperature. The proposed methodology is examined using a single path acoustic system which consists of a source and two sensors. A linear chirp signal with a duration of 0.1 s and frequencies of 200-500 Hz is generated and transmitted through stored biomass pellets. The time of flight of sound waves between the two acoustic sensors is measured through correlation signal processing. The relative error of measurement results using the proposed method is no more than 4.5% over the temperature range from 22℃ to 48.9℃. Factors that affect the temperature measurement are investigated and quantified. The experimental results indicate that the proposed technique is effective for the temperature measurement of stored biomass with a maximum error of 1.5℃ under all test conditions.

**Keywords -** biomass; temperature measurement; sound wave; acoustic sensor; linear chirp signal; correlation.

## List of symbols:

| | | | |
|---|---|---|---|
| $a$ | Sound absorption coefficient (1/m) | $T$ | Air temperature (℃) |
| $c$ | Sound speed (m/s) | $T_1$ | Ambient temperature (℃) |
| $c_g$ | Group speed in a thin pipe (m/s) | $T_2$ | Initially measured biomass temperature (℃) |
| $c_p$ | Phase speed in a thin pipe (m/s) | $V_1$ | Amplitude of sound signal received by sensor 1 (V) |
| $d$ | Equivalent pipe diameter of air gaps (m) | $V_2$ | Amplitude of sound signal received by sensor 2 (V) |
| $f$ | Sound frequency (Hz) | $x_w$ | Mole fraction of water vapour |
| $f_1$ | Enhancement factor for water vapour | $Z$ | Compressibility factor |
| $F$ | Combined thermo-dynamic parameter | $\alpha$ | Characteristic factor |
| $k$ | Wavenumber ($m^{-1}$) | $\alpha_1$ | Initial value of characteristic factor |
| $M_a$ | Molar mass of dry air (kg/mol) | $\gamma$ | Specific heat ratio |
| $M_w$ | Molar mass of water content (kg/mol) | $\kappa$ | Thermal diffusivity of air |
| $P$ | Air pressure (Pa) | $\mu$ | Viscosity of air |
| $P_{sv}$ | Saturation vapour pressure (Pa) | $\nu$ | Kinematic viscosity of air |
| $R$ | Universal gas constant (J/(mol·K)) | $\rho$ | Air density |
| $RH$ | Relative humidity (%) | $\tau$ | Tortuosity factor |
| $s$ | Distance between acoustic sensors (m) | $\omega$ | Angular frequency (rad/s) |
| $\Delta t$ | Time of flight of sound waves (s) | | |

## 1. Introduction

Biomass fuels, as a substitute of fossil fuels, are being widely adopted in new and existing power plants to generate electricity and heat [1, 2]. Biomass materials like wood pellets are generally stored indoors either in silos or other containers to maintain their structure and control their humidity. A common problem encountered in biomass storage is intrinsic self-heating and potential spontaneous combustion due to biological metabolic reactions (microbiological growth), exothermic chemical reactions (chemical oxidation) and heat-producing physical processes (e.g. moisture absorption). There have been a number of serious fire incidents due to stored biomass at power stations in recent years, including those in Kristinehamn, Sweden in 2007, Hallingdal, Norway in 2010, and Tilbury, UK in 2012 [3]. The temperature of stored biomass needs to be measured continuously to ensure plant safety and minimise fire risks in the power generation industry. Current practice to measure the temperature of stored biomass is to use a matrix of thermocouples, temperature cables or temperature spears [3, 4]. These measurement devices provide only point temperature measurements and can easily be bent, destroyed and moved away from their original locations during loading and unloading. A non-intrusive technique is therefore highly desirable to measure the internal temperature of stored biomass. Unfortunately, infrared thermometers can only measure the surface temperature of a target object and are thus unsuitable for the temperature measurement of stored biomass.

Acoustic techniques have been used to measure air temperature non-intrusively. By measuring the sound speed in free space, the air temperature can be determined with the physical relationship between the two parameters. Hickling et al. studied the transmission of sound waves in stored food grain and found that the attenuation of an audible sound wave increases with its frequency [5, 6]. If the sound speed in the air gaps can be measured, then the corresponding air temperature and hence the biomass temperature will be determined. Stored biomass like wood pellets have a low heat conduction coefficient, so the temperature of the air gaps should be the same as that of surrounding biomass. Acoustic techniques have been used to measure the temperature of air in free space, flame and water [7-13]. Miao et al. used a linear chirp sound wave with frequencies from 200 to 500 Hz to measure the temperature of air. The relative error of air temperature measurement is within ±3.2% with a standard deviation of less than 0.2% over the temperature range from 23.5℃ to 54.2℃ [14]. However, there is very limited work on the temperature measurement of stored biomass using acoustic techniques. Yan et al. used an acoustic tomography technique to measure the temperature distribution of stored food grain [15]. They established a model describing the relationship between the grain temperature and the measured time of flight (TOF) of sound waves between two acoustic sensors. Triple correlation and wavelet de-noising were used to estimate the TOF of sound waves. A tomography algorithm was used to reconstruct the temperature distribution of the food grain. This work demonstrates the feasibility of the acoustic technique for the temperature measurement of stored bulk materials. However, the system is validated only at two temperature points and significant further studies are required.

As a sound wave travels through the air gaps in stored biomass, due to viscous damping and heat exchange, the sound speed in the thin channels will be different from the sound speed in free space. In addition, the actual sound path length is not a straight line between a pair of acoustic sensors and depends on the structure of the air gaps and the frequency of the sound wave. In order to use the physical equation between sound speed in free space and air temperature to determine the biomass temperature, sound speed in free space but under the same atmospheric condition as the air gaps in stored biomass should be measured. The model between the sound speed in free space and the measured TOF should be established. Sound waves in stored biomass are readily absorbed and reflected by the biomass and wall of the container. A suitable TOF measurement method should be identified.

This paper presents the most recent advances in the temperature measurement of stored biomass using low-frequency sound waves and correlation signal processing techniques. A simple pipe and tortuosity model is used to describe the complex sound transmission in stored biomass. A characteristic factor is introduced to solve the problem of determining the sound speed in free space but under the same atmospheric condition as the air gaps in stored biomass from the measured TOF. A single path system is constructed to validate the proposed method. The factors influencing the biomass temperature measurement using acoustic methods are analysed and discussed.

## 2. Methodology

### 2.1 Relationship Between Sound Speed in Free Space and Measured TOF in Stored Biomass

Wood pellets are the most common type of biomass fuel in industrial and domestic applications. Stored biomass like wood pellets is a rigid porous media. When a low-frequency sound wave in the audible range propagates from the air to the surface of pellets, the ratio of the intensities of the reflected wave to the incident wave is $0.99$ [16]. This means that when the sound wave meets wood pellets, almost all of the wave will be reflected. The sound wave only propagates through the air gaps between wood pellets.

Air gaps in stored biomass can be approximated as rigid and narrow cylindrical pipes [6]. Additionally, the sound wave does not travel along a straight line in stored biomass. The ratio between the actual sound path length from one acoustic sensor to another and the distance between the two sensors is denoted as tortuosity factor. This simple pipe and tortuosity factor model has been adopted in the transmission analysis of sound waves and grain temperature measurement using acoustic sensors [6, 15]. The sound speed in a thin pipe $c_p$ [6, 15] is:

$$c_p = \frac{c}{1+\frac{F}{d\sqrt{\pi f}}} \tag{1}$$

where c is sound speed in free space, F is a combined thermo-dynamic parameter determined by the air gaps in the stored biomass, d is equivalent pipe diameter of the air gaps in stored biomass and f is sound frequency. From eq. (1) the sound speed in the air gaps depends on sound frequency f. This means that the sound transmission in stored biomass has a frequency dispersion phenomenon. Therefore, there exist a group speed and a phase speed of the sound wave. Eq. (1) yields the phase speed $c_p$ (hence the subscript p) whilst the group speed $c_g$ is determined as follows:

$$c_p = \frac{\omega}{k} \tag{2}$$

$$\frac{c}{1+\frac{\sqrt{2}F}{d\sqrt{\omega}}} = \frac{\omega}{k} \tag{3}$$

$$ck = \omega + \frac{F}{d}\sqrt{2\omega} \tag{4}$$

$$c_g = \frac{\partial\omega}{\partial k} \tag{5}$$

$$c_g = \frac{\mathrm{c}}{1+\frac{F}{2d\sqrt{\pi f}}} \tag{6}$$

where $\omega$ and k are the angular frequency and wavenumber of the sound wave, respectively. Due to viscous stress and heat conduction in the air gaps, $c_g$ and $c_p$ are smaller than c. The sound speed measured using the phase difference method is the phase speed. By generating a sinusoidal wave at a single frequency and measuring the phase difference between the received sinusoidal signals, the TOF of the sound wave and hence the sound speed is determined. As the sound wave will be reflected on the wall of the container during transmission, which will change the phase of received signals, the phase difference method is not suitable to measure

TOF in this study. Cross-correlation methods are thus utilized. The sound speed measured through cross-correlation is $c_g$ as the correlation method determines TOF of the sound wave based on the similarity of the received waveforms.

