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Temperature fluctuations and moisture migration in wheat stored for 15 months in a metal silo in Canada

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ABSTRACT

Temperatures and moisture contents inside a metal silo filled with 20 t of wheat were monitored from August 2003 to October 2004 in Western Canada. In the summer and then repeated in the autumn of 2005, grain moisture contents inside small columns, inserted in the top of the grain bulk in the same metal silo, were measured after 4 and 8 weeks. The columns had the following configurations: 1) both the top and bottom of the column were open; 2) the top of the column was open and the bottom was sealed; and 3) the top of the column was sealed and the bottom was open.

During the 15-month period, headspace temperature averaged 2.9 ± 0.2 °C higher than that of the ambient air with a maximum of 18.3 °C and a minimum of 0 °C. There was larger temperature fluctuation in the headspace than inside the grain mass. The average temperature gradient was 5.09 ± 1.24 °C/m inside the grain mass. The highest temperature gradient was 32.4 °C/m and it was located at the center of the bin at 1.6 m high. "Inside" grain had a lower moisture change than the surface grain.

Grain in the top section of the column with the column configuration of Top End Open had the largest change of its moisture content, and grain in the middle section of the column with any of the configurations did not change. Grain inside the small columns at different locations in the silo had different moisture movement trends. These trends were consistent with the measured moisture migration in the entire silo. These results confirm that even in a small silo there were temperature gradients large enough to drive air movement and the induced convection currents could cause moisture migration.

1. Introduction

Grain on farms in Canada is stored for up to two years (Muir, 1998). Common storage structures on the Canadian Prairies are free-standing, corrugated galvanized steel, cylindrical bins (Alagusundaram et al., 1989). For satisfactory storage, preventing grain moisture migration and controlling moisture exchange is an important management process of farm-stored grain because grain adsorbs or desorbs moisture under changing environmental conditions.

Due to heat-induced natural convection currents, moisture migration occurs within the stored grain bulk (Thorpe, 1981; Smith and Sokhansanj, 1990; Thorpe et al., 1991). Air convection currents induced by temperature gradients are detected in metal silos filled with maize (Gough et al., 1990). Laboratory experiments have also demonstrated that moisture-carrying convection currents could be induced by temperature gradients in grain (Close and Peck, 1986; Gough et al., 1987). Mass diffusion occurs in the intergranular air (Thorpe, 1980) and on the surface of the grain bulk. Diffusion could be a dominant mechanism of moisture transfer when assisted by natural convection currents. The movement of moisture is a slow process and equilibrium conditions are never established for any practical length of time in a mass of wheat due to hysteresis and the fluctuation of water vapor pressure.

Most of the mathematical models that attempted to simulate these moisture migrations predicted moisture accumulation of up to 2 percentage points (Khankari et al., 1994, 1995a,b; Navarro and Noyes, 2002). Based on their model's prediction, Montross et al. (2002) showed that moisture accumulation is primarily due to equilibration with the headspace and plenum air due to natural convection, diffusion, or both. Based on these model analyses, moisture should accumulate near the top center region when outdoor temperatures are lower than the grain temperature and accumulate near the bottom center when outdoor temperatures are higher than grain temperature (Jayas, 1995). Hellevang and Hirning (1988) monitored sixteen bins of various sizes between April and August 1987. They observed an average moisture decrease of 2.6 percentage points at the top surface and average increase of 0.5 percentage points between 0.6 and 1.8 m below the top surface of a bulk. Reed (1992) measured moisture movement during the

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autumn and winter in three round metal bins containing about 270 t of wheat per bin located on farms in Kansas. His results indicated that moisture accumulated nearly uniformly at the surface of a naturally cooling grain mass but not at the center surface. There are no published data to show the entire moisture migration in a stored grain silo for longer than one year of grain storage.

Headspaces inside galvanized silos experience large temperature and relative humidity fluctuations due to the large roof surface area and solar radiation during the day. Temperature, moisture, and air movement inside the headspace might influence temperature gradients at the top of the stored grain mass which might cause moisture migration (Jayas, 1995; Navarro and Noyes, 2002). Based on their developed model, Montross et al. (2002) highlighted the moisture change at the grain surface and the interaction between the headspace moisture and grain surface. However, there are few measured data available on these changes and interactions.

The published models (Jayas, 1995; Navarro and Noyes, 2002) also assume that the grain near the bin walls will be warmed up or cooled down by ambient temperature uniformly along the entire wall or the walls facing in the same direction. However, bin walls facing in different directions or locations will receive different amounts of solar radiation. Different wind directions and speeds at different locations also influence the grain temperature at the locations near the bin walls. These differential energy exchanges might cause different temperature gradients and different directions of temperature gradients. Jian et al. (2005) developed a three-dimensional, asymmetric, and transient model to predict grain temperature based on different solar radiations on bin walls exposed at different directions. There are no published data available showing the temperature fluctuations inside silos induced by different wind directions and speeds.

The aim of this study was to: 1) measure temperature fluctuations and temperature gradients; 2) quantify the moisture migration; and 3) study the trend of the moisture migration inside a silo holding 20 t of wheat during a 15-month storage period.

