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
University of Manitoba
Winnipeg, Manitoba

January, 1979

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ABSTRACT

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

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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.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. W. E. Muir for his guidance throughout the course of this study. Sincere thanks are extended to Dr. G. E. Laliberte, Dr. E. D. Murray and Professor L. C. Buchanan for their interest and involvement in the project.

I am grateful to the Manitoba Department of Agriculture and National Research Council of Canada for their financial support of this project.

Thanks are due to Mr. J. G. Putnam and Mr. R. H. Mogan for their technical help in the installation of experimental equipment for this study.

The author is obliged to Mr. B. M. Fraser for his interest and assistance throughout this study.

Sincere appreciation is extended to my wife Madhuri and daughter Deepa for their sacrifices, patience and understanding during the course of this study.

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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° to 5° 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

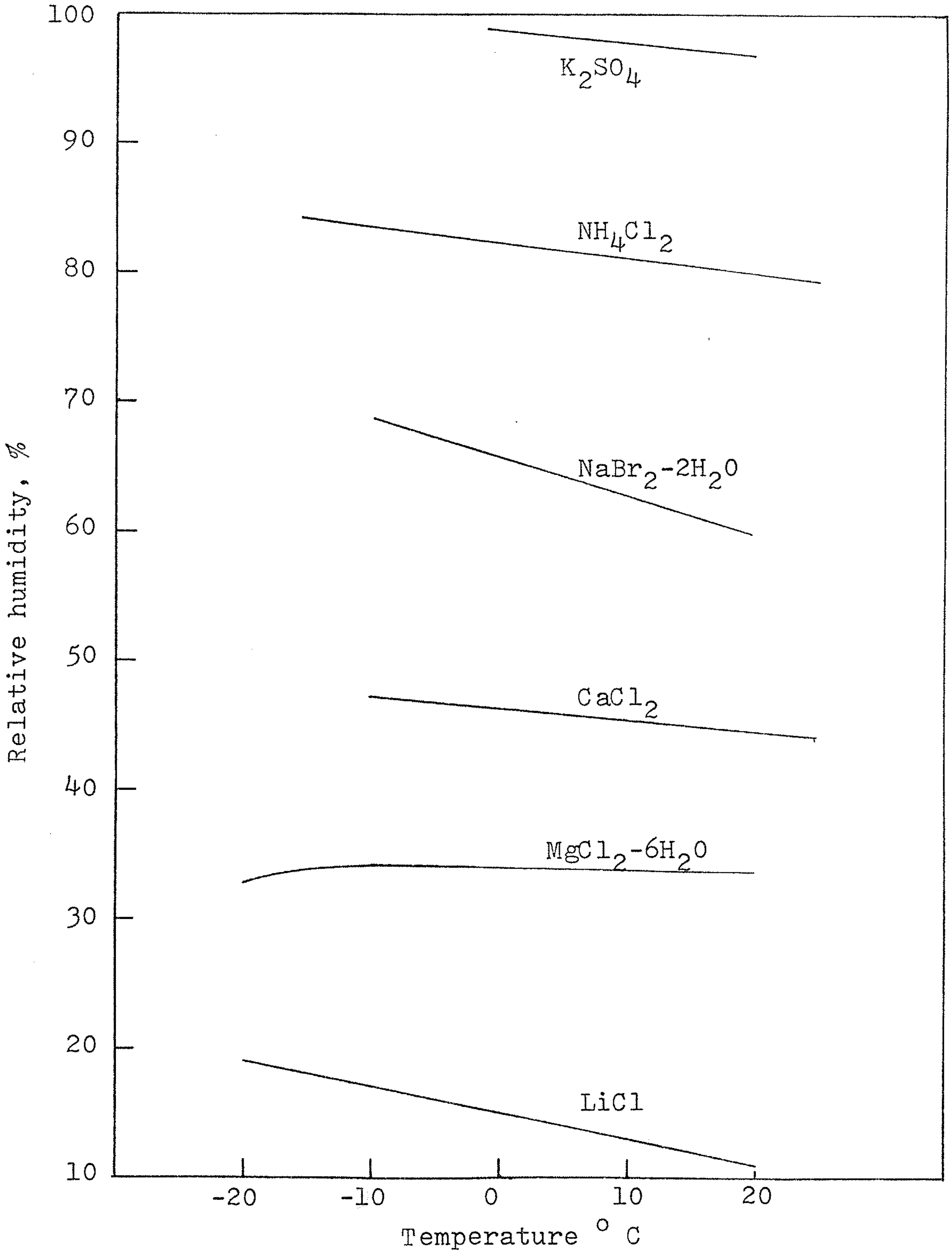

Fig. 2.1 Variation with temperature of relative humidities over saturated salt solutions.
Source: Young (1967)

