THE UNIVERSITY OF MANITOBA

EQUILIBRIUM MOISTURE CONTENT AND DRYING OF WHEAT AT AMBIENT CONDITIONS IN MANITOBA

by

Madhukar Sonawane

A thesis
Submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements
for the degree of Master of Science

Department of Agricultural Engineering
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ABSTRACT

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The need to conserve energy has created interest in improving the performance of grain drying systems and in studying the potential of ambient or low temperature drying systems. Equilibrium moisture content data are required to analyze the low temperature drying systems. Due to lack of equilibrium moisture content data below 20° C, the main objective of this study was to determine equilibrium moisture contents of wheat below 20° C.

Equilibrium moisture contents of wheat were determined at five temperatures ranging from -21° to 22° C. Desired relative humidities (in the range of 12 to 90%) were maintained in wooden cabinets by using saturated salt solutions. Temperatures in the test cabinets were controlled by placing the cabinets inside an environmental chamber. Wheat samples with three different moisture contents were placed in the test cabinet until constant mass was indicated. Moisture contents were determined by heating the samples in an air oven at 130° C for 19 h.

Equilibrium was attained within 6 to 14 days. Rate of approach to equilibrium was fastest at the higher

relative humidities and temperatures. For all temperatures (except -21° C) both adsorption and desorption isotherms were of the sigmoid type. At the lowest temperature (-21° C) equilibrium moisture content was highest. The effect of temperature was most prominent in the relative humidity range of 35 to 70%. The maximum hysteresis observed was 6% at -21° C.

Using the equilibrium moisture content data, theoretical calculations were performed to predict the energy consumption in low temperature drying, for various grain and weather conditions. A rise in air temperature of 1° C due to fan heat can save a maximum of 33% of the energy in low temperature drying. Adding more than 1° C supplemental heat to the drying air caused energy consumption to increase sharply. Drying with winter air at -20° C and 75% relative humidity can increase the energy consumption by 150% above that used in drying at 0° C and 70% relative humidity. It appears that before the spoilage of high moisture grain can occur, the most suitable time for low temperature drying with minimum energy requirement is in the spring.

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1. INTRODUCTION

In Manitoba harvesting of wheat usually begins in mid-August and continues until mid-October. The harvesting date of any particular field depends on the planting date, the weather conditions, and farming practices. Maturation usually allows the crop to be dried in the field before combining. Unfavorable weather in occasional years makes it difficult and sometimes impossible to harvest the grain crop at a moisture content that is safe for storage. In such circumstances farmers have to harvest the grain in damp condition or leave it in the field until spring, which can lead to a great loss in yield and grade.

The drying of damp grain can be done in several ways. One of the most common methods is heated air drying. Heated air drying is a convective process. The rate of drying is a function of the temperature and relative humidity of the drying air, mass flow rate of the air, equilibrium moisture content which the product would acquire at the temperature and relative humidity of the incoming air, and the moisture content of the product. Heated air drying does the job faster than unheated drying and it is not dependent on weather conditions. However, because of high-temperature grain damage, high energy requirements, and high initial costs of the drying systems, interest has developed in more efficient and economical drying systems.

The need to conserve energy has led to efforts to improve the efficiency of grain drying systems. To meet this need, attempts are being made to investigate the potential of the combination of high and low temperature drying, ambient drying, low temperature drying (temperature rise of 1^{o} to 5^{o} C), and solar heated drying.

A reasonable amount of drying can be accomplished in most years in Western Canada with low-cost ambient air drying systems (Moysey and Wilde, 1965). Even if the relative humidity of the air were too high to allow drying of the grain to occur, it should be possible during the winter months to lower the temperature of the grain sufficiently to prevent spoilage. It could then be stored until more favorable weather conditions in spring would make it possible to dry the grain. Low temperature drying is possible in farm bins installed with a duct system or perforated floors that ensure a uniform distribution of forced air flow through the grain.

