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Full Length Article

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 °C to 48.9 °C. 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 °C under all test conditions.

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

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List of symbols

a	Sound absorption coefficient (1/m)
c	Sound speed (m/s)
c_g	Group speed in a thin pipe (m/s)
c_p	Phase speed in a thin pipe (m/s)
d	Equivalent pipe diameter of air gaps (m)
f	Sound frequency (Hz)
f_1	Enhancement factor for water vapour
F	Combined thermo-dynamic parameter
k	Wavenumber (m^{-1})
M_a	Molar mass of dry air (kg/mol)
M_w	Molar mass of water content (kg/mol)
P	Air pressure (Pa)
P_{sv}	Saturation vapour pressure (Pa)
R	Universal gas constant (J/(mol·K))
RH	Relative humidity (%)
s	Distance between acoustic sensors (m)
Δt	Time of flight of sound waves (s)
T	Air temperature (°C)
T_1	Ambient temperature (°C)
T_2	Initially measured biomass temperature (°C)
V_1	Amplitude of sound signal received by sensor 1 (V)
V_2	Amplitude of sound signal received by sensor 2 (V)
x_w	Mole fraction of water vapour
Z	Compressibility factor
α	Characteristic factor
α_1	Initial value of characteristic factor
γ	Specific heat ratio
κ	Thermal diffusivity of air (m^2/s)
μ	Dynamic viscosity of air (kg/(m·s))
ν	Kinematic viscosity of air (m^2/s)
ρ	Air density (kg/m^3)
τ	Tortuosity factor
ω	Angular frequency (rad/s)

temperature range from 23.5 °C to 54.2 °C [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:

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

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

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

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

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

where ω 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