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 rapeseed 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 higher interseed relative humidity should be stored at 0.5 to 1.0% lower moisture than naturally dried corn to prevent mold development.

Relative humidity measurement technique may affect the equilibrium moisture content values. Accuracy of equilibrium moisture content depends on precise measurement of relative humidity or vapor pressure of the surrounding air to which the product is exposed. As there is a definite relation between grain moisture content and relative humidity of the air with which the grain is in moisture equilibrium, incorrect relative humidity values may give false equilibrium moisture contents. Equilibrium moisture content values, using the dew-point method, reported by Ayerst (1965) were higher than those of Pichler (1957) who used the vapor pressure measurement technique. The maximum difference in equilibrium moisture values was 0.7%.

Moisture content determination methods may cause variations in equilibrium moisture contents. At 80% relative humidity using the Brown-Duvel method, the equilibrium moisture content was 14.6%, while it was 15.2% using the two-stage method (Brockington et al, 1949). Cook et al.(1935) compared different methods of determining moisture with the vacuum oven method. They found that the Brown-Duvel method is most accurate for hard spring wheat throughout the moisture range of 11 to 17%.

2.3 Hysteresis

The difference between desorption and adsorption isotherms is called hysteresis. There can be a significant difference at certain relative humidities and temperatures between the desorption and adsorption equilibrium moisture content values. A number of theories have been advanced to explain the hysteresis phenomenon in cereal grains (Babbitt, 1959; Young and Nelson, 1967; Chung and Pfost, 1967).

Babbitt (1949) was one of the first workers to demonstrate the effect of hysteresis in adsorption and desorption of water from wheat and flour. He observed that hysteresis is not as pronounced with flour as it is with whole wheat, indicating that the structure of cereal grains had an influence. He found that hysteresis in wheat caused a moisture content difference of over 4% at relative humidities from 20 to 40% and that the effect only diminished markedly above 60% relative humidity.

Young and Nelson (1967) studied the hysteresis effect in wheat and developed a theory relating equilibrium moisture content to temperature, relative humidity and to the previous condition of the material. They hypothesized three mechanisms by which water was held by the material: (a) unimolecular layer of water molecules bound to the surface of the cells; (b) multimolecular layers of water molecules stacked on top of the first layer; and (c) moisture within the cells. They developed mathematical relations to describe these three mechanisms. They observed a maximum hysteresis of about 4% in equilibrium moisture content.

Chung and Pfost (1967) hypothesized that the hysteresis effect in grains may be due to the molecular shrinkage of the grain, thereby reducing the availability of water binding polar sites on the grain surface following desorption. They found that for wheat at 50° C the hysteresis effect disappeared in the third successive cycle of desorption and adsorption.

Hubbard et al. (1957) established hysteresis loops for wheat at 25, 30 and 35° C. Both the adsorption and desorption isotherms were of the sigmoid type. The maximum hysteresis was found between 12 to 44% relative humidity and diminished to less than 0.2% at 92%. They suggested that initial moisture content is one of the factors affecting equilibrium moisture contents of the given material. Breese (1955) and Hart (1964) confirmed the results of Hubbard et al.

The hysteresis effect diminishes with increasing temperature. Hart (1964) divided each of ten samples of red winter wheat at 12.2% moisture content in two lots. One test lot was dried to 9.6% while the other lot was wetted to 16%. One lot of each sample was dyed. After 5 days the lots of each sample were mixed together and were kept until no change of mass of each lot was observed. The dyed and undyed lots were then separated and their moisture contents were determined. He observed hysteresis of 0.76% moisture content at 24.5° C and 0.37% at 32° C.