Low temperature drying in the low moisture content range takes advantage of the drying capacity of the ambient air and is therefore usually fairly efficient (Shove, 1973). At moisture contents above 22 to 24% (wet basis) decreased allowable storage times dictate higher air flow rates and shorter drying times which reduce performance and feasibility of the low temperature drying systems.

To analyze low temperature or ambient air drying systems for wheat the moisture contents of wheat in equilibrium with air at low temperatures are needed. Although the equilibrium moisture content of wheat has been studied extensively, little attention has been given to temperatures blow 20° C making it impossible to analyze adequately grain drying systems operating during autumn and winter in Canada.

The main objective of this study was to determine equilibrium moisture contents of wheat below 20° C; secondly, using these data to predict the effect of variables such as grain depth, air flow rate, air temperature, relative humidity, grain moisture content, and supplemental heat on the expected energy consumption during drying.

2. REVIEW OF LITERATURE

2.1 Experimental Methods to Determine Equilibrium Moisture Contents

When the vapor pressure of water held by a cereal grain is equal to the water vapor pressure of the surrounding air, the moisture content of the material is the equilibrium moisture content. The relative humidity of the air surrounding a cereal grain in equilibrium with its environment is called the equilibrium relative humidity.

A useful approach to study the adsorption of water is given by means of an isotherm. An isotherm is a curve describing the amount of water absorbed by a material at a particular constant temperature as a function of relative humidity. Equilibrium moisture content of a material may have two values, one when the material is adsorbing (gaining) moisture, and another when it is desorbing or drying out. An isotherm may, therefore, be an adsorption or a desorption isotherm. In general, the isotherm can be described as a sigmoid type (S-shaped) curve, which rises sharply above 85% relative humidity.

Equilibrium moisture contents have been determined by a number of methods (Wilson and Fuwa, 1922; Coleman and Fellows, 1925; Karon and Adams, 1949; Houston, 1952; Hubbard et al. 1957; Haynes, 1961). The simplest method is to place the test samples in a controlled environment of known temperature and relative humidity. When the sample has come into equilibrium with its surroundings, that is when sample ceases to lose or gain mass, the moisture content of the sample is determined.

Two common methods are employed to control relative humidity. One method uses saturated salt solutions and the other uses sulfuric acid solutions to maintain constant relative humidities. Reliable and comprehensive information is not available relating relative humidity and temperature for the various saturated salt solutions. However, Stokes and Robinson (1949), Carr and Harris (1949), Young (1967), Hall (1957), and Rockland (1960) have given temperature-relative humidity relationships for some of the salts.

Wexler and Hasegawa (1954) compared the relative humidity values reported by different investigators. They found that for a given salt solution and temperature there is 2 to 6% variation in relative humidity values. Young (1967) summarized changes in relative humidity values due to temperatures (Fig. 2.1).

The two methods, salt and acid, can both be used in combination with either static or dynamic methods. In the static method the atmosphere surrounding the product comes into equilibrium with the product without mechanical agitation of the air or product. In this method several weeks may be required before equilibrium is reached. In the dynamic method the surrounding atmosphere or product is mechanically moved. The dynamic method is faster; therefore, it is preferred.

Bosin and Easthouse (1970) suggested a rapid method in which the air inside the test chamber is circulated with a fan operated by a magnetic field outside the chamber. They found this dynamic method to be 3 to 15 times faster than the static method. However, they reported higher equilibrium moisture contents with the dynamic method than with the static method.

The static method has been used extensively in the past because of its simplicity. Houston (1952) used this method by placing 5g of rough rice in copper screen baskets in 300 ml wide-mouth bottles where the desired relative humidity (ranging from 11.1 to 92.5%) was achieved with saturated salt solutions. The equilibrium moisture contents were calculated from the original moisture contents and change in mass.

