Journal of Stored Products Research 55 (2013) 21–26

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Diffusion and production of carbon dioxide in bulk corn at various temperatures and moisture contents

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ARTICLE INFO

Article history:
Accepted 11 July 2013

Keywords:
Corn
Carbon dioxide
Effective diffusion coefficient
Respiration rate
Storage

ABSTRACT

The effective diffusion coefficient of carbon dioxide (CO_2) through bulk corn was determined at various temperatures (10, 20 and 30 °C) and grain moisture contents (14.0, 18.8 and 22.2% w.b.). The diffusion coefficient measurements were conducted using a diffusion cell surrounded by a water jacket, which was used to control the bulk corn temperature in the diffusion cell. A source term (CO_2 respiration rate) was introduced in the diffusion equation to account for CO_2 production by corn during the diffusion process. Corn respiration rate increased when temperature and grain moisture content increased. As respiration rate increased, it had a larger effect on the diffusion pattern when measuring the effective CO_2 diffusion coefficient. The effective CO_2 diffusion coefficients through bulk corn ranged between 3.10×10^{-6} and 3.93×10^{-6} m^2/s, depending on temperature and moisture conditions. As temperature increased from 10 to 30 °C, the effective CO_2 diffusion coefficient through bulk corn increased from 3.21×10^{-6} to 3.76×10^{-6} m^2/s. As corn moisture content increased from 14.0 to 18.8% (w.b.), the effective CO_2 diffusion coefficient through bulk corn decreased from 3.59×10^{-6} to 3.39×10^{-6} m^2/s, respectively. There was no difference observed in the effective CO_2 diffusion coefficient when corn moisture content increased from 18.8 to 22.2%.

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1. Introduction

Postharvest losses due to spoilage during grain storage remain a major problem around the world. Early detection of grain spoilage will reduce grain quantity and quality losses, decrease mycotoxin production in the food chain, and avoid financial loss by applying timely storage management, such as aeration (Ileleji et al., 2006). Utilizing thermal cables in a storage bin for temperature monitoring has been a typical method for detecting grain spoilage, since microorganisms produce a large amount of heat in the spoilage location. However, temperature monitoring is usually not sensitive enough due to its low thermal diffusivities in bulk grain (Singh et al., 1983; Gonzales et al., 2009). Furthermore, measured temperature cannot be easily interpreted due to the influence of the ambient air fluctuation. For example, temperature of 35 °C of bulk grain may mean there is an active spoilage spot in storage bin or that bulk grain was heated by high temperature ambient air. In addition to the temperature monitoring, studies reported that increases in carbon dioxide (CO_2) concentration in bulk grain is another indicator of grain deterioration (Steele et al., 1969; Seitz et al., 1982; Fernandez et al., 1985; Pronyk et al., 2004; Moog et al., 2010). The CO_2 concentration measured in a stored bulk can be compared to the CO_2 concentration of the ambient air (around 400 ppm) as a standard to interpret the readings (Singh et al., 1984). Muir et al. (1985) measured concentrations of CO_2 in interstitial air in 39 farm-stored bulks of wheat, rapeseed, barley and corn. Spoilage was confirmed by analyses of grain samples in 97% of the 34 bins having CO_2 concentrations greater than ambient air. More recently, it has been reported that monitoring CO_2 concentration in the headspace of the storage bin with a CO_2 sensor can lead to earlier detections of grain spoilage compared to the temperature monitoring (Maier et al., 2006; Ileleji et al., 2006). CO_2 monitoring in bulk grain in silo bags is even more important since it is an indicator of whether hermetic conditions are being maintained.

In order to further develop effective and commercially feasible techniques for utilizing CO_2 sensors for grain quality monitoring in storage bins and silo bags, knowledge of movement of CO_2 in bulk grain is necessary. Since diffusion is one of the most important factors in gas movement in bulk grain, the effective CO_2 diffusion coefficient D_e through bulk grain must be determined. Singh et al. (1984) determined the effective CO_2 diffusion coefficient through wheat, rapeseed, oats and corn by a steady state method and reported the diffusion rate was dependent on temperature, moisture content and porosity. The main advantage of the steady state

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0022-474X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jspr.2013.07.002

method is that it can provide direct measurement of the effective diffusion coefficient. However, since measurements are possible only after equilibrium is reached, steady state methods are usually slow; several days are often required for one measurement (Flegg, 1953). Thereafter, Singh et al. (1985) developed a transient method to determine the effective CO_2 diffusion coefficient through bulk wheat. Recently, Shunmugam et al. (2005) determined the effective CO_2 diffusion coefficient through bulk wheat, barley and canola by using a transient diffusion model.

None of the previous studies on measuring the effective CO_2 diffusivity through bulk grain considered CO_2 produced by grain respiration. CO_2 flux through bulk grain can be influenced by CO_2 production during the diffusion process, especially when the grain respiration rate was high at elevated temperatures and high grain moisture contents. At these conditions, CO_2 production must be taken into consideration when measuring the effective diffusivity through bulk grain. Furthermore, to date, the effective CO_2 diffusion coefficient through bulk corn has been reported at only one temperature (10 °C) and one moisture content (14.0%) (Singh et al., 1984) (unless noted otherwise, all moisture values are on a wet basis). Moisture content and temperature of the bulk corn varies during corn storage period, especially when corn spoils. Hence, it is necessary to measure CO_2 diffusivity through bulk corn at different temperatures and grain moisture contents. The objective of this paper was to measure effective CO_2 diffusion coefficient through bulk corn at different temperatures and grain moisture contents, including CO_2 production by corn respiration during the diffusion process.