Breese (1955) measured hysteresis in rough rice at relative humidities from 10 to 90%. At 25° C, a difference greater than 1% between the adsorption and desorption equilibrium moisture content was observed over the relative humidity range of 20 to 80% but exceeded 1.5% only at relative humidities from 50 to 70%. His desorption isotherm is in close agreement with those obtained by Karon and Adams (1949).

If the relative humidity in the test chamber is not maintained constant, hysteresis may occur. The varying vapor pressure of the surrounding air results in alternate swelling and drying of kernels. During adsorption cracks and fissures develop in the kernel which produce an increased surface area for holding moisture during desorption. Ayerst (1965) observed hysteresis of about 1.5 to 2.0% moisture content in test samples exposed to the controlled environment, pointing out that in practice, relative humidity was never constant.

Volume hysteresis is greater than moisture content hysteresis in hard red spring wheat (Bushuk and Hlynka et al, 1960). Plastic deformation occurs during adsorption, leaving a residual increase in volume at the end of desorption. Above 13% moisture content, kernel volume increases 10% more than moisture content which may open up new adsorption sites. The rapid increase in equilibrium moisture content at high relative humidities may be caused by this rapid swelling.

2.4 Equilibrium Moisture Content Models

Many equations have been suggested for describing equilibrium moisture content isotherms. Some of the proposed equations are entirely empirical in nature while others have a theoretical basis. A selected few are reviewed below.

One of the best known relationships for predicting equilibrium moisture content of cereal grains, is the semi-empirical model proposed by Henderson (1952). He derived the following equation:

$$1 - rh = e^{-kTM^n} \quad \ldots\ldots\ldots\ldots \quad \text{(Eq. 2.1)}$$

where:

M = moisture content, % dry basis

rh = relative humidity, decimal

k = product constant

n = product constant

T = absolute temperature, K.

Henderson's equation in its original form has been found to be inadequate. Pichler (1957) found that equation (2.1) does not adequately predict the shift in equilibrium moisture content due to temperature because n and k are assumed constant for all temperatures.

Day and Nelson (1965) proposed the following modified form of Henderson's equation for wheat:

$$1 - rh = e^{-iM^k} \quad \ldots\ldots\ldots\ldots \quad \text{(Eq. 2.2)}$$

where:

$$i = (5.7336 \times 10^{-10})\ T^{3.3718}$$

$$k = 14.863 \ T^{-0.41733}$$

They found that this relationship is appropriate for relative humidities below 70%.

Chen (1969) proposed a three-parameter equation which takes the following form:

$$Y = \exp(k - m \exp(-nX)) \quad . . . . (\text{Eq. } 2.3)$$

where

Y = relative humidity, decimal

X = moisture content, dry basis decimal

k, m, n = functions of temperature.

For hard red spring wheat at 25° C, the values of these constants are $k = 0.07$, $m = 9.75$, and $n = 23.18$. Chen's equation does predict a single sigmoid curve and has no inherent limitation at relative humidities above 70%.

Haynes (1961) proposed the following empirical relationship for determining equilibrium moisture content of grains:

$$\ln Pv = C + C_1 \ln Pvs + C_2 M + C_3 M^2 + C_4 M \ln Pvs \quad . . . . (\text{Eq. } 2.4)$$

where:

Pv = vapor pressure of the grain moisture

Pvs = saturated vapor pressure of water at test temperature

M = moisture content, % dry basis

C-$C4$ = product constants.

The values of the product constants for wheat are:

$C = -1.61379$

$C1 = 1.26937$

$C2 = 0.12543$

$C3 = -0.00250$

$C4 = -0.01182$

Agreement between experimental and calculated equilibrium moisture content values is good within the relative humidity range of 10 to 80% and temperature range of 10 to 50° C, for which product constants are determined.

2.5 Low Temperature Drying

In the U.S.A., extensive work has been done on corn drying (Shove, 1967, 1971, 1972, 1974; and Foster, 1953). However, little work is reported on the drying of wheat with low temperature air. In western Canada a few workers have investigated the potential of low temperature drying systems (Treidl, 1974; Clayton et al, 1976; Roberts et al, 1978; Moysey, 1969).