The relationship between $c_g$ and TOF of sound wave Δt measured through cross-correlation is given by:

$$c_g = \frac{\tau s}{\Delta t} \tag{7}$$

where $\tau$ is the tortuosity of sound path in stored biomass, s is the distance between the acoustic sensors. The product $\tau s$ denotes the actual sound path length in stored biomass. Then the relationship between c and Δt is:

$$c = \frac{(1+\frac{F}{2d\sqrt{\pi f}})\tau s}{\Delta t} \tag{8}$$

By calculating c from the measured Δt, air temperature T is acquired based on the relationship between c and T, which is the same as the temperature of surrounding biomass.

In eq. (8), $\tau$ and d are difficult to determine as they depend on biomass properties (particle size, shape etc.), sensor depth below surface of stored biomass and sound frequency. Besides, the actual air gap in stored biomass is not a perfect thin cylindrical tube, which makes the actual $c_g$ different from the theoretical value obtained from eq. (6). Therefore, a characteristic factor $\alpha$ is defined as:

$$\alpha = (1 + \frac{F}{2d\sqrt{\pi f}})\tau \tag{9}$$

Then eq. (8) can be rewritten as:

$$c = \frac{\alpha s}{\Delta t} \tag{10}$$

According to eq. (10), by measuring Δt in stored biomass and using a reference thermometer to measure the biomass temperature, the initial value of $\alpha$ is determined inversely. Once $\alpha$ is known, eq. (10) is then used to measure biomass temperature with measured Δt under other temperatures.

## 2.2 Relationship Between the Characteristic Factor and Air Temperature

In order to use eq. (9) to investigate the influence of T on $\alpha$, the values of d, $\tau$ and F should be acquired. There is no theoretical method to calculate d and $\tau$ directly as the simple pipe and tortuosity model is only an approximate model. The experimental fitting approach proposed by Hickling et al. [6] is thus adopted in this study. The theoretical sound absorption coefficient [6] is:

$$a = \frac{2\sqrt{\pi f}F\tau}{dc} \tag{11}$$

According to eq. (7), the relationship between the group speed and measured sound speed using the sensor distance as sound path length is:

$$\frac{c_0}{\tau+\frac{\tau F}{2d\sqrt{\pi f}}} = \frac{s}{\Delta t} \tag{12}$$

The biomass used in this study is wood pellets which complies with the ENplus A1 standard (see section 3.2). By measuring the sound absorption coefficient and sound speed in stored biomass and using eq. (11) and (12) to fit the experimental results, $\tau$ is calculated to be 1.512 and d is 0.581 mm. A detailed procedure for the measurement of sound absorption coefficient and sound speed in stored biomass is given in section 3.2.

The combined thermos-dynamic parameter F [6] is:

$$F = \sqrt{\nu} + (\sqrt{\gamma} - \frac{1}{\sqrt{\gamma}})\sqrt{\kappa} \tag{13}$$

$$\nu = \frac{\mu}{\rho} \tag{14}$$

where $\nu$ is kinematic viscosity of air, $\gamma$ is ratio of specific heat of air, $\kappa$ is thermal diffusivity of air, $\mu$ is viscosity of air and $\rho$ is air density. In this study $\mu$ is acquired using method proposed by Zoran et al [17]. $\rho$ is calculated using method proposed by Giacomo [18]. $\gamma$ is calculated using the equation proposed by Bohn [19]. $\kappa$ is obtained using the method from Tsilingiris [20]. During experiments air pressure P was 101.6 kPa. By assuming T is 0-100℃, RH is 50% ($\alpha$ is independent of RH, see section 3.4.2), $\alpha$ is obtained from eq. (9) as shown in Fig 1. f is set to 350 Hz which is the centre frequency of the frequency band 200 to 500 Hz.

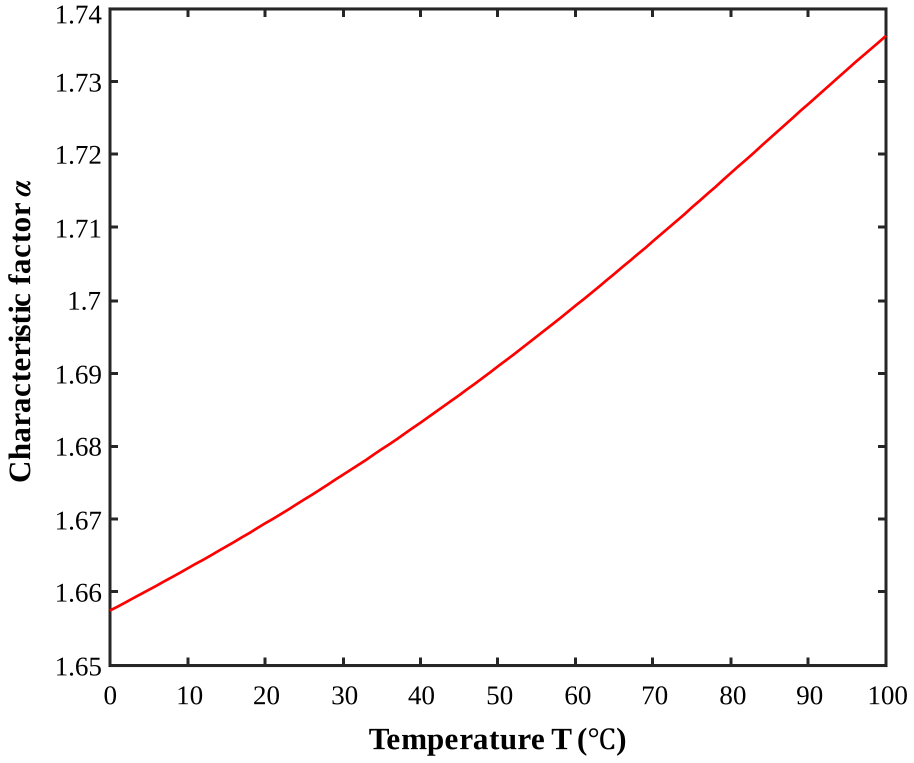


**Figure 1.** Relationship between characteristic factor and air temperature

Initial value of characteristic factor is calculated from measured Δt in stored biomass under ambient temperature $T_1$. If using this value of α, measured Δt at higher biomass temperatures and eq. (10) to calculate biomass temperature, initially measured temperature $T_2$ will be smaller than the actual temperature due to the error in $\alpha$. Therefore, in order to increase the accuracy of biomass temperature measurement $\alpha$ needs to be updated according to the relationship between $\alpha$ and T with initially measured temperature $T_2$. The flowchart of updating $\alpha$ according to the relationship between $\alpha$ and T is shown in Fig. 2. By updating the characteristic factor based on initially measured biomass temperature and applying a reiteration process the biomass temperature to be measured is finally determined.

The plot in Fig. 1 is obtained from the simple pipe and tortuosity model which is an approximate model. The actual relationship between $\alpha$ and T may be different from the theoretical relationship in Fig. 1. Thus it is better to obtain the experimental relationship between $\alpha$ and T through reference temperature experiments in a lab-scale. By heating the stored biomass to different temperatures and measuring the corresponding Δt, eq. (10) is used to obtain characteristic factor under different biomass temperatures. Then the experimental relationship between characteristic factor and air temperature is established by fitting the data with a polynomial.