2. Materials and methods

2.1. Sample preparation

Corn (P1395R, Dupont Pioneer, Johnston, IA) harvested at 22.2% moisture content in October 2012 was used for the experiment. The wet corn was dried at 49 °C in a convection oven to 18.8 and 14.0% moisture content. The moisture content was determined according to ASABE Standard S352.2 (1988). Prepared samples were transferred to a plastic bag, sealed and placed in a −10 °C freezer. Prior to each test, samples were warmed to the designated temperature in an incubator. Because porosity has a close relationship with gas diffusivity (Shunmugam et al., 2005), porosity of bulk corn was determined using the following equation:

$$\text{Porosity}(\%) = \left(1 - \frac{\text{bulk density}}{\text{unit density}}\right) \times 100\% \qquad (1)$$

where corn bulk density was determined by the volume of the grain column and the mass of corn placed into the grain column. Unit density was determined according to the methodology of volume complementation (Sacilik et al., 2003). In the diffusion measurement, a fixed mass of corn (1.3 kg) was put into the grain column in the diffusion cell. Therefore, in situ bulk density of corn was determined by dividing the mass of corn in the grain column by the volume of the grain column. Unit densities, bulk densities and porosities of corn at three moisture contents were shown in Table 1. Differences of the unit densities and porosities among corn at three moisture contents were within ±2% (Table 1).

2.2. Diffusion measurement

A diffusion apparatus (Fig. 1) was designed and fabricated to measure the effective CO_2 diffusion coefficient through bulk corn based on the concept by Reible and Shair (1982). The apparatus consisted of two cylindrical gas chambers connected by a cylindrical grain column. Cumberland and Crawford (1987) reported that the diameter of the chamber should be at least 10 times larger than the size of the granular media to provide a representative volume. Since a corn kernel is approximately 0.5 cm in volumetric equivalent diameter, a 10.2 cm diameter and 20 cm length grain column was designed in order to minimize the kernel size and column edge effects. The two identical cylindrical gas chambers measuring 19.1 cm diameter and 15 cm length were made of acrylic tubes with 6.4 mm wall thickness. Bulk corn was placed within the grain column. To hold the bulk corn in place, a wire mesh was fixed on both ends of the grain tube. A retractable seal (11 cm diameter) was made from soft rubber to block gas diffusion between gas chamber A and grain chamber before the diffusion test. Two 0.5 cm diameter holes were drilled in gas chamber A, one for gas injection and one for gas venting. A 2 cm diameter hole was drilled in chambers A and B and in the grain column for installing CO_2 gas probes. A digital manometer (Extech HD755, Extech Instruments, Nashua, NH) connected between gas chambers A and B was used to monitor pressure differences across both chambers during testing. A low speed motor fan (ebm-papst Inc., Farmington, CT) was installed in gas chambers A and B to mix gas. Apparatus temperature was controlled by placing a cooling/heating water jacket (plastic tubing) around the gas chambers and

Table 1
Unit densities and porosities of corn with different moisture contents.

Corn moisture content	14.0%	18.8%	22.2%
Unit density (kg/m^3)	1235.5 ± 5.8	1224.0 ± 5.4	1229.9 ± 7.1
Bulk density (kg/m^3)[a]	801.7 ± 0.0	801.7 ± 0.0	801.7 ± 0.0
Porosity (%)	35.1 ± 0.3	34.5 ± 0.3	34.8 ± 0.4

[a] In situ bulk density was measured by putting a fixed mass of corn (1.3 kg) into the grain column in each test. Therefore, the bulk density of corn was the same at all three moisture contents.

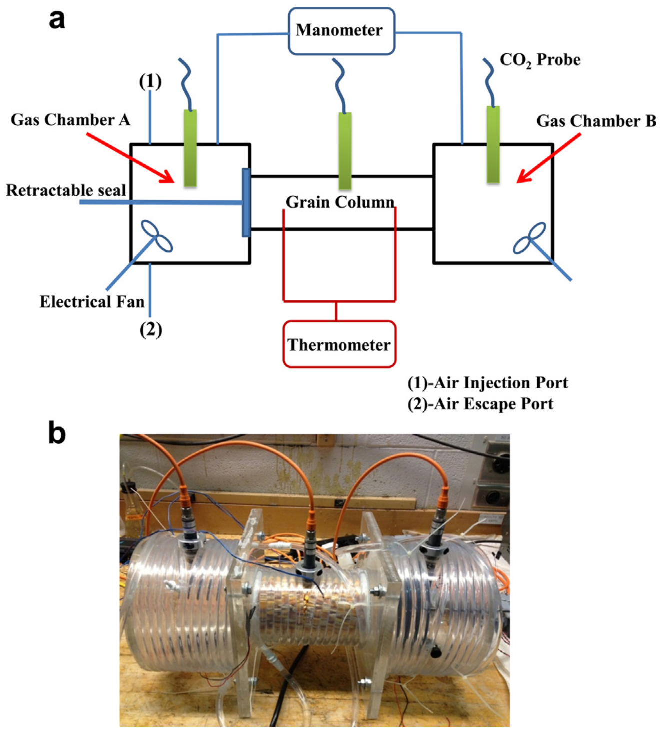

Fig. 1. An apparatus for CO_2 diffusivity measurement. a) schematic and b) fabrication. CO_2 gas was injected into gas chamber A. After allowing gas to be well mixed, the retractable seal was opened to start the diffusion process from chamber A to chamber B.

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