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Superheated steam drying characteristic and moisture diffusivity of distillers' wet grains and condensed distillers' solubles

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ABSTRACT

Samples of distillers' spent grains were prepared by blending different proportions of distillers' wet grains (DWG) with condensed distillers' solubles (CDS). Such samples when dried with superheated steam (SS) at 110, 130 and 160 °C showed typical behaviour of drying in the falling rate period. The overall moisture diffusivity (D_m) increased with a decrease in moisture content under all drying conditions. An increase in moisture diffusivity with respect to the SS temperature was also observed. For all drying conditions, the values of average diffusivities $(D_m)_{avg}$ non-corrected for shrinkage ranged from 0.52×10^{-9} to 3.08×10^{-9} m^2/s. For distillers' spent grains of different ratios of DWG to CDS, the decrease in SS temperature from 160 to 110 °C caused a decrease in $(D_m)_{avg}$ by 69–82%. Increasing the amount of CDS added to the DWG from 0% to 100% caused an increase in $(D_m)_{avg}$ by 14–35% for the temperature range tested in this study. The values of $(D_m)_{avg}$ corrected for shrinkage ranged from 0.17×10^{-9} to 0.86×10^{-9} m^2/s for all drying conditions studied. The decrease in SS temperature from 160 to 110 °C caused a decrease in $(D_m)_{avg}$ by 70–74%. Not much differences were observed for the same drying temperatures and different ratios of DWG to CDS. The differences between the values of average overall moisture diffusivity $(D_m)_{avg}$ corrected and non-corrected for shrinkage were significant, nearly one order of magnitude.

1. Introduction

Mathematical modeling and computer simulation of drying processes is one of the most advanced tools in studying various configurations of the process. Experimental studies of drying kinetics of a single element can provide fundamental knowledge on drying theory. Mathematical models require information about the thermophysical properties of dried material and empirical relationships on material drying characteristics named thin-layer drying equations. One such parameter is coefficient of moisture diffusivity. Knowledge of product moisture diffusivity is essential in simulation and optimization of the drying process. A number of papers have been published on the subject of moisture diffusivity for various food products where researchers determined values for diffusivity using different experimental and data processing methods (Kiranoudis et al., 1995; Azzouz et al., 2002; Doymaz, 2004; Sharma and Prasad, 2004; Zielinska and Markowski, 2010). Drying can contribute to a formation of porous structure, shrinkage and crack formation. The effect of a drying method on the physical properties and structure of food products has been reported by Krokida and Maroulis (1997). The reduction in volume of agricultural products occurs simultaneously with moisture diffusion during drying and may have a significant effect on the mass diffusivity and thus, on the moisture removal rate. Thus, shrinkage and formation of porous structure appear to be an important aspect to be considered during modeling of food drying kinetics (Mulet, 1994; Arevalo-Pinedo and Murr, 2006).

Traditionally, hot air (HA) is used as a drying medium in spent grains processing. Hot air could be replaced by superheated steam (SS) (Zielinska et al., 2009). The use of SS as a drying medium has many benefits over traditional HA drying, and has been used for drying a variety of products such as carrots, potatoes, cauliflower, celery, asparagus, leek, seeds, meat, herbs, spices, rice, noodles, brewers spent grain and distillers' spent grains etc. (Woods et al., 1994; Tang and Cenkowski, 2000; Deventer van and Heijmans, 2001; Markowski et al., 2003; Tang et al., 2005; Taechapairoj et al., 2006; Zielinska et al., 2009). However, drying with SS materials such as sludge, slurry, or paste-like materials has not been studied widely (Keey, 1972; Smollen, 1990). Slurries and pulps can be dried more effectively when mixed in a bed of inert particles (Kudra and Mujumdar, 2002). The experiments carried out to date with glass beads, PVC pellets, spherical resin particles, ceramic balls, silica gel spherical particles and Teflon cubes and spheres proved that Teflon is the most suitable because of no attrition and its high thermal capacity (Benali and Amazouz, 2006). Despite

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Nomenclature

A, B, n	coefficients of Eqs. (2) and (3) (–)	t	drying time (min)
D_m	overall moisture diffusivity (m^2/s)	T	drying medium temperature (°C)
F_{0m}	Fourier number for mass transfer (–)	SH	shrinkage (–)
Err	local error of approximation (–)	R^2	coefficient of determination (–)
MR	dimensionless moisture ratio (–)	z	number of constants or coefficients
M_0	initial moisture content (kg/kg db)	0	initial
M	moisture content at any time (kg/kg db)	avg	average
M_e	equilibrium moisture content (kg/kg db)	e	equilibrium
N	number of observations (–)	DWG	distillers' wet grains
N-SH	non-shrinkage (–)	CDS	condensed distillers' solubles
s	thickness of a layer of a sample on the inert material (m)	DWGS	distillers' wet grains with solubles
V_0	initial volume (cm^3)	SS	superheated steam
V	volume at any time (cm^3)		

numerous published papers on drying of slurry and paste-like material on inert particles, there is insufficient data available in the literature that can be used for modeling of drying.