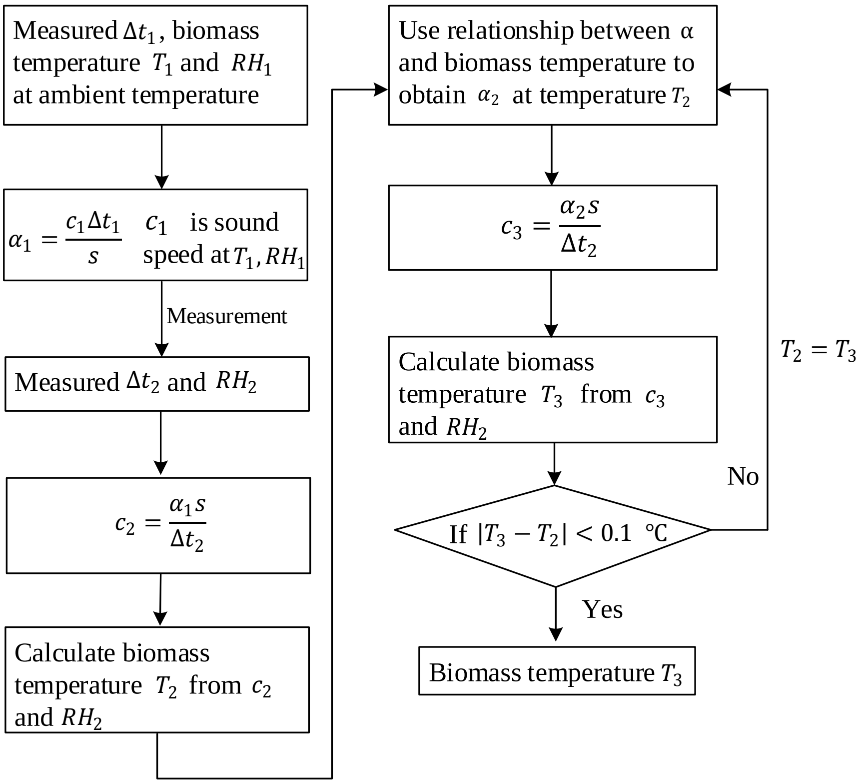


**Figure 2.** Flow chart of updating $\alpha$ according to the relationship between $\alpha$ and T

### 2.3 Relationship Between Sound Speed in Free Space and Air Temperature

In order to use the acoustic technique to measure biomass temperature, first the relationship between sound speed and air temperature needs to be established. Sound speed in the air mainly depends on air temperature and relative humidity. Sound speed c [18] is:

$$c = \sqrt{\frac{\gamma Z R (T + 273.15)}{M_a[1 - x_w(1 - \frac{M_w}{M_a})]}} \tag{15}$$

where R is universal gas constant (8.3144598 J/(mol·K)) [21], Z is compressibility factor [22], $M_a$ is molar mass of dry air, $x_w$ is mole fraction of water vapour and $M_w$ is molar mass of water content. The values of $M_a$ and $M_w$ are from international standard organisation ISO-2533-1975 [23]. $x_w$ is calculated from the measured RH [18]:

$$x_w = \frac{0.01 RH f_1 P_{sv}}{P} \tag{16}$$

where $f_1$ is enhancement factor for water vapour [20], $P_{sv}$ is saturation vapour pressure [24], and P is the atmospheric pressure.

P in the laboratory where this research was undertaken is 101.6 kPa. The critical temperature for emergency discharge of stored biomass in a silo is 80℃ [3, 25, 26]. Besides, large power plants often have a temperature limit of 45℃, above which shipments are rejected [3]. Therefore, assuming T is 0-100℃, RH is 0-100% and air constituent concentrations are the same as the standard air, c calculated from eq. (15) is shown in Fig. 3. The sound speed has a monotonic relationship with air temperature for a given RH. With the measured c, RH, P and assuming that air constituent concentrations are the same as that of standard air, T is calculated inversely from eq. (15).

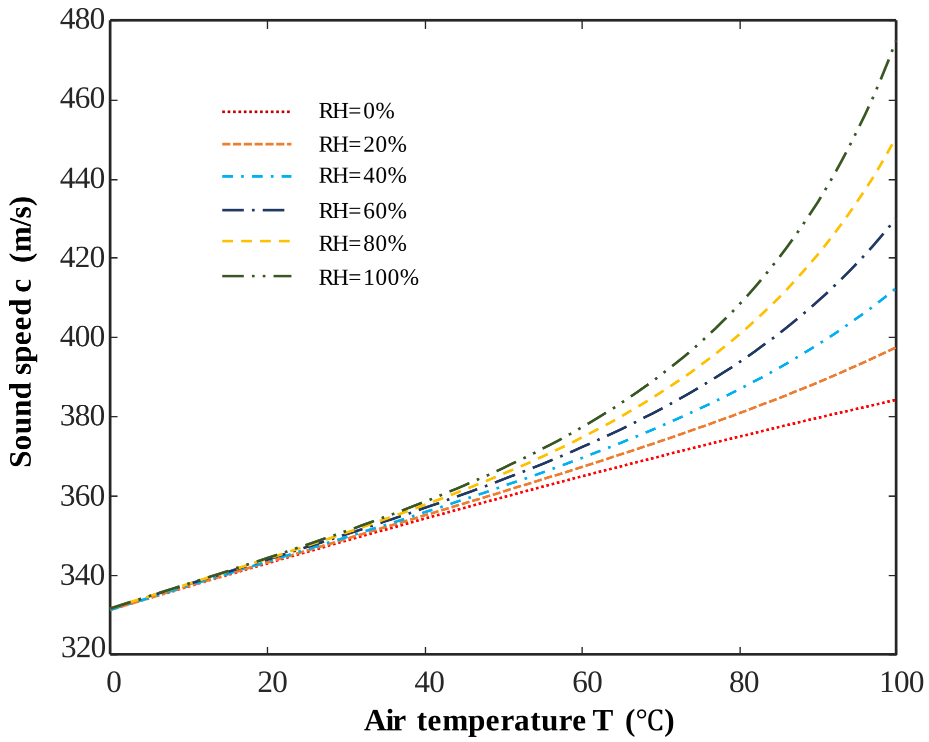


**Figure 3.** Relationship between sound speed and air temperature

2.4 Methodology of Biomass Temperature Measurement Using Low-frequency Sound Waves

Fig. 4 shows the procedure for temperature measurement of stored biomass using low-frequency sound waves and correlation signal processing techniques. An acoustic source is used to generate low-frequency sound waves into the biomass in a container. Two acoustic sensors are put inside stored biomass to receive the sound waves. One humidity meter is used to measure the RH inside stored biomass. A correlation algorithm is used to process the signals from the two acoustic sensors to determine the TOF of sound waves Δt. With introduction of characteristic factor $\alpha$ eq. (10) is used to calculate sound speed in free space (c) but under the same atmospheric condition as the air in the gaps of stored biomass. Then the updating procedure shown in Fig. 2 is applied to obtain the final temperature.

