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Direct measurements of thermal properties of wood pellets: Elevated temperatures, fine fractions and moisture content

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HIGHLIGHTS

- Thermal conductivity k, and heat capacity c_p, of bulk pellets can be measured by TPS.
- The temperature and moisture dependences are investigated.
- Bulk and solid properties are related through a parallel network model.
- Crushed pellets have lower density, bulk k scales linearly with density.

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ABSTRACT

The self-heating propensity of biomass fuels is a major challenge to the large scale handling of e.g. wood pellets. The insulating properties in combination with exothermal processes sometimes lead to fires when larger volumes of wood pellets are stored. Recently, the thermal conductivity and specific heat of wood pellets have been investigated (Gou et al., 2013) through back-calculations of transient temperatures in wood bulk storage. Such properties are important in order to make simulations and predictions about safe storage and use. However, little information is available about the temperature dependence of these properties as well as the bulk properties of broken pellets, which is abundant in critical parts of a storage facility. In this study we show that the specific heat and thermal conductivity of wood pellets can be directly measured using the Transient Plane Source technique. We present data between 22 and 120 °C for bulk wood pellets and investigate the change in conductivity for fine particle bulk material. In addition, we investigate the possibility of measuring on individual pellets while studying the moisture content dependence.

1. Introduction

Self-heating leading to fires in large accumulations of biomass fuels occurs frequently both at deposits and storage silos. Often this self-heating leads to fires that sometimes damages the whole storage facility [1]. The underlying mechanisms are weak exothermal processes, which produce off-gassing products [2] and heat [3]. In combination with low thermal conductivity of the fuel self-heating might be critical. With an increasing use of biomass fuel in large scale facilities the self-heating propensity constitute a major challenge to the use and handling of modern fuels like e.g. wood pellets. Understanding how and at which conditions the self-heating phenomenon occurs is important for efficient use of the material. The possibility of modeling the thermal behavior in specific situations would be of great benefit for the industry. Such models require a priori knowledge of the thermal properties of bulk wood pellets such as thermal conductivity (k), specific heat (c_p) and density (ρ). For detailed knowledge, also specific properties such as porosity (ϕ) and thermal properties of individual pellets are important. Recently, the thermal conductivity and specific heat of wood pellets have been investigated [4] through back-calculations of temperature distributions in wood bulk storage. However, little information is available about the temperature dependence of these properties.

In addition, since the exothermal processes are driven by oxygen, it is likely that fires in wood pellet storage silos starts where oxygen content can be kept at a high level due to ventilation. Where forced air flow is not used (e.g. Europe) these could be around the auger for the transportation of pellets. Close to the auger the pellets might be crushed and/or grinded. Further are pellets broken during the filling process, which results in accumulation

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of finer fraction in the bottom center part of the silo. Thus, the thermal properties of finer fractions of the wood pellets are also of importance as input to realistic models of self-heating.

The typical behavior of most solids is that conductivity decreases while heat capacity increases with increasing temperature. However, for porous materials like bulk wood pellets, the conductivity is actually an effective combination of pure conductivity within the pellets, convective heat transfer to the gas phase and radiation exchange between pellets. This combination often leads to increasing conductivity with increasing temperature. Also, distinguishing between changes in conductivity, specific heat, density and evaporation can be difficult when performing back calculations of temperature diffusion. This can have consequences when varying different parameters in a predictive model. Thus, there is a need for direct measurements of the different thermal properties including also the temperature dependence.

Some work on moisture content (MC) dependence for the thermal conductivity of wood can be found in the literature [5,6]. Regarding porous biomass, data is available for dried softwood particles [7], Alfalfa pellets (MC dependence [8]) and soft wood pellets (MC dependence [4]). A more detailed description of the available literature can be found in Ref. [4].

Heat capacity in a binary mixture is simply given by a weighted average of the constituents. Treating the single pellets as a homogeneous material the two-phase heat capacity is:

$$\rho^{bulk} c_p^{bulk} = (1-\phi)\rho^s c_p^s + \phi \rho^g c_p^g, \quad (1)$$

where ϕ is the porosity of the bulk and s and g represent the solid and gas phase, respectively, in this case represented by individual pellets and air.