Distillers' spent grains are the major by-products generated in the fermentation of whole grains for the production of ethanol. After removal of ethanol through distillation, the whole stillage is centrifuged where grain particles are separated from dissolved solids. The solid phase known as distillers' wet grains (DWG) contains primarily unfermented grain residues and up to 75% of moisture, wb (wet basis) (Zielinska et al., 2009). The dissolved solids are concentrated into thin stillage, which is either marketed as syrup or condensed/concentrated distillers' solubles (CDS).

Distillers' wet grains, known as whole stillage, can be sold directly to livestock producers. However, the whole stillage is quite perishable because it contains about 80% moisture. The shelf life for wet by-products is less than 1 week, thus limiting their transportation and market area to within 100 km from an ethanol plant (Christiansen, 2009). Increasing production of bioethanol processing plants increases the supply of DWG which may eventually become an environmental problem and a waste of resources. Increasing the ease of handling, transporting, and storing can provide the ethanol processors an additional source of revenue.

Distillers' dried grains with solubles (DDGS) are a good source for energy with available phosphorus, protein and dietary fibre and are mainly utilized by animal producers (Amani et al., 2009). In January 2010, the Renewable Fuels Association reported that about 27.5 million tons of DDGS were produced in the US in 2008–2009 contributing up to 20% of the income of ethanol plants (Ileleji, 2010).

The fractions of DWG and CDS are dried separately to form distillers' dried grains (DDG) and distillers' dried solubles (DDS). Alternatively, the mixture of CDS and DWG is processed to remove water and form distillers' dried grains with solubles (DDGS). The ratio of DWG:CDS usually varies among plants. The common industrial practice is to mix centrifuged DWG with CDS and already dried DDG to bring the moisture of the mixture down to a consistency of a paste. Hence, the same material is recycled and dried many times, which eventually burns causing a loss of quality in the final product.

The amount of CDS added to DWG affects physical and chemical properties of a final product (Ganesan et al., 2008; Ileleji, 2010; Kingsly et al., 2010). This work is intended to report on moisture changes during superheated steam drying of distillers' spent grains of different CDS:DWG ratio and to present moisture diffusivity calculations based on analytical processing of the experimental drying curves. Therefore, the objective of this study is (i) to determine the effect of SS drying temperature and the DWG to CDS feed ratios on drying kinetics of distillers' spent grains, (ii) to determine moisture diffusivity of distillers' spent grains of different CDS:DWG ratios during drying in SS and (iii) to show the effect of shrinkage phenomena on the calculated values of moisture diffusivity of distillers' spent grains.

2. Material and methods

2.1. Material

The raw material used in this study was a mixture of corn and wheat (50:50) stillage obtained from a local distillery (Mohawk Canada Limited, a division of Husky Oil Limited, Minnedosa, MB).

2.2. Sample preparation

The whole stillage was centrifuged to produce three fractions: liquid, semi-solid and coarse fractions. During this step, the non-dissolved solid grain particles were separated from the dissolved solids. The upper liquid layer was decanted, leaving concentrated thin stillage. The coarse and semi-solid fractions of the dewatered product formed DWG and CDS, respectively. The whole stillage was separated using a Sorvall General Purpose, RC–3 centrifuge (Thermo Scientific Co., Asheville, NC, USA). The centrifuge operated at a relative centrifugal force of 790*g*, with a 1000 mL sample container rotating at a speed of 2200 rpm, on a radius of 0.146 m for 10 min. The coarse phase containing DWG and the semi-solid phase containing CDS were dried separately and then mixed together in different proportions to produce distillers' dried grains (DDG), distillers' dried solubles (DDS) and distillers' dried grains with solubles (DDGS). The different ratios of blending DWG:CDS used for further processing were: 1:0, 0.90:0.10, 0.75:0.25, 0.50:0.50, 0:1. These samples were then bagged, placed in a deep freezer at −15 °C and when needed thawed at room temperature 2 h before using them in further experiments.

Drying experiments were conducted using a single hollow sphere (50 mm in diameter) made of polytetrafluoroethylene (Virgin Teflon®, PTFE 860, Applied Plastic Technology Inc., Bristol, RI) which served as an inert particle. The Teflon sphere was then covered with a 3-mm thin layer of material of different blends which deposited mass was approximately 22.0 ± 0.1 g. A single drying experiment generated approximately 5 g of dried material. To ensure good contact with the inert material (Teflon sphere), wet product of different blends was applied to the inside surfaces of two hemispherical tea strainers (Norco Pro, Everett, WA). The radius of the tea strainers was approximately 3 mm greater than the radius of the inert material. Then, two hemispherical tea strain-