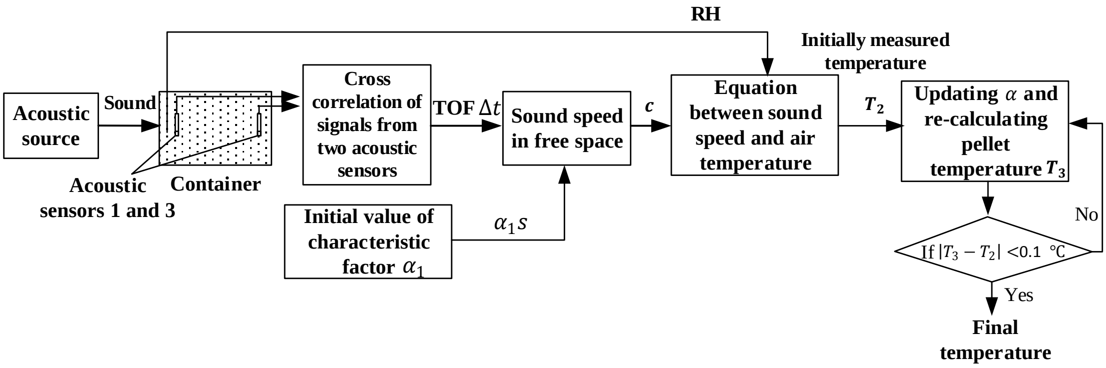


**Figure 4.** Procedure of temperature measurement of stored biomass using low-frequency sound waves

## 3. Experimental Results and Discussion

### 3.1 Experimental Setup

Figs. 5 and 6 show the schematic and experimental setup of the hardware system for the temperature measurement of stored biomass. Wood pellets are one of the most common biomass fuels used in the power generation industry in many countries. For this reason, wood pellets are selected as a test material in this study (bulk density: 600 to 750 kg/m$^3$, moisture: ≤10 w-%). The diameter and length of a single pellet is 8 mm and 3.15 to 40 mm, respectively. A cuboid wooden box of 120 cm × 40 cm × 40 cm is made to store the wood pellets. The two end sides are made of 3 mm hardboard. The cover and other three long sides of the wooden box are made of 25 mm Medium Density Fibre Board. This type of board is thick enough to insulate divergent sound waves and vibrations. An array of 12 aluminium clad resistors (0.47 Ω, 100 W) is mounted onto aluminium plates as a heating source. Asbestos are used as heat protection materials. The heat generated by the resistors will rise up and increase the pellet temperature.

A sound signal generated in a laptop is sent to the power amplifier (Model type PULSE VS120). After amplified the signal is sent to the acoustic source (Model type Tectonic Elements Round Speaker, nominal rated power 30 W, impedance 8 Ω, working frequency band 60 Hz to 20 kHz) to generate audible sound waves. Three acoustic sensors (Model type MPA201, BSWA Technology) are used to collect the sound signals. The acoustic sensors should be located at the same depth as sound source in the same stored biomass. Acoustic sensors should have sufficient sensitivity in the low frequency band as the low-frequency sound waves are used as sound source and the stored biomass is a sound absorbing material. The sensitivity of the sensors is 42.2 mV/Pa. The sensors are mounted at an equal spacing of 0.5 m. The sensing elements of acoustic sensor are positioned 0.2 m below the surface of wood pellets. A data acquisition card (Model type USB-6366, National Instruments (NI)) is used to collect the output signals of the sensors simultaneously. The sampling frequency is set to 2 MHz which is to increase the time resolution in TOF measurement (time resolution: 0.5 μs). The temperature in stored wood pellets is unlikely uniformly distributed and natural variations across the biomass are expected due to the dimensions of the experimental setup and use of the discrete heaters. In view of this fact the temperature inside the stored biomass is measured using 8 K-type thermocouples (accuracy: ± (0.1% × reading +0.7°C) (-100℃─1300℃)) and two thermocouple data loggers (Model type Omega HH147U). RH is measured using a thermo-hygrometer (Model type C.A 1244). The thermocouple and hygrometer are located 0.2 m below the surface of wood pellets. The average value of the thermocouple measurement results at the 8 locations was taken as the reference temperature of biomass to reduce the influence of temperature variation along the sound path between acoustic sensors 1 and 3. After the wood pellets were heated for about 10 hours, they were left to settle for an hour to minimise temperature variation along the acoustic path. Although the temperature increases with the depth of biomass as it is closer to the resistors, the temperature throughout the acoustic path is assumed to be constant.

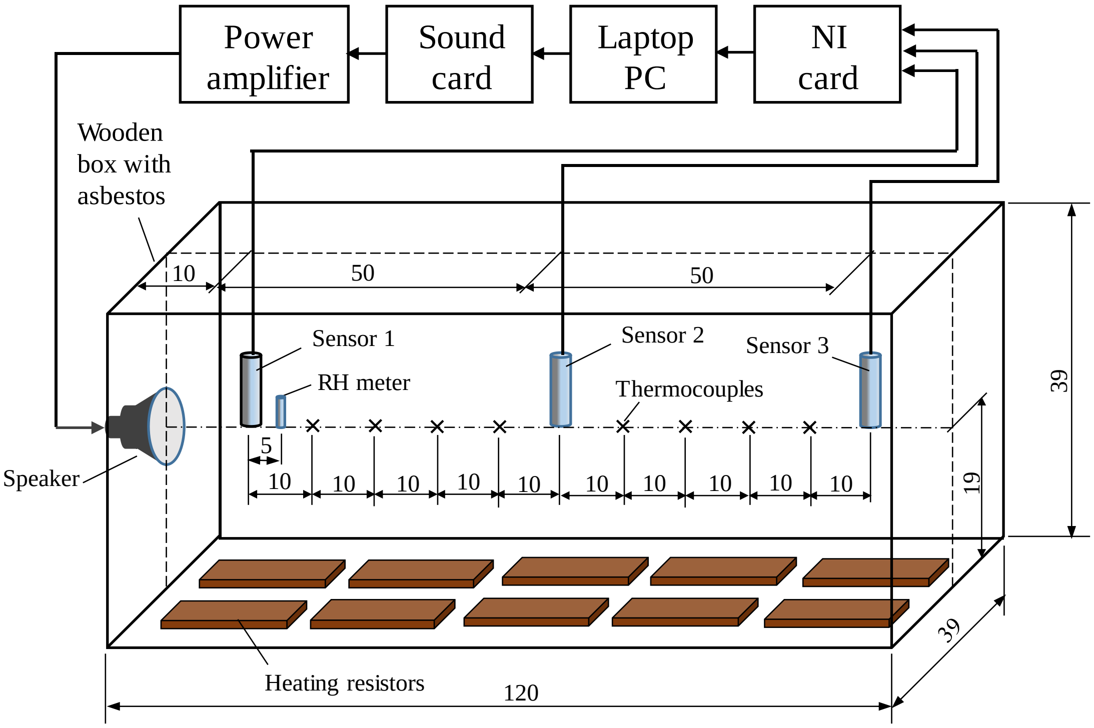


**Figure 5.** System schematic for temperature measurement of stored biomass using low-frequency sound waves (Unit: cm)

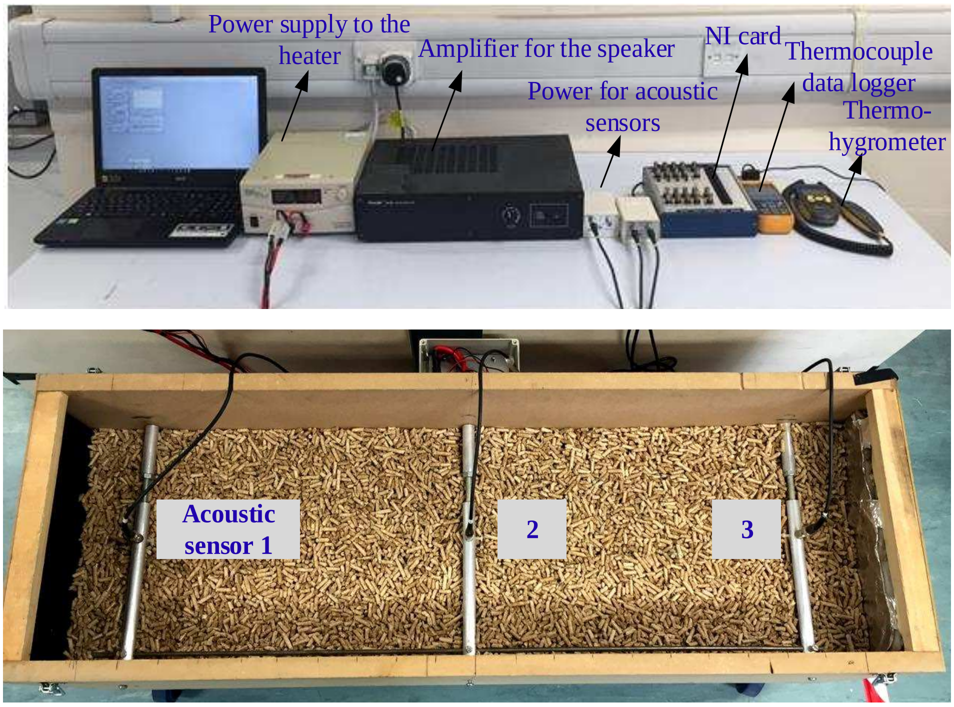
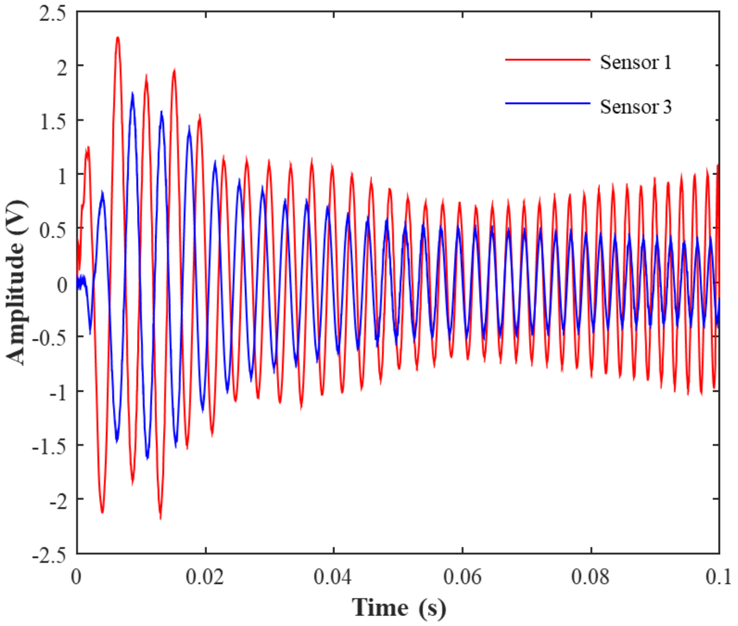