Drying with low temperature air is a slow process because of the limited capacity of the air to absorb moisture. Each 1 kg of air with average temperature of 5° C and 70% relative humidity can adsorb only 0.8 g of water if it is exhausted at 100% relative humidity.

A small rise in air temperature is sufficient to lower the relative humidity and dry corn to moisture contents below 16% (Shove, 1971). If air having a temperature of 4° C and 80% relative humidity is heated to 6° C, it will dry corn to about 15% moisture content. A rise of 1° to 2° C in air temperature will reduce air relative humidity by about 5 to 10%.

Low temperature drying is not practical during warm weather (average daily temperature above 10° C) or during cold weather (average daily temperature below -1° C) (Shove, 1974). During warm weather the drying potential is relatively high; however, allowable drying time is short because of the danger of heating and spoilage by microorganisms. Cold weather extends the allowable drying time but cold air has low potential for drying. Thus, at low temperatures, drying becomes slow and less efficient use is made of the energy supplied.

Grain harvested with a high moisture content should be dried as fast as possible to ensure the maximum length of storage without spoiling. To achieve this proper selection of rate of air flow is an important management decision. According to Foster (1953), minimum air flow rates depend upon amount of grain spoilage that is acceptable, length of drying time and temperature of the drying air. The air flow rate used in unheated air drying greatly affects the equipment required and the operating cost. For the same grain depth the power required will increase about six-fold, while the drying rate will be doubled if air flow rate is doubled (Foster, 1953).

Grain depth and resistance to the air flow greatly affect the power requirement for drying. Resistance to air flow increases as air flows and depths increase and size of grain kernels decrease (Shedd, 1953). Grain should be cleaned before drying to reduce air flow resistance and thereby reduce energy consumption. The resistance to air flow increased by more than 50% when grain was tightly packed. Further, it was observed that resistance to air flow in damp grain was up to 20% less than in dry grain. Fine dust in the grain also caused an increase in the air flow resistance.

The speed of drying depends on the rate of air flow at any given ambient temperature and relative humidity. At 5^{o} C and 65% relative humidity, shelled corn at 30% moisture content will take 92 days at an air flow rate of 1 m^3/(min-t), 46 days at 2 m^3/(min-t) and 30 days at 3 m^3/(min-t), to be dried to 17% (Shove, 1974).

The success of low temperature drying depends upon the weather conditions. If the weather conditions are favorable considerable drying can be achieved. Because weather varies from place to place, before planning low temperature drying systems knowledge of daily weather data is essential. Using 10 years of weather data, Treidl (1974) established equilibrium moisture content curves for different parts of Canada. Weekly average ambient air temperature and relative humidities indicate that moisture content in corn could be lowered to between 15.8% and 18.5% in mid-September to late November, using selective fan operation in Manitoba.

By moving low humidity air through the grain, some drying can be achieved at low temperatures. To achieve this the fan should be operated only at air relative humidities lower than 70%. By using a humidistat the drying fan can be switched on or off at desired relative humidities. Moysey (1969) and Treidl (1974) demonstrated the potential of low temperature drying using selective fan operation in western Canada.

In contrast to the above, Shier et al.(1943) and Shove (1972) suggest that the fan should be operated continuously if drying is to be achieved. According to Shier et al.(1943) during periods of sharp temperature difference between night and day, a fan in unheated air drying should be operated continuously to take advantage of favorable heat exchange and relative humidity conditions. If the temperature of wet grain can be alternately raised and lowered by the application of fluctuating air temperatures, moisture will be removed as the grain is cooled. When wet warm grain is cooled with air having a temperature lower than grain temperature and containing an amount of moisture less than the air can contain in moisture equilibrium with the grain at the grain temperature, the grain will lose moisture to the air during the cooling process. Therefore, it is suggested that no control device, such as humidistat or thermostat which might dampen daily temperature differences, be used on low temperature grain drying systems.

To determine the suitability of low temperature drying, a study was conducted in western Ontario. A drying unit with a perforated floor bin of 152 t capacity was used in the study. Data on energy input to low temperature drying were recorded by Clayton et al.(1976). Comparing the cost of low temperature drying units with heated air drying, they reported little difference in cost between low temperature drying and heated air drying.

