Thermal properties of sweet sorghum bagasse as a function of moisture content

Ajit K. Mahapatra[1*], Daniel E. Ekefre[1], Nalini K. Pattanaik[2], Umakanta Jena[3], Archie L. Williams[4], Mark Latimore, Jr.[5]

(1. *Food Engineering Laboratory, Agricultural Research Station, College of Agriculture, Family Sciences and Technology, Fort Valley State University, Fort Valley, GA 31030, USA*;
2. *Agricultural Economics, College of Agriculture, Family Sciences and Technology, Fort Valley State University, Fort Valley, GA 31030, USA*;
3. *Chemical & Materials Engineering, New Mexico State University, 1780 E University Ave., Las Cruces, NM 88003, USA*;
4. *Engineering and Technology, College of Agriculture, Family Sciences and Technology, Fort Valley State University, Fort Valley, GA 31030, USA*;
5. *Cooperative Extension, College of Agriculture, Family Sciences and Technology, Fort Valley State University, Fort Valley, GA 31030, USA*)

Abstract: In this study, we examined the relationship between thermal properties and moisture content of sweet sorghum bagasse. A KD2 Pro Thermal Properties Analyzer was used to measure the thermal conductivity, thermal diffusivity, and volumetric specific heat of sweet sorghum bagasse across a range of moisture contents (8.52%-28.62% w.b.). The thermal conductivity of sweet sorghum bagasse ranged from 0.0921 to 0.1096 W m^{-1} K^{-1} and increased with increase in moisture content through the range of 8.52%-28.62% w.b. The thermal diffusivity ranged from 0.1225 to 0.1596 mm^2 s^{-1} and increased with moisture content through the range of 8.52%-28.62% w.b. The volumetric specific heat of sweet sorghum bagasse ranged from 0.7537 to 0.6869 MJ m^{-3} K^{-1} and decreased with moisture content through the range of 8.52%-28.62% w.b. Quantitative empirical equations incorporating moisture content and room temperature dependent terms were developed to predict thermal conductivity, thermal diffusivity, and volumetric specific heat of sweet sorghum bagasse between 8.52% and 28.62% (w.b.) moisture content. The models are valid within the limits of the parameters used in the experiments.
Keywords: bagasse, KD2 pro thermal properties analyzer, moisture content, sweet sorghum, thermal properties

Citation: Mahapatra, A. K., D. E. Ekefre, N. Pattanaik, U. Jena, A. L. Williams, and M. L. Jr. 2017. Thermal properties of sweet sorghum bagasse as a function of moisture content. Agricultural Engineering International: CIGR Journal, 19(4): 108–113.

1 Introduction

Sweet sorghum (*Sorghum bicolor* L. Moench) is a promising crop for bioethanol production. It can be used for different purposes which include using the grains for food, production of fuel in the form of ethanol from its stem juice. Bagasse is the solid material that is left after the juice is squeezed from sweet sorghum stalk. About five to six tons of wet bagasse is obtained from 10 tons of crushed sweet sorghum (Khalil et al., 2015; Negro et al., 1999). Sweet sorghum bagasse can be used in many green technology applications and is mainly suitable for use in the emerging bioenergy technologies including cellulosic ethanol production. It can also be used as a raw material for thermal decomposition processes and production of bio-oil, gaseous fuels and biochar (Monti and Venturi, 2003; Piskorz et al., 1998; Zhang et al., 2007). The use of sweet sorghum bagasse could improve the economy of the global use of the crop since a huge quantity of biomass will result from a large scale production of sweet sorghum juice (Li et al., 2010). The

Received date: 2015-05-27 **Accepted date:** 2017-08-25
*** Corresponding author: Ajit Kumar Mahapatra**, ASABE Member, Associate Professor, Food and Bioprocess Engineering, Fort Valley State University, Fort Valley, GA 31030, USA. Email: mahapatraa@fvsu.edu.