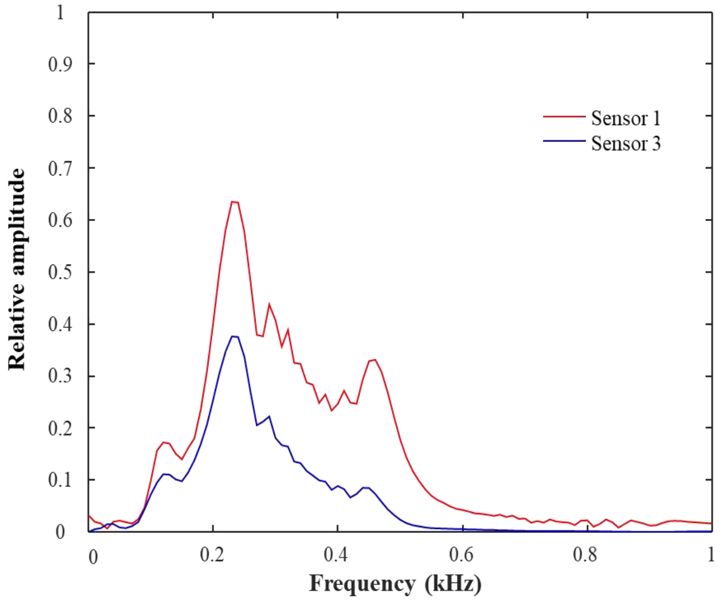
**Figure 6.** Experimental setup of biomass temperature measurement system

## 3.2 TOF Measurement Based on Cross-correlation Signal Processing Technique

Chirp signals are widely used as a sound source for time delay estimation [27-29]. Through a series of experimental observations, a linear chirp signal with a duration of 0.1 s in the frequency band of 200-500 Hz is chosen as the sound source. Fig. 7 shows the chirp signals received by sensors 1 and 3 in the time and frequency domains. As can be seen, the chirp signal is attenuated due to biomass absorption. The frequency band of 200-500 Hz is selected in consideration of the absorption characteristics of stored biomass in the frequency domain and cross-correlation results between the two received signals. Fig. 7 indicates that the received sound waves are still similar in the time and frequency domains.



(a) Waveforms in time domain



(b) Frequency spectra

**Figure 7.** Chirp signals received by Sensors 1 and 3

Cross-correlation signal processing technique is used to calculate the TOF [30-35]. Fig. 8 shows a typical cross-correlation function of the sound signals received by acoustic sensors 1 and 3. The location of the dominant peak determines the TOF of sound waves between the two sensors.

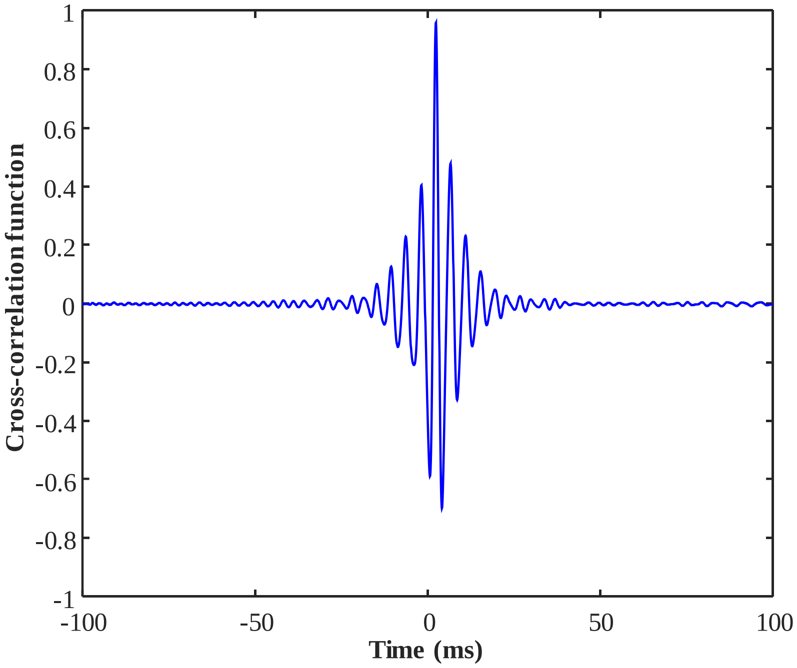
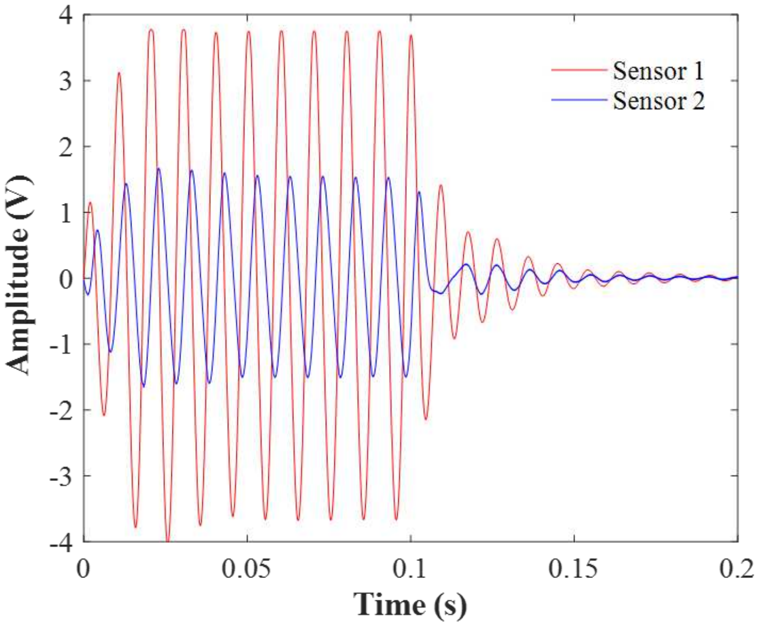