Drying potential of ambient air during fall, winter and spring is reported by Roberts et al.(1978). They used a 4.2 m diameter bin with 2.3 m grain depth to conduct the study. Air flow rate of 25 $L/(s.m^3)$ was used in the study. They report that by running the fan continuously (490 h) from late October to mid-November (temperature -3 to -4° C) corn moisture content of 20.9% can be reduced to 17.5%. Running the fan in the spring for 361 h reduced the moisture content to 13.7%. They reported a higher drying rate in spring than in the fall, and energy required for ambient air drying was higher than would be expected for heated air drying.

3. MATERIALS AND METHODS

3.1 Test Sample

The wheat used in this study was hard spring wheat (cultivar, Neepawa), obtained from P. Johnson, Domain, Manitoba. The wheat was certified seed grain grown in 1977 and it had a moisture content of 12.4%, wet basis. From the bright red colour of the wheat it appeared that it was not subjected to the wetting and drying cycles in the field.

All the moisture contents were determined according to ASAE standards, ASAE Yearbook (Baxter and Hahn, 1977). Test samples of about 15 g each in aluminum moisture dishes were measured with an analytical balance (Mettler, model H1OT, precision 0.1 mg, Mettler Instrument Co., Zurich, Switzerland). The uncovered dishes with their covers were then placed in an air oven at 130° C for 19 h. From the change of mass of sample after heating, moisture contents were determined on wet basis.

Three lots of wheat, about 3 kg each, were preconditioned by wetting and drying to study adsorption and desorption isotherms. Moisture contents of lots were increased by adding a calculated amount of water to obtain 14.8 and 20.0% moisture lots. Each lot was thoroughly mixed in a rotating drum so as to achieve uniformity of moisture in each kernel. To get 10.6% moisture content one lot was dried in an oven at 35° C. After preconditioning, each lot was stored in closed wide-mouth jars in a refrigerator (4° C) until the moment of being used.

3.2 Equilibrium Cabinet

The equilibrium cabinet used in this study is shown in Fig. 3.1. Three such cabinets were fabricated so as to be able to maintain simultaneously three different relative humidities at a given temperature. Each cabinet was made from 15 mm thick plywood. The cabinet walls were made vapor-proof by lining them with polyethylene sheeting. A 400x400 mm wide shelf was made to facilitate the movement of air through the test samples placed on the shelf.

A small ventilating fan (0.5 A) circulated air upward through the cabinet and back down through a flexible tube of 75 mm diameter connecting the top and bottom of the cabinet.

Wet and dry bulb temperatures were measured in the cabinet with two thermocouples (0.127 mm diameter, copper-constantan) and temperatures were indicated by thermocouple thermometer (Model 590 TC Type T, United System Corporation, Dayton, U.S.A.). A relative humidity sensor (made of sulfonated polystyrene ion-exchange humidity sensitive element) was inserted through a 30 mm hole in the cabinet to measure relative humidity. Relative humidity was indicated by relative humidity and temperature indicator (model 400C, General Eastern Corporation, Mass., 02172, U.S.A.)