structure and composition of lignocellulosic makes it naturally resistant to enzymatic and microbial degradation during hydrolysis and fermentation processes, hence, pretreatment is a major step involved in most bioenergy conversion processes (Iroba et al., 2013). Pretreatment of lignocellulosic biomass prior to hydrolysis and fermentation includes the application of heat and there is a need to understand how the lignocellulosic structure breaks down during the pretreatment process and how different heat transfer properties affect the breakdown, so that the mechanics of degradation process can be better explained (Pandey, 2012). The response of biomass to heat transfer is dependent on thermal properties of the biomass. Knowledge of thermal properties of biomass is thus important not only for designing optimal processing systems but also for the prediction and control of various changes occurring in biomass during thermal processing and storage (Fennell and Boldor, 2014). Precise data of thermal properties are required both for existing biomass and for new products to understand and model heat transfer processes. Therefore, a need exists to measure the thermal properties of biomass materials.

Thermal conductivity, thermal diffusivity and specific heat are three important engineering properties of a material related to heat transfer characteristics (Carson, 2015; Fennell and Boldor, 2014; Yang et al., 2002). These properties are essential in studying heating, drying, and cooling processes for sweet sorghum bagasse. Determination of these properties will assist in modeling and designing of appropriate equipment for drying of sweet sorghum bagasse. The key factors that significantly affect thermal properties of biomass include density, temperature, and moisture content (Raigar and Mishra, 2014). Several researchers have determined the thermal properties of various food products and flours as a function of moisture content. Pandey (2012) measured the thermal properties of poplar wood grind at different moisture contents using a KD2 Pro Thermal Properties Analyzer. Iroba et al. (2013) measured the thermal properties of barley straw using a differential scanning calorimeter. A literature survey, however, reveals that there is no experimental data on the effect of moisture content on thermal properties of sweet sorghum bagasse. The objective of this study was to determine the thermal conductivity, thermal diffusivity and specific heat of sweet sorghum bagasse as a function of moisture content. We measured thermal properties of sweet sorghum bagasse across a range of moisture contents and derived relationships from these data. The experimental data were fitted to develop equations predicting the thermal conductivity, thermal diffusivity, and volumetric specific heat of sweet sorghum bagasse as a function of moisture content between 8.52% and 28.62% (w.b.).

2 Materials and Methods

2.1 Sweet sorghum bagasse

The bagasse used in this study were obtained from three cultivars of sweet sorghum (Dale, Theis and M81 E). The bagasse was air dried and then shredded with a Troy-Bilt chipper shredder (Model no: CS 4265 Cleveland Ohio, USA). The shredded bagasse samples were oven dried at 60°C in a convection oven (Thermal Product Solutions, White Deer, PA). The oven dried bagasse were further ground with a Thomas-Wiley laboratory mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA). The particle size ranged from 0.18 to 0.25 mm (A.S.T.M. E-11 specification sieves number 60-80, W.S. Tyler Inc., Mentor, Ohio). Equal amounts of bagasse grind from three cultivars were mixed.

2.2 Sample preparation

Moisture content of sweet sorghum bagasse was determined in three replicates using oven drying method following the ASAE Standard S358.2 (ASABE, 2008). Assessment of the effect of moisture content on thermal properties of sweet sorghum bagasse was carried out at five levels of moisture contents (8.52%, 12.93%, 18.95%, 24.63%, and 28.62%; w.b.). The initial moisture content of sweet sorghum bagasse mix was measured as 8.52%. The samples at moisture contents above 8.52% were obtained by spraying predetermined amount of pure analytical-grade water (Elix 35, Elix Water Purification System, EMD Millipore, Billerica, MA) on sweet sorghum bagasse (Mahapatra et al., 2011; Mahapatra et al., 2013; Singh et al.; 2016; White and Jays, 2001). The amount of pure analytical-grade water to be added was computed using the following Equation (1) (Coşkun et al., 2005; Mahapatra et al., 2013; Wang et al., 2007):

$$Q = W_i (M_f - M_i) / (100 - M_i) \quad (1)$$

where, Q is the mass of pure analytical-grade water added, kg; W_i is the initial mass of sweet sorghum bagasse, kg; M_i is the initial moisture content of sweet sorghum bagasse (%, d.b.); M_f is the desired moisture content of sweet sorghum bagasse (%, d.b.).