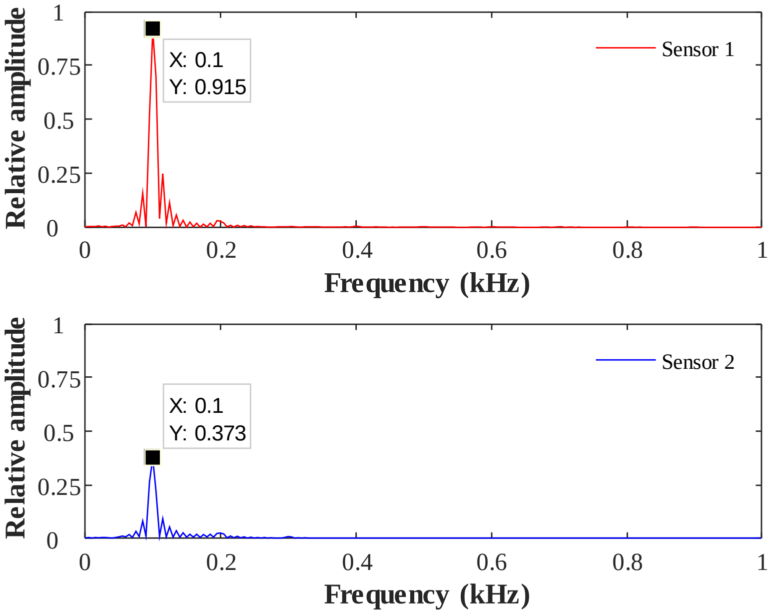
**Figure 8.** Typical cross-correlation function of the sound signals received by Sensors 1 and 3

### 3.3 Sound Absorption and Sound Speed

In order to obtain the values of $\tau$ and d in eq. (9), sound absorption coefficient and sound speed should be measured. Then $\tau$ and d are obtained by using Eq. (11) and (12) to fit the experimental results. In order to measure the sound absorption under different frequencies, sinusoidal waves with a duration of 0.1 s and a single frequency from 100 Hz to 1500 Hz with an interval of 100 Hz are sent through the wood pellets respectively. In order to reduce the influence of sound reflection on sound absorption in stored biomass, sound signals received by sensors 1 and 2 are used to calculate the sound absorption coefficient. Taking the sinusoidal waves under the frequency of 100 Hz for example, Fig. 9 shows the received sound signals in the time and frequency domains.



(a) Waveforms in the time domain



(b) Frequency spectra

**Figure 9.** Waveforms in time domain and their corresponding frequency spectra

In order to reduce the influence of noise on the amplitude of received sound signals, the amplitudes of the main peak in the spectra are taken to calculate the sound absorption coefficient. Sound absorption coefficient a is:

$$a = \frac{1}{s}\ln(\frac{V_1}{V_2}) \tag{17}$$

where $V_1$ and $V_2$ are the amplitudes of sound signals received by sensors 1 and 2 in Fig. 9 (b), respectively. The absorption coefficient computed based on the experiments is shown in Fig. 10. As can be seen, the absorption coefficient of sound wave increases with sound frequency. This is reasonable as the biomass is a porous medium. During the experiments, biomass temperature and RH are 22.9℃ and 49.6%, respectively. According to eq. (13) and (15), c is 345.445 m/s and F is 0.004066. After using eq. (11) to fit the measured absorption coefficients, $\tau/d$ is found to be 2601.

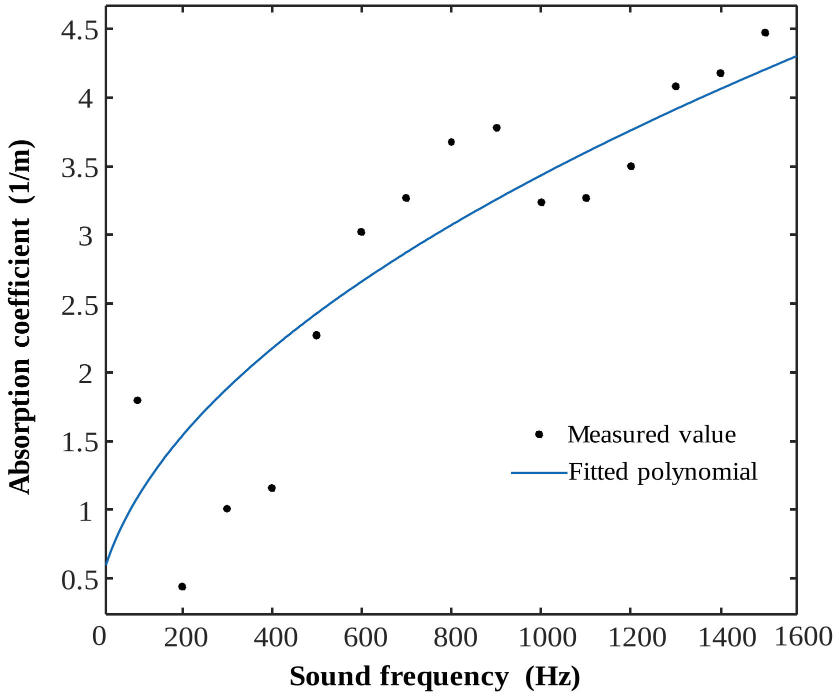


**Figure 10.** Sound absorption coefficient under different sound frequencies

In order to measure the speed of sound wave under different frequencies in the wood pellets, a linear chirp signal with a duration of 0.1 s and frequency bands of 200-300 Hz, 300-400 Hz, 400-500 Hz, 500-600 Hz, 600-700 Hz, 700-800 Hz, 800-900 Hz and 900-1000 Hz was transmitted through the wood pellets, respectively. $\Delta t$ is computed through cross-correlating the sound signals from sensors 1 and 2 (s=0.5 m). By using the distance between the two sensors as sound path length, the sound speed is determined, as shown in Fig. 11. Using the left part in eq. (12) to fit the measured sound speed, $\tau$ is found to be 1.512 and thus d 0.581 mm.

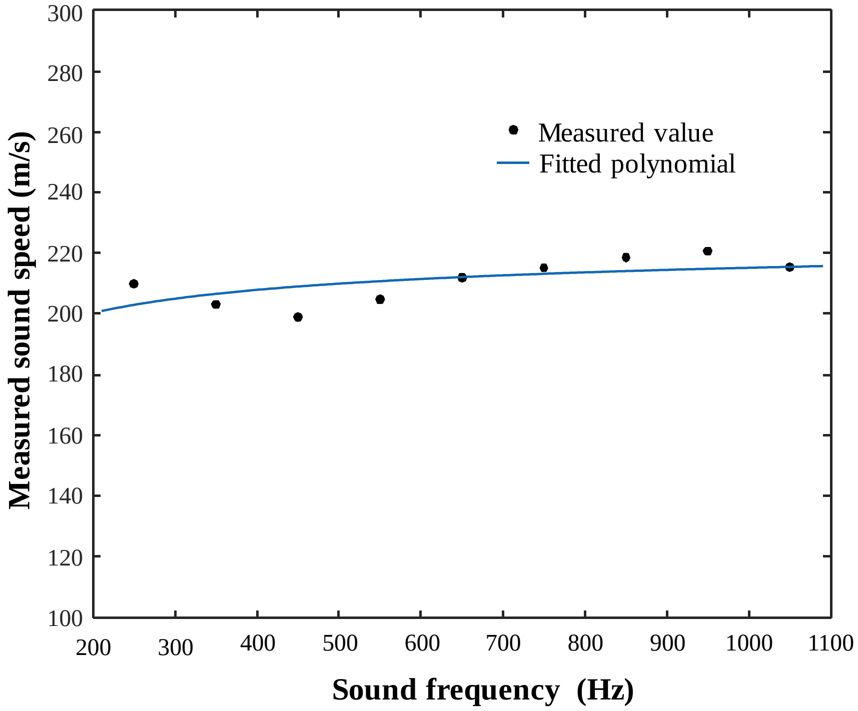


**Figure 11.** Measured sound speed under different sound frequencies

## 3.4 Temperature Measurement Results

The temperature of the wood pellets was set to the values as shown in Table 1, respectively. The chirp signal was transmitted through the wood pellets 20 times with an interval of 1 minute. By cross-correlating the sound signals from sensors 1 and 3 (sensor depth 0.2 m), the average value and standard deviation (STD) of Δt are computed for each temperature point and the results are summarised in Table 1.