Karon and Adams (1949) determined equilibrium moisture contents of rough rice using the static method. Relative humidities were maintained by saturated salt solutions in desiccators at 25° C. Test samples were suspended over the solution by means of partitioned wire mats and exposed to a controlled environment until constant mass was obtained. They reported that 35 days were required to reach equilibrium.

Using the salt solution method, Babbitt (1949) determined the adsorption and desorption isotherms for wheat. Each test sample (approximately 10 kernels) was suspended on a quartz spiral in a glass tube containing a saturated salt solution held at constant temperature by a

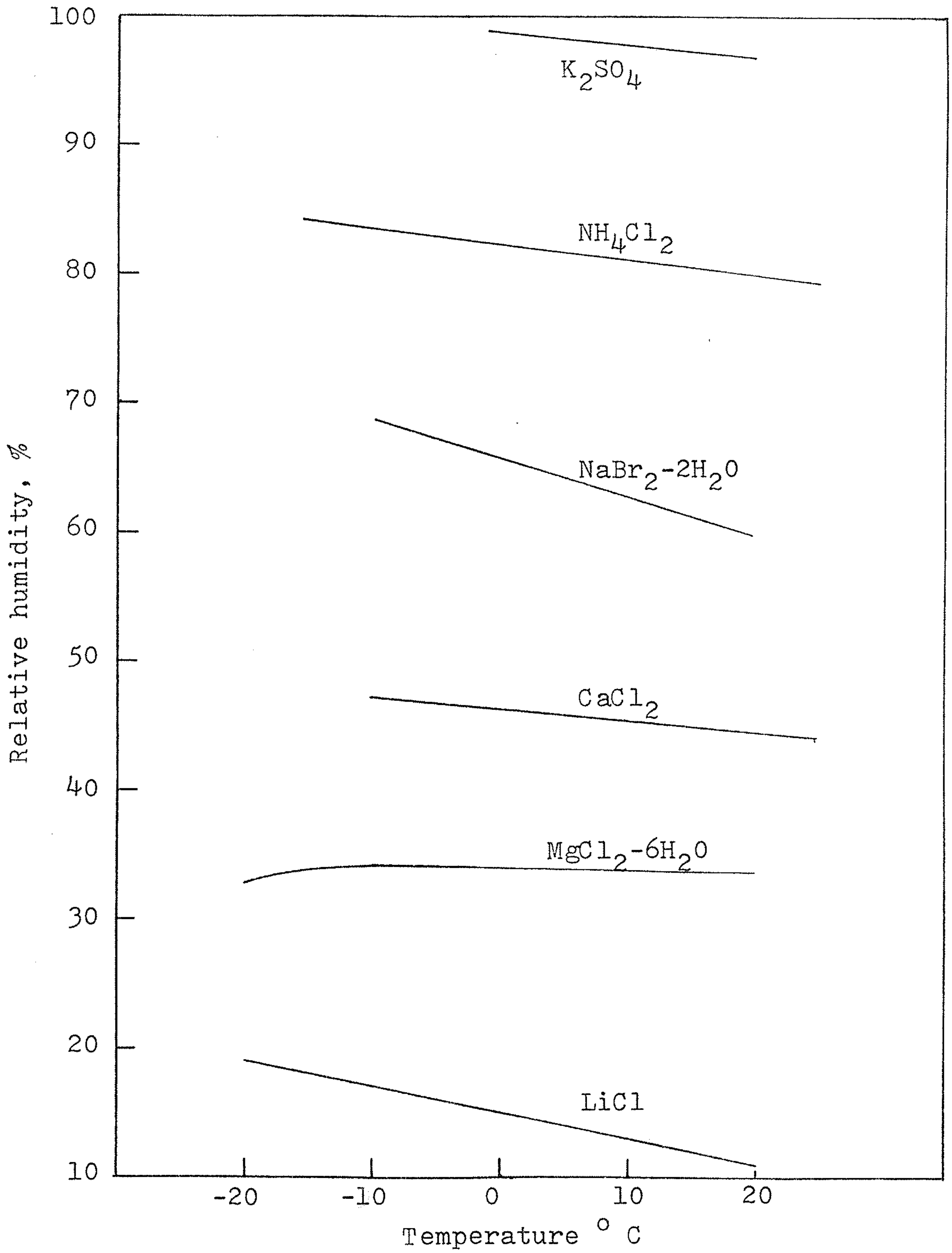

Fig. 2.1 Variation with temperature of relative humidities over saturated salt solutions.
Source: Young (1967)