The conditioned bagasse samples were sealed in separate Ziploc bags (S. C. Johnson Co., Racine, WI) and stored in a refrigerator (VWR, Model GDM-47, True Manufacturing, Inc., O'fallon, MO) for 24 h before measurement. To ensure a uniform distribution of moisture in the bag, the bag was mixed by rolling and shaking the contents periodically (Mahapatra et al., 2011). Bulk density was calculated by dividing the sample weight by sample volume (10 replicates at each moisture content).

2.3 Thermal property measurement

We began measuring thermal conductivity, thermal diffusivity, and specific heat of sweet sorghum bagasse using the KD2 Pro Thermal Properties Analyzer (Decagon Devices, Inc., Pullman, WA) at five moisture contents (8.52%, 12.93%, 18.95%, 24.63%, and 28.62%; w.b.). The KD2 Pro takes measurements using the transient line heat source method (O'Donnell et al., 2009). The probe (SH-1) length is 30 mm (duel needle), six mm spacing, and its diameter is 1.3 mm. This analyzer offers a simultaneous direct measurement of thermal conductivity, thermal resistivity, thermal diffusivity, and volumetric specific heat. Samples from each moisture content were placed at room temperature and the KD2 Pro probe was inserted horizontally into the middle of each sweet sorghum bagasse sample to equilibrate to the sample temperatures before the readings were taken. Fifteen min gap was provided between each reading to ensure thermal gradients had dissipated from the previous test. The room temperature recorded was in 21.7°C-26.4°C range. Thermal properties were measured in triplicate and repeated 10 times (n = 30). Repeated measurements of thermal conductivity, thermal diffusivity and volumetric specific heat at similar moisture contents varied by 5.87%.

2.4 Data analysis

Thermal conductivity, thermal diffusivity and volumetric specific heat were measured at five moisture contents and the mean values calculated for thirty replications at each moisture content. Data were analyzed using the general linear models (GLM) procedures of the Statistical Analysis System version 9.4 (SAS, 2012). Least Significant Difference (LSD) among means was calculated at 5% significant level (p<0.05). Linear regression techniques were used to assess the relationship between thermal properties and moisture content.

3 Results and Discussion

3.1 Bulk density

Bulk density of sweet sorghum bagasse was obtained by dividing the mass of sweet sorghum bagasse by the effective volume. The resultant bulk density data are presented in Table 1.

Table 1 Bulk density of sweet sorghum bagasse

Moisture content, % w.b.	Mean bulk density, kg m^{-3}	±SE*
8.52	227.26	3.32
12.93	198.22	4.73
18.94	203.48	5.11
24.63	178.27	2.27
28.62	198.70	2.17

Note: *SE = standard error.

3.2 Thermal conductivity (*k*)

The average thermal conductivity (k) of sweet sorghum bagasse increased from 0.0921 to 0.1096 W m^{-1} K^{-1}, with increase in moisture content from 8.52% to 28.62% (Figure 1). The standard deviations ranged from 0.004 to 0.009 W m^{-1} K^{-1}. The increasing trend was because of the presence of more water, which has a higher thermal conductivity than bagasse and air. In general, moisture content had a significant effect on the thermal conductivity of sweet sorghum bagasse (p<0.05). However, pairwise comparison of thermal conductivity values did not show any significant difference between 12.93% and 24.63% (p = 0.08) and between 18.94% and 24.63% moisture contents (p = 0.28). Fennell and Boldor (2014) determined the thermal conductivity of sweet sorghum biomass as 0.13±0.003 W m^{-1} K^{-1}.