3.3 Atmospheric Relative Humidity Control

The salt solution method was used to maintain the

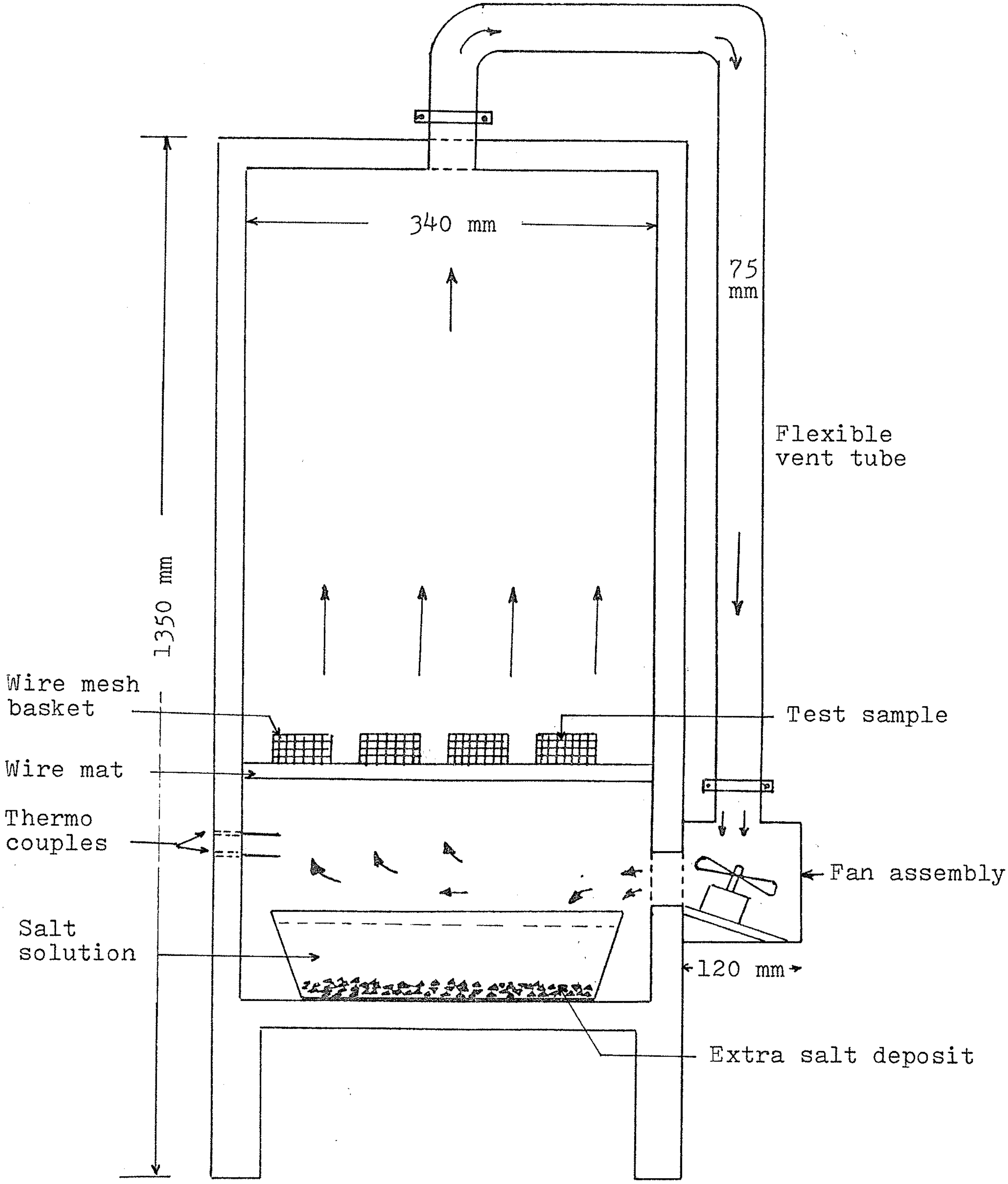

Fig. 3.1 Schematic diagram of the equilibrium cabinet. (Not to scale)

desired relative humidities in the equilibrium cabinet. The advantages of this method over the acid solution method are:

1. As long as the solution is saturated there is no change in the vapor pressure as a result of adsorption or loss of water.
2. The solution may be used indefinitely as long as an excess of the salt is present.
3. They are non-corrosive and therefore much easier to handle.

The salts were selected from the graphs presented by Young (1967), considering freezing point temperatures and low temperature coefficients. Guidance in preparing saturated salt solutions was obtained from the salt solubility information provided by Hall (1957) and Hodgeman (1960). Salt solubility is a function of temperature. To assure that the solution remained saturated at higher temperatures, almost 100% more salt was added than the solubility values given by Hodgeman (1960) for 20° C. Salt solutions were prepared in plastic pans using distilled water. The different humidity levels maintained by the saturated salt solutions are given in Table 3.1.

3.4 Calibration of Relative Humidity Sensor

The relative humidity sensor was calibrated before its use in the tests. In brief the procedure used was as follows: Two calibration points, one near saturation and one near 30% relative humidity, were established. Potasium

Table 3.1. Relative humidity range of the atmosphere in contact with saturated solutions of various salts at test temperatures.