water bath. The change in mass of the sample was determined from the extension of the spiral spring which was calibrated using standard masses. The vapor pressure produced by the test sample was measured by means of an oil manometer.

Hubbard et al. (1957) reported equilibrium moisture contents for wheat and shelled corn at different relative humidities maintained by saturated salt solutions in desiccators. Temperatures were controlled by immersing the desiccators in a water bath. Relative humidities were measured by an electrical hygrometer consisting of a humidity sensing element and a micro-ammeter. Equilibrium is stated to have taken place in 2 to 4 h.

To obtain relative humidities between 0 and 100% a large number of salts are required. Therefore, the sulfuric acid solution method is preferred in hygroscopic studies of grains. Various concentrations of the same acid permits studies of the entire relative humidity range. The sulfuric acid solution method is similar to the salt solution, except humidity is controlled by maintaining sulfuric acid solutions of known concentrations. The method is known as the gravimetric correction method. It is relatively temperature insensitive, but relative humidity is likely to be affected if the material adsorbs or gives out relatively large amounts of water, causing large changes in concentration of the acid solution. Coleman and Fellows (1925), and Chung and Pfost (1967) used this method in equilibrium moisture content studies of grains.

Gur-Arieh et al. (1965) combined the dynamic method with the gravimetric correction method. Since the gravimetric correction method is temperature insensitive, a rise in temperature due to fan heat does not affect the relative humidity values maintained by the sulfuric acid solutions, thus giving constant controlled environment throughout the test. Air, after conditioning in sulfuric acid solution, was forced through a packed column of the test material. About 25 to 36 h were sufficient for wheat flour to reach equilibrium.

To study equilibrium moisture contents of various substances Wilson and Fuwa (1922) employed the dynamic method combined with the acid solution method. They pumped air through adsorption towers containing acid solution and thus obtained air of known relative humidity.

Coleman and Fellows (1925) used a method similar to that of Wilson and Fuwa. Desired relative humidities were maintained by passing compressed air at the rate of 4 ml/s through the acid solution and then through the test sample. The sample of about 60g was placed in a U-tube and the change in mass was observed until constant mass was indicated. Time required to reach equilibrium was 6 to 8 days.

To determine isotherms for wheat, Gane (1941) used the static method with sulfuric acid solution to maintain desired relative humidities in a jar. A small aluminum dish holding 2 g of wheat was suspended through a hole in the lid of the jar until constant mass was indicated. Breese (1955) used a similar method to study hysteresis in the hygroscopic moisture of rough rice.

In another method a small volume of air is allowed to come into moisture equilibrium with a test sample and then its relative humidity is measured. The main advantage of this method is that, because the water content of the air is relatively small, equilibrium is attained quite rapidly. The main difficulty is in the accurate measurement of the relative humidity or vapor pressure of small volumes of air, but several workers have used vapor pressure measurement techniques, dew-point techniques and electrical hygrometers to do this.

Ayerst (1965) and Pixton and Warburton (1971) used a dew-point technique to determine equilibrium relative humidities of agricultural products. They suggest this method has significant advantages over other methods of relative humidity measurement; for example, calibration does not drift, the equilibrium relative humidity can be determined at wide ranges of temperature and the use of a water bath gives precise temperature control ($\pm 0.05^{\circ}$ C).