3.3 Thermal diffusivity (*α*)

The average thermal diffusivity (α) of sweet sorghum bagasse increased linearly from 0.1225 to 0.1596 mm^2 s^{-1}, as moisture content increased from 8.52% to 28.62% (Figure 2). The standard deviations ranged from 0.007 to 0.011 mm^2 s^{-1}. As moisture content increased, the pores and capillaries of sweet sorghum bagasse grind which were initially filled with air was gradually displaced by absorbed water. Heat was released by water adsorption in sweet sorghum bagasse and as a result the thermal diffusivity increased (Kostaropoulos and Saravacos, 1997; Mahapatra et al., 2013). Moisture content had a significant effect on the thermal diffusivity of sweet sorghum bagasse (p<0.05). However, pairwise comparison of thermal diffusivity values did not show any significant difference between 18.94% and 24.63% moisture contents (p = 0.36). Fennell and Boldor (2014) determined the thermal diffusivity of sweet sorghum biomass as 0.37±0.01 mm^2 s^{-1}.

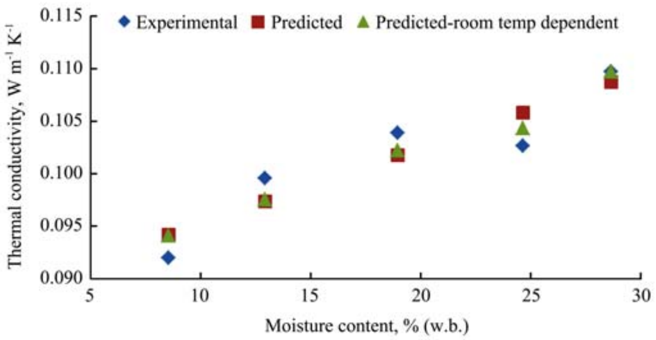

Figure 1 Effect of moisture content on thermal conductivity (k) of sweet sorghum bagasse

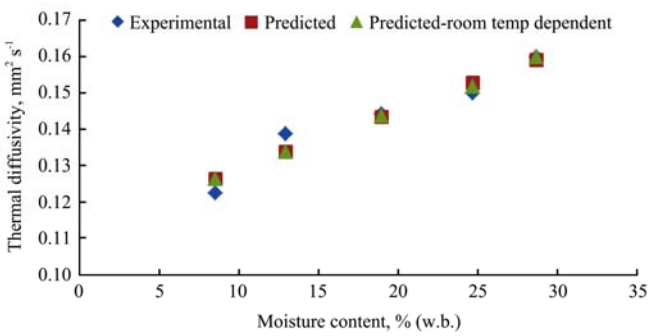

Figure 2 Effect of moisture content on thermal diffusivity (α) of sweet sorghum bagasse

3.4 Volumetric specific heat (C_p)

The average values for C_p of sweet sorghum bagasse ranged from 0.7537 to 0.6869 MJ m^{-3} K^{-1} through the moisture contents tested in this study. The standard deviations ranged from 0.011 to 0.039 MJ m^{-3} K^{-1}. The values for C_p decreased with increasing moisture content (Figure 3). In general, moisture content had a significant effect on the volumetric specific heat of sweet sorghum bagasse (p<0.05). However, pairwise comparison of volumetric specific heat values did not show any significant difference between 12.93% and 18.94% (p = 0.41) and between 24.63% and 28.62% moisture contents (p = 1.0). Fennell and Boldor (2014) determined the specific heat of sweet sorghum biomass as 2321.2± 43.12 J kg^{-1} K^{-1}.

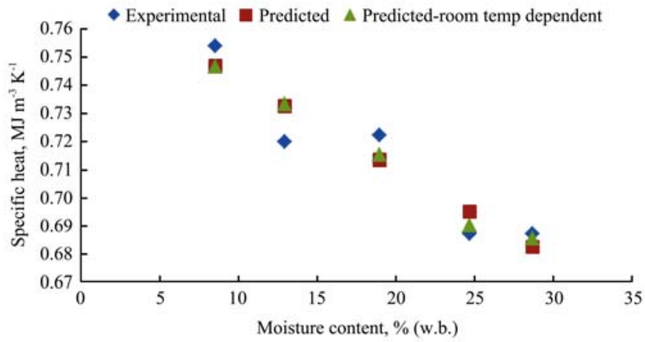

Figure 3 Effect of moisture content on volumetric specific heat (C_p) of sweet sorghum bagasse

Based on the experimental data, the relationships between thermal conductivity, thermal diffusivity and volumetric specific heat with moisture content can be expressed using linear regression equations (Table 2). The regression equations were validated to see if they can be used to describe the effect of moisture content on thermal properties of sweet sorghum bagasse. The R^2 (the proportion of the total variance explained by the equations) ranged between 0.309 and 0.624 (Tables 2 and 3). The mean relative percentage deviation was also calculated.