The bulk conductivity is more difficult and depends on the specific geometry of the solid. However, Guo et al. [4] successfully used a model describing a parallel network of solids resulting in an equivalent weighted average just as the expression for the heat capacity. Thus, it appears as both thermal conductivity and specific heat can be extrapolated from solid to bulk behavior using the simplest possible averaging.

$$k_{bulk} = (1-\phi)k_{solid} + \phi k_{air}. \quad (2)$$

In this study we show that the specific heat and thermal conductivity of bulk wood pellets can be directly measured using the Transient Plane Source (TPS) technique. We present data between 22 and 120 °C and investigate the changes for fine particle bulk material. We also investigate the possibility of expanding measurements on single pellets to bulk behavior and study the moisture content behavior.

2. Experimental

2.1. Materials

The wood pellets investigated are cylindrical pellets produced in the south of Sweden from a mixture of pine and spruce, with a diameter of 8 mm. Before further conditioning the pellets had been stored indoors during several weeks. The density of the solid material was determined by hydrostatic weighing of five randomly chosen pellets. The average solid density was 1290 kg/m^3 with a spread of ±2.2%. The bulk density was determined by weighing the material in a cubic box with a volume of 8000 cm^3. Some pellets were also conditioned for several days in 22 °C in controlled relative humidities (RH) of 33%, 50% and 75% RH as well as in a dry atmosphere controlled by silica gel. For each batch measured, a number of pellets were used to determine moisture content (MC) by heating in a 105 °C electrical furnace overnight. The material characteristics are shown in Tables 1 and 2.

Table 1
Material characteristics of normal fraction pellets. Densities for MC = 6.6% are measured. Other densities are calculated by scaling with MC.

RH (%)	MC (%)	Solid density (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)
Dry	2.9	1245 ± 27	669	46 ± 2.5
–	6.6	1290 ± 28	693	46 ± 2.5
33	7.5	1301 ± 28	699	46 ± 2.5
50	9.6	1326 ± 29	713	46 ± 2.5
75	11.7	1352 ± 30	726	46 ± 2.5

Table 2
Measured densities for fine fraction pellets.

MC (%)	Grid size (mm)	Bulk density (kg/m^3)
6.6	None	693
6.6	8	629
6.6	4	502

The moisture contents obtained by conditioning in different relative humidities are in line with the equilibrium moisture content tabulated for wood [9].

The length distribution of the original pellets is measured on 140 pellets using a caliper and the result is shown in Fig. 1. The MC = 6.6% pellets were also investigated in states of finer solids. The original pellets were split and two new size fractions were created. An intermediate fraction was selected from filtering through a sieve of 8 mm quadratic cells and a fine fraction through 4 mm quadratic cells.

2.2. STA measurements

The material was also analyzed using Simultaneous Thermal Analysis (STA), which simultaneously runs a thermogravimetric analysis and differential scanning calorimetry on the same sample. The measurements are performed in air atmosphere using an STA F3 Jupiter from Netzsch using 85 µl PtRh crucibles with pin holed lids. The sample was heated at 5 K/min from 25 to 600 °C. A background scan was subtracted from the data. In addition, a sapphire reference disc was also measured for the same thermal conditions for calibration.

2.3. Conductivity measurements

Conductivity measurements are performed using the Transient Plane heat Source (TPS) technique on a hotdisk 2500s. The method is standardized (ISO 22007-2) for measuring thermal conductivity and diffusivity of plastics but is here employed on granular material. An etched nickel double-spiral insulated on both sides with

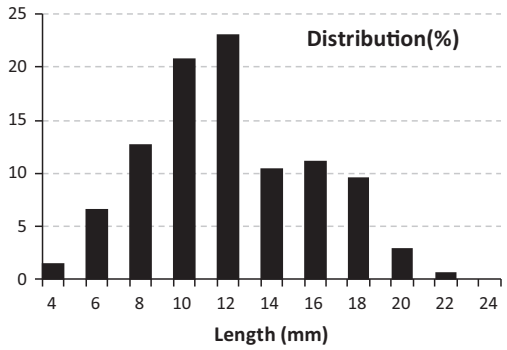

Fig. 1. Distribution of pellet length based on 140 random measurements.