Brockington et al. (1949) used an electrical hygrometer to determine equilibrium relative humidity of yellow corn. It essentially consists of a humidity sensing element and a micro-ammeter with necessary electrical connections. The operation of the element is based on the ability of a hygroscopic film to change its electrical resistance quickly with a small change in moisture content of the surrounding air. They suggest that the electrical hygrometer used in their study is the best available method to measure relative humidity under conditions of still or slowly moving air. However, according to Henderson (1952) this device did not yield satisfactory isotherm curves below 25° C because of inadequate temperature correction data.

Equilibrium moisture isotherms can also be obtained by measuring the vapor pressure of the test sample at known moisture contents and temperatures under high vacuums. From the measured vapor pressure and the saturated vapor pressure at the test temperatures, equilibrium relative humidities can be determined. Pichler (1957) used this method. Haynes (1961) also used this method with some modifications and called it the "isotenoscope method."

The isotenoscope method is fast; equilibrium can be attained in less than a day, usually about 8 to 10 h, but it has a few limitations. For example: (1) it is difficult to measure vapor pressure of low moisture content values, unless a precise pressure instrument is used; (2) there is difficulty with high moisture samples because evacuation may not be possible due to the steady release of vapor from the wet sample; (3) this method requires preparation of samples at preset moisture levels; (4) the complicated method requires special skills to perform; and (5) this method cannot produce adsorption isotherms.

2.2 Variables Affecting Equilibrium Moisture Content

Many workers have investigated the relation between equilibrium moisture contents and atmospheric relative humidities for a given constant temperature, but have reported widely different values (Gane, 1941; Becker and Sallans, 1956; Coleman and Fellows, 1925; Hubbard et al, 1957). Variations in these values may be caused by the following variables: grain maturity, grain history, relative humidity measuring techniques and moisture content determination methods.

Temperature has a significant effect on the equilibrium values of grain. For wheat the equilibrium moisture content at 75% relative humidity was about 15.3% at 25° C, while at 35° C it was about 14.4% (Hubbard et al, 1957). Pichler (1957) reports 1.2% decrease in equilibrium moisture content of wheat with an increase of 20° C. Other cereal grains behave similarly, with an increase in temperature there is a decrease in equilibrium values.

At a given temperature the equilibrium moisture increases with an increase in relative humidity. Equilibrium moisture content of wheat at 25° C was 6.5% at 15% relative humidity while at 100% relative humidity it was 36% (Coleman and Fellows, 1925). The change in equilibrium moisture content was greater in the relative humidity range of 75 to 90% than in the range of 45 to 60%. Pichler (1957) reported a 9% change in equilibrium moisture content of wheat in the relative humidity range of 10 to 65%.

Equilibrium moisture contents of grains vary with their chemical composition. Grains with high oil contents adsorb less moisture from the surrounding air than grain with high starch contents. Due to the difference in chemical composition both materials show different behaviour with regard to uptake of water vapor. According to Pichler (1957), in the case of rape seed a change in moisture content of 5% occurred over the relative humidity range of 10 to 65%, while in the case of wheat the change was 9%, that is, almost twice as high. Thus, for safe storage rape-seed should be stored at lower moisture content than wheat and other cereal grains.

Kind of grain and its cultivar affects equilibrium moisture contents. For example, at 10° C and 70% relative humidity the equilibrium moisture content of weak wheat (white english) was 15.3%, while for medium wheat (plate) it was 14.3% (Gane, 1941). Similar variations in equilibrium moisture contents may occur with other cereal grains.

Equilibrium moisture content also varies with the age of the test samples. Equilibrium moisture content decreases with increasing age of the sample. Robertson et al. (1939) reported about 0.5% decrease in equilibrium moisture content in 8-year-old wheat at 21° C and 68% relative humidity. At 80% relative humidity, he observed 1.5% decrease in equilibrium moisture content.

History of the grain affects its equilibrium moisture values. Tuite and Foster (1963) showed that drying at 60° C decreased the equilibrium moisture content of corn by 0.5 to 1.0%, concluding that artificially dried corn with its