The thermal properties measurements were conducted over a period of several weeks during which the room temperature varied from 21.74°C to 26.38°C. Inclusion of the room temperature in the empirical equation slightly enhanced the predictive capacity of the equations (Table 3). The percentage deviation ranged between –17% and +20%. It has been reported that the percent deviation for predicting the specific heat of wheat flour and wheat flour dough ranged between –20% and +36% (Kaletunç, 2007). The mean relative percentage deviation ranged between –0.22% and –0.44% (Table 3). Mean relative percentage deviation below 10% indicates a reasonable good fit for practical purposes (Wang and Brenan, 1993).

Table 2 Relationship between thermal properties and moisture content of sweet sorghum bagasse

Thermal properties	Relationship	Coefficient of determination, R^2	Root mean square error	Deviation range, %
Thermal conductivity (k), W m^{-1} K^{-1}	k = 0.08807 + 0.00072 MC	0.359	0.00713	–20 and +22 (–0.45)*
Thermal diffusivity (α), mm^2 s^{-1}	α = 0.11259 + 0.00162 MC	0.607	0.00964	–16 and +18 (–0.45)*
Specific heat (C_p), MJ m^{-3} K^{-1}	C_p = 0.77369 – 0.00319 MC	0.309	0.03537	–18 and +13 (–0.24)*

Note: *Mean relative deviation, %.

Table 3 Relationship between thermal properties and moisture content of sweet sorghum bagasse and room temperature

Thermal properties	Relationship	Coefficient of determination, R^2	Root mean square error	Deviation range, %
Thermal conductivity (k), W m^{-1} K^{-1}	k = 0.00378 + 0.00086 MC + 0.00350 T	0.475	0.00647	−16 and +20 (−0.38)*
Thermal diffusivity (α), mm^2 s^{-1}	α = 0.05768 + 0.00171 MC + 0.00228 T	0.624	0.00947	−17 and +18 (−0.44)*
Specific heat (C_p), MJ m^{-3} K^{-1}	C_p = 0.48409 – 0.00270 MC + 0.01202 T	0.369	0.03391	−15 and +12 (−0.22)*

Note: *Mean relative deviation, %.

4 Conclusions

Thermal conductivity, thermal diffusivity, and volumetric specific heat of sweet sorghum bagasse were measured experimentally at different moisture contents by using a KD2 Pro Thermal Properties Analyzer. Thermal conductivity and thermal diffusivity of sweet sorghum bagasse increased linearly with moisture content. However, the volumetric specific heat decreased linearly with moisture content. Empirical equations were developed to predict the thermal conductivity, thermal diffusivity, and volumetric specific heat of sweet sorghum bagasse as a function of moisture content. Inclusion of a room temperature dependent term improved the predictability of thermal properties.

Acknowledgement

This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2010-38821-21570.

References

ASABE Standards. 2008. S358.2: Moisture measurement-forages. St. Joseph: MI.

Carson, J. K. 2015. Thermal conductivity measurement and prediction of particulate foods. *International Journal of Food Properties,* 18(12): 2840–2849.

Coşkun, M. B., I. Yalçin, and C. Özarslan. 2005. Physical properties of sweet corn seed (*Zea mays saccharata Sturt*). *Journal of Food Engineering,* 74(4): 523–528.

Fennell, L. P., and D. Boldor. 2014. Dielectric and thermal properties of sweet sorghum biomass. *Journal of Microwave Power and Electromagnetic Energy,* 48(4): 244–260.

Iroba, K. L., L. G. Tabil, V. Meda, and O. D. Baik. 2013. Thermal properties of lignocellulosic biomass barley straw. ASABE Paper No. 1594972. Kansas City: ASABE.