**Table 1.** Computed TOF for different temperature settings

| Temperature (℃) | RH (%) | Average TOF (ms) | Standard deviation (μs) | Theoretical sound speed (m/s) |
|---|---|---|---|---|
| 22.0 | 54.9 | 4.5469 | 0.68 | 344.97 |
| 26.4 | 51.9 | 4.5167 | 3.28 | 347.67 |
| 29.5 | 63.4 | 4.5029 | 2.84 | 349.89 |
| 33.6 | 65.5 | 4.4875 | 1.13 | 352.65 |
| 36.3 | 66.1 | 4.4669 | 0.77 | 354.49 |
| 39.3 | 60.4 | 4.4547 | 0.99 | 356.33 |
| 40.2 | 69.1 | 4.4484 | 1.04 | 357.33 |
| 43.8 | 67.4 | 4.4337 | 1.29 | 359.85 |
| 48.9 | 76.3 | 4.4132 | 1.11 | 364.33 |

Experimental values of $\alpha$ under different temperatures in Table 1 are calculated using eq. (10), which is plotted in Fig. 12. Fig. 12 also shows the theoretical relationship between $\alpha$ and T (Fig. 1). A 2-degree polynomial is adopted to fit the experimental value of $\alpha$ in Fig. 12, which yields:

$$\alpha = 2.877 \times 10^{-5} T^2 - 6.034 \times 10^{-4} T + 1.568 \tag{18}$$

If using the fitted equation in Fig. 12 for the biomass temperature measurement in Fig. 4, then $\alpha_2$ at temperature $T_2$ is corrected from $\alpha_1$ through the following equation:

$$\alpha_2 = \alpha_1 + 2.877 \times 10^{-5} (T_2^2 - T_1^2) - 6.034 \times 10^{-4} (T_2 - T_1) \tag{19}$$

The methodology in section 2.4 is used to determine the biomass temperature. Initial characteristic factor $\alpha_1$ is calculated using the data measured at room temperature (22℃), which is 1.5685. Fig. 13 shows the temperature measurement results when $\alpha$ is updated based on the theoretical and experimental relationships (Fig. 12), respectively. In order to compare the temperature measurement results with and without updating $\alpha$, eq. (10) and $\alpha$ measured under the room temperature are used to determine the biomass temperature and the results are also shown in Fig. 13.

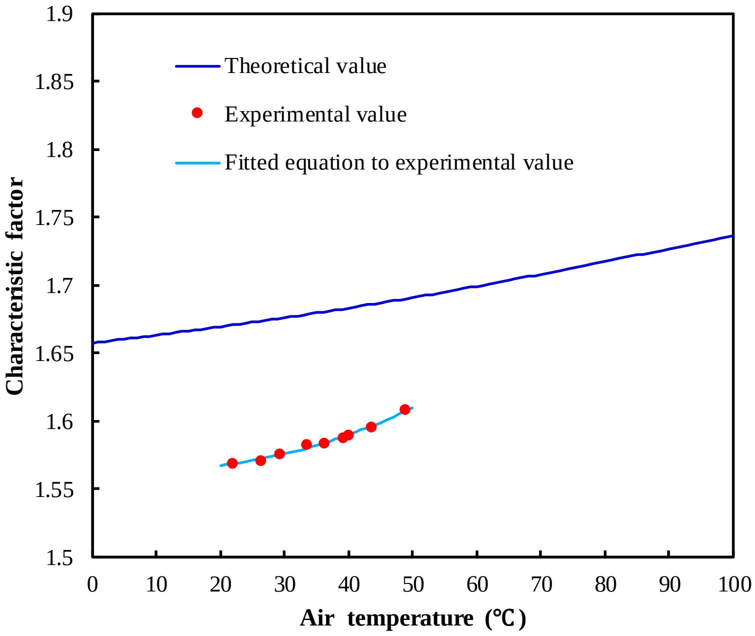
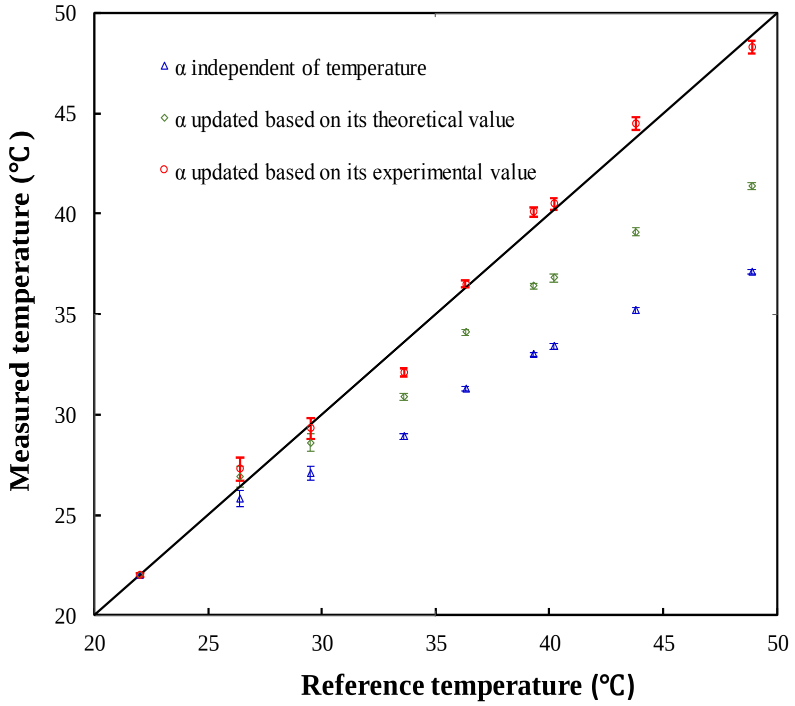
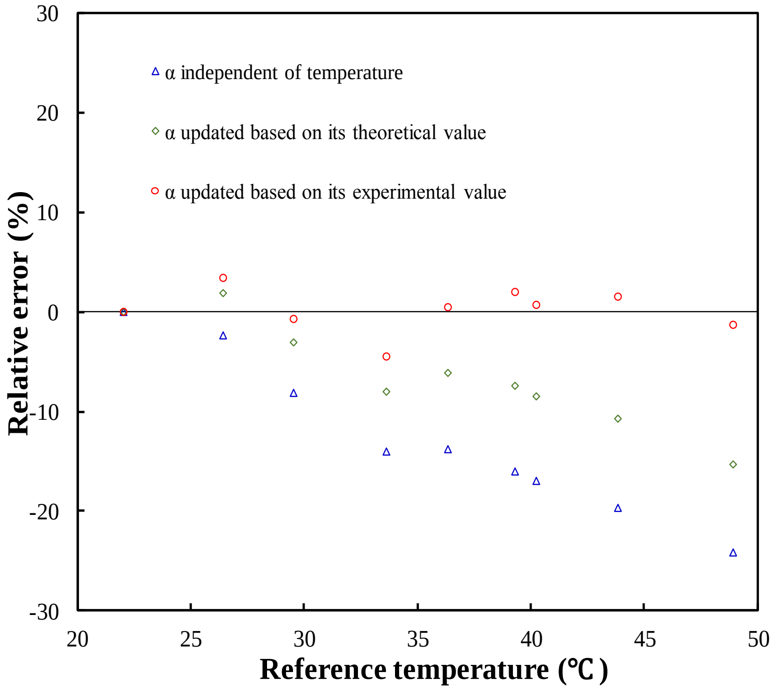


**Figure 12.** Relationship between characteristic factor and temperature



(a) Comparison between the measured and reference temperatures



(b) Relative error

**Figure 13.** Measured temperature and relative error

As can be seen in Fig. 13, the result with $\alpha$ updated based on the experimental relationship of $\alpha$ and T is better than that based on the theoretical relationship of $\alpha$ and T. The relative error of temperature in the former case is no greater than 4.5% whilst the relative error in the latter case is around 15% over the temperature range 22℃ to 48.9℃. Fig. 13 indicates that the accuracy of temperature measurement results is very sensitive to the error in $\alpha$. The experimental value of $\alpha$ increases with air temperature T at a higher rate than the theoretical value. According to the reiteration process shown in Fig. 2, if using theoretical relationship between $\alpha$ and T, the measured temperature of stored biomass will be under-estimated due to the error in $\alpha$. Therefore, to ensure the accuracy of temperature measurement, the experimental relationship between $\alpha$ and T should be established. According to eq. (9), except biomass temperature the value of $\alpha$ also depends on many other factors such as frequency of the acoustic signal, sensor depth in stored biomass, etc. In order to use the method proposed in section 2.4 to measure biomass temperature, all the factors affecting the experimental relationship between $\alpha$ and T and hence the biomass temperature measurement should be considered and analysed (see section 3.4).