2. Materials and methods

2.1. Wheat bin

The experiment was conducted in one galvanized steel silo located at Glenlea, MB, 15 km south of Winnipeg, MB, Canada (49°54′N, 97°14′W). The flat bottom bin was 3.7 m in diameter, 5.7 m in height which includes 2.0 m from the top of the cylinder to the peak of the roof, 3.6 m cylinder part, and 0.1 m concrete foundation above the ground. The bin roof had a 0.4 m diameter vent at the peak and it was closed during the experimental period. At both the west and south of the bin, the ground surface was concrete. At the east, there was a 1.5 m dike located about 4 m away and the dike extended in a south–north direction. The dike was covered by grass in summer and snow in winter. At the north of the silo, there was another identical silo located 4 m away.

The bin was filled with hard red spring wheat (Canada Western No. 2) to a depth of 2.6 m and the surface of the grain was leveled on August 14, 2003. This created a 0.64:1 ratio of the headspace to grain volume. The initial moisture content was 13.64 ± 0.14% (wet basis, $n = 7$). The entire experiment ended on October 26, 2005. During the experimental period, insects and mold inside the samples (the samples for the moisture content measurement in Section 2.3 and 2.4) were visually inspected inside the laboratory. No insects or visible mold were found. There was no observed condensation and blown snow or rain inside the silo. The wheat was considered to be in good storage condition (always <14.5% moisture content when grain temperature was >0 °C and when grain moisture content was ≥14.5%, its temperature was <0 °C), and visual degradation of grain quality (on the grain bulk surface and in the grain samples) was not observed.

2.2. Temperature and relative humidity test

Temperatures inside the silo were recorded every 3 h at 54 locations during the whole storage period (Fig. 1). Thermistors (Model: 44007, OMEGA Engineering Inc., Stanford, CT, USA) with an accuracy of ±0.5 °C were used to measure the temperatures. The thermistors were mounted on plastic ropes which were anchored on the floor and ceiling of the silo. The thermistors were connected to a data acquisition and control unit (Model: HP 38524, Hewlett–Packard Co., Loveland, CO, USA). One relative humidity sensor (Model: MMR31-R3A1B, TekKnow, St. Petersburg, Russia) with 2% repeatability was mounted at the center of the headspace (Fig. 1). This relative humidity sensor only worked when temperature was above −15 °C. Therefore, the relative humidity inside the headspace was not recorded during the winter but it was recorded every 3 h during other seasons. To calculate the absolute water contents in the headspace and the ambient air, the equations in ASAE Standard (2002) were used assuming the atmospheric pressure at 101 kPa.

2.3. Moisture content measurement in the grain bulk

At the end of each month, grain was sampled by using a bullet probe at 36 locations (Fig. 1). The sample size at each location was about 0.25 kg. Moisture content of the sampled grain was determined by drying triplicate samples at 130 °C for 19 h (ASAE Standard, 2002) in an oven (Model: TFO-5 Forced Air Lab Oven, Cascade

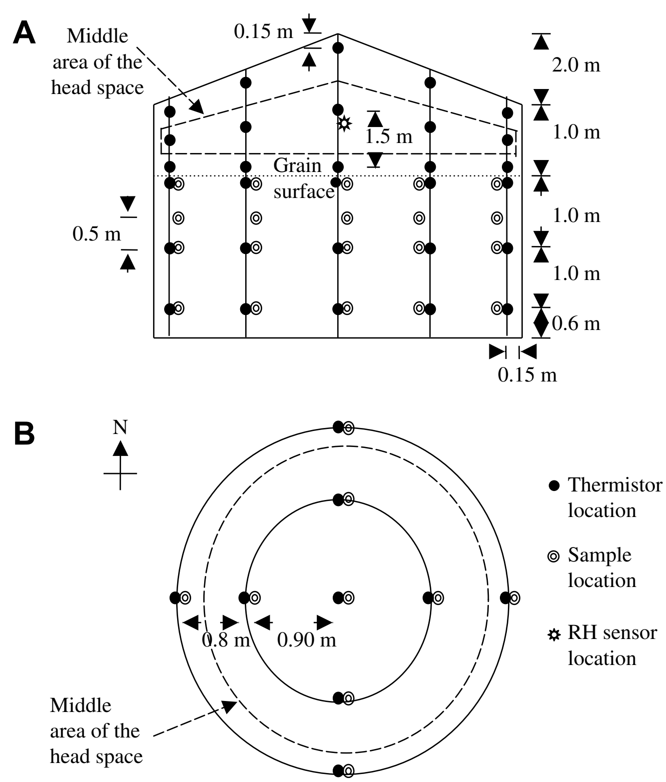

Fig. 1. Locations of the thermistors, relative humidity (RH) sensor, and the grain samples in the silo holding 20 t of wheat. Thermistors at the grain surface were located at 1 cm above or below the grain surface. Thermistors near the walls and roof were 15 cm away from the walls and 15 cm below from the roof. Side view (A) shows the thermistor and grain sample depth and top view (B) shows the thermistor and grain sample locations at one level.