Kaletunç, G. 2007. Prediction of specific heat of cereal flours: A quantitative empirical correlation. *Journal of Food Engineering,* 82(4): 589–594.

Khalil, S. R. A., A. A. Abdelhafez, and E. A. M. Amer. 2015. Evaluation of bioethanol production from juice and bagasse of some sweet sorghum varieties. *Annals of Agricultural Science,* 60(2): 317–324.

Kostaropoulos, A. E., and G. D. Saravacos. 1997. Thermal diffusivity of granular and porous foods at low moisture content. *Journal of Food Engineering,* 33(1): 101–109.

Li, B. Z., V. Balan, Y. J. Yuan, and B. E. Dale. 2010. Process optimization to convert forage and sweet sorghum bagasse to ethanol based on ammonia fiber expansion (AFEX) pretreatment. *Bioresource Technology,* 101(4): 1285–1292.

Mahapatra, A. K., S. L. Melton, and E. M. Isang. 2013. Effect of moisture content on thermal properties of cowpea flours. *CIGR Journal,* 15(2): 251–255.

Mahapatra, A. K., Y. Lan, and D. L. Harris. 2011. Influence of moisture content and temperature on thermal conductivity and thermal diffusivity of rice flours. *International Journal of Food Properties,* 14(3): 675–683.

Monti, A., and G. Venturi. 2003. Comparison of the energy performance of fiber sorghum, sweet sorghum and wheat monocultures in northern Italy. *European Journal of Agronomy,* 19(1): 35–43.

Negro, M. J., M. L. Solano, P. Ciria, and J. Carrasco. 1999. Composting of sweet sorghum bagasse with other wastes. *Bioresources Technology,* 67(1): 89–92.

O'Donnell, J. A., V. E. Romanovsky, J. W. Harden, and A. D. McGuire. 2009. The effect of moisture content on the thermal conductivity of moss and organic soil horizons from black spruce ecosystems in interior Alaska. *Soil Science,* 174(12): 646–651.

Pandey, J. L. 2012. Effects of pretreatment conditions on downstream bioconversion of poplar wood into biofuels. M.S. thesis. The Pennsylvania State University: State College, PA.

Piskorz, J., P. Majerski, D. Radlein, D. S. Scott, and A. V. Bridgewater. 1998. First pyrolysis of sweet sorghum and sweet sorghum bagasse. *Journal of Analytical and Applied Pyrolysis,* 46(1): 15–29.

Raigar, R. K., and H. N. Mishra. 2015. Effect of moisture content and particle sizes on physical and thermal properties of roasted Bengal gram flour. *Journal of Food Processing and Preservation,* 39(6): 1839–1844.

SAS. 2012. *SAS/STAT User's Guide*, Version 9.4. Cary, NC: SAS Institute Inc.

Singh, A. K., P. K. Singh, and R. Kumar. 2016. Moisture dependent thermal properties of ground flaxseed (Linum usitatissimum). *CIGR Journal,* 18(1): 256–262.

Wang, B., D. Li, L. Wang, Z. Huang, L. Zhang, X. Chen, and Z. Mao. 2007. Effect of moisture content on the physical properties of fibered flaxseed. *International Journal of Food Engineering,* 3(5): 1–11.

Wang, N., and J. G. Brenan. 1993. The influence of moisture content and temperature on the specific heat of potato measured by differential scanning calorimetry. *Journal of Food Engineering,* 19(3): 303–310.

White, N. D. G., and D. S. Jayas. 2001. Physical properties of canola and sunflower meal pellets. *Canadian Biosystems Engineering,* 43: 3.49–3.52.

Yang, W., S. Sokhansang, J. Tang, and P. Winter. 2002. Determination of thermal conductivity, specific heat and thermal diffusivity of borage seeds. *Biosystems Engineering,* 82(2): 169–176.

Zhang, P., S. Din, J. R. Mielenz, J. Cui, R. T. Elander, and M. Laser. 2007. Fractionating recalcitrant lignocellulose at modest reaction conditions. *Biotechnology and Bioengineering,* 97(2): 214–33.