Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Analysing the effect of particle size on the disintegration of distiller's spent grain compacts while drying in superheated steam medium

Praveen Johnson [a,1], *Jitendra Paliwal* [b,*], *Stefan Cenkowski* [c,2]

[a] Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada
[b] E2 – 376 Engineering and Information Technology Complex (EITC), Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada
[c] Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada

ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
18 March 2015
Accepted 7 April 2015

Keywords:
Asymptotic modulus
Compacts
Particle size distribution
Hardness
Superheated steam drying
Wet distiller's spent grain

Particle size distribution (PSD) in distiller's spent grain compacts was varied and their effect on the disintegration characteristics of compacts while drying in superheated steam (SS) was monitored. Volumetric change and stress-relaxation characteristics, in terms of hardness and asymptotic modulus (E_A) for a 40% deformation, were analysed during the warm-up period (5 s) and after reaching the moisture levels of 40, 30 and 20% (w.b.) in SS. Results showed that particle size was inversely correlated with the expansion or the increase in volume of the compact during SS drying, and the hardness as well as the E_A of the compact increased with a decrease in particle size of the compact. A stepwise regression method was used to determine appropriate variables for developing a multiple linear regression model for predicting the E_A of the compact.

1. Introduction

Distiller's spent grain is generated as a co-product from the ethanol production process. Distiller's spent grain is an easily degradable material containing about 70–80% moisture (Stroem, Desai, & Hoadley, 2009). Although distiller's spent grain is mainly used as a cattle feed, studies have proved that it can be used in human food products, and industrial and agricultural sectors (Liu, Singh, & Inglett, 2011; Tavasoli, Ahangari, Soni, & Dalai, 2009). The presence of high digestible fibre, protein, fat and other bioactive compounds in distiller's spent grain makes it suitable for human consumption and animal feed (Cenkowski, Sosa-Morales, & Flores-Alvarez,

* Corresponding author. Tel.: +1 204 474 8429.
E-mail addresses: umjoh526@myumanitoba.ca (P. Johnson), J.Paliwal@umanitoba.ca (J. Paliwal), stefan_cenkowski@umanitoba.ca (S. Cenkowski).
[1] Tel.: +1 204 899 6701.
[2] Tel.: +1 204 474 6293.
http://dx.doi.org/10.1016/j.biosystemseng.2015.04.005

Nomenclature

A_0	Cross-sectional area of the original specimen
CDS	Condensed distiller's solubles
D_i	Diameter of the ith particle (mm)
$D[4,3]$	Volume mean diameter
$D[3,2]$	Surface area mean diameter
DDGS	distiller's dried grains with solubles
d(0.1)	Diameter of particle below which 10% of the sample volume exists
d(0.5)	Median diameter
d(0.9)	Diameter of particle below which 90% of the sample volume exists
E_A	Asymptotic modulus (MPa)
$F_{(t)}$	Force at time t (N)
H_0	Initial specimen length
$\Delta H_{(t)}$	Absolute deformation
k	Number of independent variables
k_1	Empirical constant
k_2	Empirical coefficient
n	Sample size
PSD	Particle size distribution
R^2	Coefficient of determination
$\underline{R}^2$	Adjusted R^2
SP	Span
SS	Superheated steam
SSE	Sum of squares for error
SST	Total sum of squares
t	time (s)
Tg	glass transition temperature
UTM	Universal testing machine
VMD	Volume median diameter
V_i	initial volume before drying
V_f	final volume after drying
w.b.	wet basis
WDG	Wet distiller's spent grain
σ_0	initial stress (MPa)
σ_t	stress (MPa) at relaxation time t
$\sigma_{0(t)}$	true stress (MPa) (initial)
$\varepsilon_{H(t)}$	true strain

2012; Johnson, Paliwal, & Cenkowski, 2015). Rosentrater (2008) reported that distiller's spent grain can be used as a potential alternative to bio-based fillers and to produce hydrogen, syngas (H_2+CO) and hydrocarbons through further processing (Tavasoli et al., 2009).

Drying of distiller's spent grain is done to increase its shelf-life, and ease of handling and transportation (Mosqueda, Tabil, & Christensen, 2013). Drying also increases its quality and market value by reducing its off-flavours and specific aroma (Ezhil, 2010). Though conventional hot-air dryers are commonly used for drying spent grain, there are issues related to the grain sticking to the dryer surface, dryers catching fire and the overall high energy consumption during drying (Stroem et al., 2009; Tang, Cenkowski, & Izydorczyk, 2005). Sticking of grain to the dryer surface is a major industry concern that is significantly perceptible during drying. Studies have found that superheated steam (SS) drying has the ability to dry the spent grain to a non-sticky level (Stroem et al., 2009). Superheated steam drying has a number of benefits over hot-air drying process including higher energy savings, lower environmental impact, decontamination of microbes, no fire hazard and limited oxidation of the dried product (Ezhil, 2010; Tang et al., 2005).

Densification of biomass has several advantages including better flow properties, lower cost of transportation and storage, and less feed wastage (Kaliyan & Morey, 2009). Moreover, densification creates larger contact surface area for drying. However, during the SS drying of densified biomass, processing plants have reported the specific problem of breaking and disintegrating of biomass compacts during the initial stage of the SS drying process (van Deventer, 2004; Prachayawarakorn & Soponronnarit, 2010). These disintegrated particles may aggregate and can interrupt the drying system leading to process inefficiencies. Previous studies on densification found that particle size of the feed has a significant role in the pellet durability (Grover & Mishra, 1996; Kaliyan & Morey, 2009). Larger particles in the compact may act as fissure points for breaking the pellet. Grover and Mishra (1996) and Payne (1978) reported that apart from using a single particle size, a mixture of different particle sizes produces pellets of more durability.

Until now, no studies have documented the effect of particle size distribution (PSD) on the physical and rheological properties of wet distiller's spent grain (WDG) compacts while drying in SS. This study aims to investigate the breakage and disintegration of WDG compacts by varying the PSD of the sample before compacting. The main objective of the study was to evaluate the effects of PSD on the volumetric change and stress-relaxation characteristics, in terms of hardness and asymptotic modulus (E_A) for a 40% deformation, for the compacts exposed to SS during the warm-up period (5 s) and after reaching the moisture levels of 40, 30 and 20% (w.b.) while being dried in SS.

2. Materials and methods

2.1. *Distiller's spent grain sample preparation for compaction*

The raw material (stillage) used for the current experiments was a mixture of corn and wheat in the ratio 9:1. The stillage was obtained from a local distillery (Mohawk Canada Limited, Minnedosa, MB, Canada). Centrifugation was employed to separate the raw material into different fractions of thin stillage, solubles or condensed distiller's solubles (CDS) and WDG. After placing the stillage in the centrifuge in 1000 ml sample containers (Sorvall General Purpose RC-3 centrifuge, Thermo Scientific Co., Asheville, NC, USA), the containers were balanced appropriately and the centrifuge was operated at a speed of 2200 rpm at a relative centrifugal force of 790 × g for 10 min. After centrifugation, the thin stillage was discarded and the solubles and WDG fractions were separated manually (Zielinska, Cenkowski, & Markowski, 2009). Only the WDG fraction was used for the current experiments.

The particle size distribution order of WDG was represented in terms of *d*(0.9) values, which is the size of particle below which 90% of the sample volume exists. The *d*(0.9) of