## 3.5 Factors Influencing the Temperature Measurement

It has been identified that main factors influencing biomass temperature measurement include variation of air gap structure, pressure and RH of air in the gaps.

### 3.5.1 Air gap structure

Air gaps in stored biomass are assumed to be connected with each other. The air gap structure inside stored biomass is subject to change due to loading and unloading and this change can lead to the variation in measured Δt. The STD of the measured Δt in ten repeated measurements under ambient temperature was 0.211 μs. The top board of the wooden box was opened and then closed ten times and the STD of measured Δt was 4.393 μs with the top board closed. The box was emptied and re-filled with wood pellets ten times. The STD of measured Δt was 14.200 μs with the box filled with pellets. Therefore, the STD caused by variation of air gap structure in stored biomass is 9.596 μs. Using the data at 22℃ in Table 1, the variation in measured temperature caused by this STD in measured Δt is 1.2℃. Therefore, the influence of the variation of air gap structure is ignored.

### 3.5.2 Air pressure

According to the atmospheric pressure information provided by the National Physical

Laboratory (UK), the pressure variation in one year at the same place in the UK is within 7 kPa. The pressure variation in one day is within 2 kPa. Fig. 14 shows absolute variation in $\alpha$ calculated using eq. (9) when air pressure changes from 101.6 kPa to 108.6 kPa, assuming temperature is 0-100℃ and RH is 0-100%. Initial value of $\alpha$ is measured under an ambient temperature of 22℃, so the variation in $\alpha$ caused by variation in air pressure is less than $5.5\times10^{-3}$, leading to about 2℃ variation in temperature measurement results. The maximum variation in $\alpha$ ($8\times10^{-3}$) in Fig. 14 leads to a variation of 2.8℃ in the temperature measurement results. Thus the influence of air pressure on $\alpha$ is neglected in the tested temperature range.

According to the sensitivity analysis in the early work by Miao et al. [14], the variation in temperature measurement due to pressure variation in one day is less than 0.5℃. The variation in temperature measurement due to pressure variation over a whole year is less than 1.6℃. Thus the local air pressure at a time is used when calculating biomass temperature and the air pressure is assumed constant during the day. For temperature measurement requiring higher accuracy, real-time air pressure information should be incorporated in the temperature measurement system.

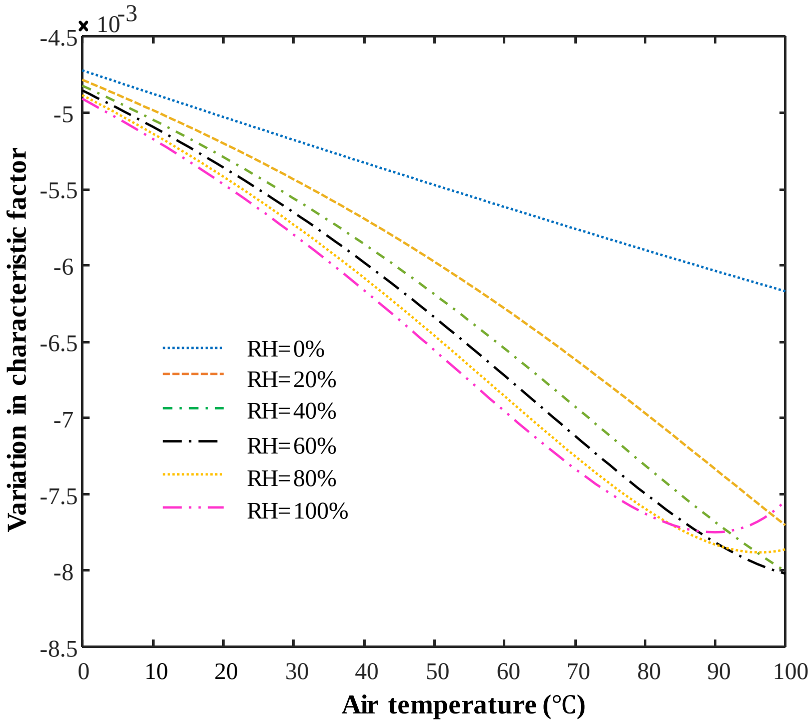


**Figure 14.** Variation of characteristic factor

### 3.5.3 Relative humidity of air

Fig. 15 shows the $\alpha$ calculated using eq. (9) for different RH values and temperatures of air. The air pressure is 101.6 kPa. As can be seen, RH of the air in the gaps of stored biomass has no significant impact on $\alpha$. For instance, if RH changes from 30% to 60%, variation in $\alpha$ is $7\times10^{-4}$ at 0°C and $8\times10^{-3}$ at 100°C, leading to 0.3°C and 2.8°C variation in temperature measurement results. However, in order to use eq. (15) to measure the biomass temperature, RH in stored biomass should be measured. The sensitivity analysis by Miao et al. [14] indicates that the absolute temperature measurement error due to 20% change in RH is less than 1℃ over the temperature range 0~30℃ and -4~5℃ when temperature is larger than 30℃.

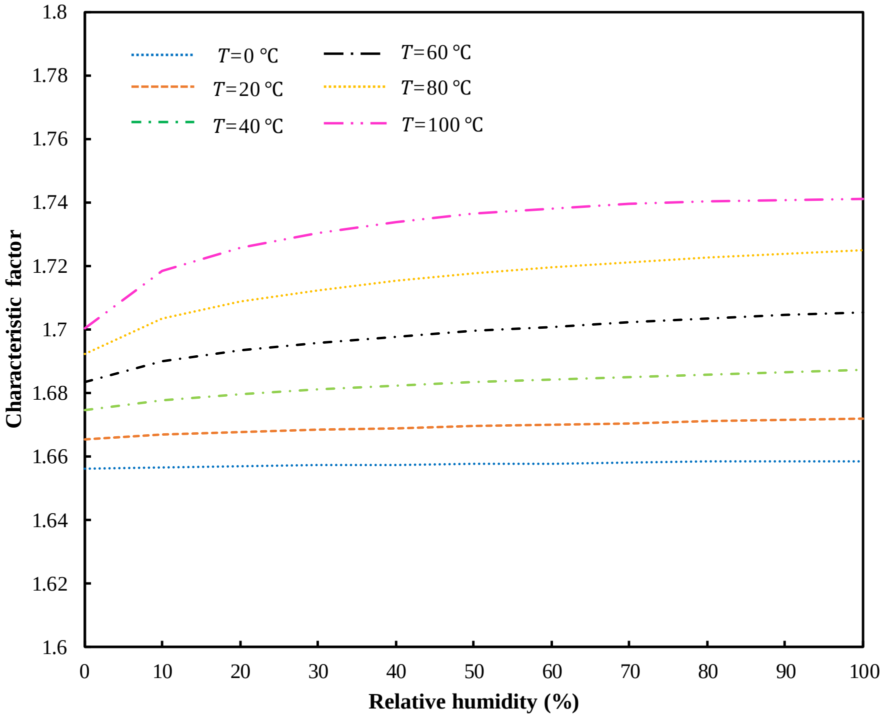


**Figure 15.** Characteristic factor for different air RH and temperatures under the air pressure of 101.6 kPa

A different biomass material may have a different bulk density, which may influence d and $\tau$ and hence $\alpha$. The size and shape of the pellets will also affect d and $\tau$. Therefore, the relationship between biomass properties (type of biomass, pellet size and shape, bulk density, etc.) and $\alpha$ needs to be investigated through experimentation in the future.

## 4. Conclusions

In this study, a method for the temperature measurement of stored biomass using low frequency sound waves and cross-correlation processing techniques has been proposed and its accuracy has been examined on a lab-scale test rig. Cross-correlation is used to determine the TOF of the generated linear chirp signal between two acoustic sensors. The sound speed in free space and thus biomass temperature is determined from the measured TOF and RH in stored biomass by introducing a characteristic factor. The accuracy of temperature measurement is improved by updating the characteristic factor based on the experimental relationship between characteristic factor and air temperature. The relative error of temperature measurement results using the proposed method is within 4.5% over the temperature range 22℃ to 48.9℃. The results presented in this paper have indicated that the acoustic methods can be used to measure the temperature of stored biomass in a non-intrusive manner, which will help achieve the temperature monitoring of stored biomass in the power industry.

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