Salt	Relative humidity range[1] %	Solubility at 20° C[2] g of solute/ 100 g of H_2O	Freezing point at saturation[3]
1. Lithium chloride ($LiCl-2H_2O$)	13-17	78	-30
2. Magnesium chloride ($MgCl_2-6H_2O$)	30-37	54	-33
3. Calcium chloride ($CaCl_2.6H_2O$)	44-49	75	-14
4. Sodium bromide ($NaBr_2-2H_2O$)	64-67	48*	-28
5. Ammonium chloride (NH_4Cl_2)	77-81	37	-15
6. Potassium sulphate (K_2SO_4)	87-88	11	- 8

*grams of anhydrous solute in 100 g or saturated solution.

Source: 1. Young (1967)

2. Hodgeman (1960)

3. Dean (1970).

sulphate (K_2SO_4) was used to produce 96% relative humidity and magnesium chloride ($MgCl_2.6H_2O$) was used to produce 33% at room temperature (20 ± 3° C). To establish the known environments, two 3-L jars with stoppers were used. The desired saturated salt solutions were prepared in the jars by adding distilled water to the salt crystals.

To calibrate the sensor, it was placed first into the 96% relative humidity container, allowing the sensor to equilibriate for at least 3 h. The 100% relative humidity control on the rear of the instrument was adjusted to produce a dial reading of 96% relative humidity.

The sensor was then placed in the 33% relative humidity jar. After allowing 3 h to reach equilibrium, the 30% relative humidity control on the rear of the instrument was adjusted to produce a dial reading of 33% relative humidity. The calibration was rechecked, repeating the same procedure until a correct dial reading of relative humidity was obtained. The calibration procedure used is given in the Instruction Manual (relative humidity and temperature indicator, model 400C, General Eastern Corporation, Mass., 02172, U.S.A.).

3.5 Experimental Procedures

The relative humidity cabinets were placed inside an environmental chamber in which the temperature could be varied from -20° to 20° C.

Four replicate wheat samples of about 20 g each were taken from the three lots and were measured in wire baskets

(80 mm diameter, 15 mm high), with a top loading balance (precision, 1 mg). The wire baskets with test samples were then placed in the equilibrium cabinets followed by making the cabinet airtight.

At 2 day intervals the wire baskets and contents were removed and placed in closed plastic dishes. Thus, exposure of samples to the outer environment was reduced as much as possible. Then change in the mass of the four replications together was observed with the top loading balance (Mettler Ploon, Mettler Instrument Co., Zurich, Switzerland) which was kept inside the environmental chamber so as to make observations within the chamber itself. Changes in the mass of the samples were observed until two successive readings indicated not more than 0.05% change in mass of the samples. It was then presumed that the samples had reached an equilibrium condition. The moisture content of the samples were then determined by the ASAE standard method as described in section 3.1.

From the measurement of change of mass of test samples made periodically during the process of reaching equilibrium, the rates of exchange of water were calculated.

For each test temperature (-21°, -10°, -5°, 0° and 22° C) the equilibrium moisture contents of wheat were determined. These temperatures were selected to represent ambient air temperatures during fall and winter, in Manitoba. Using the equilibrium moisture content data, adsorption and desorption isotherms for the five temperatures were established.

4. RESULTS AND DISCUSSION

4.1 Rate of Approach to Equilibrium

The initial rate of moisture exchange to attain equilibrium was high at higher relative humidities (Fig. 4.1). The rate of moisture exchange was much faster at relative humidities above 70%. As would be expected, the initial rate of change in moisture content were proportional to the difference between the moisture content of the sample and the moisture content at equilibrium. As equilibrium was reached the rates of change decreased.

Rate of attainment of equilibrium decreased with decreasing temperatures except at 0° C when the rate was higher than the rate at 22° C (Fig. 4.2). At 22° C the fan was operated intermittently. However, from the observations of this test it appeared that rate of moisture exchange was slow and time consuming. Therefore, the fan was operated continuously in the remaining tests. This aided in increasing the rate of exchange of moisture at 0° C.

The time required for the moisture content of wheat to come to equilibrium with any relative humidity to which it is exposed is not only of scientific interest, but because of the influence of moisture content on the keeping quality of wheat, of great commercial importance. Many factors influence the rate at which water vapor is adsorbed by wheat, and this is especially true when the kernels are

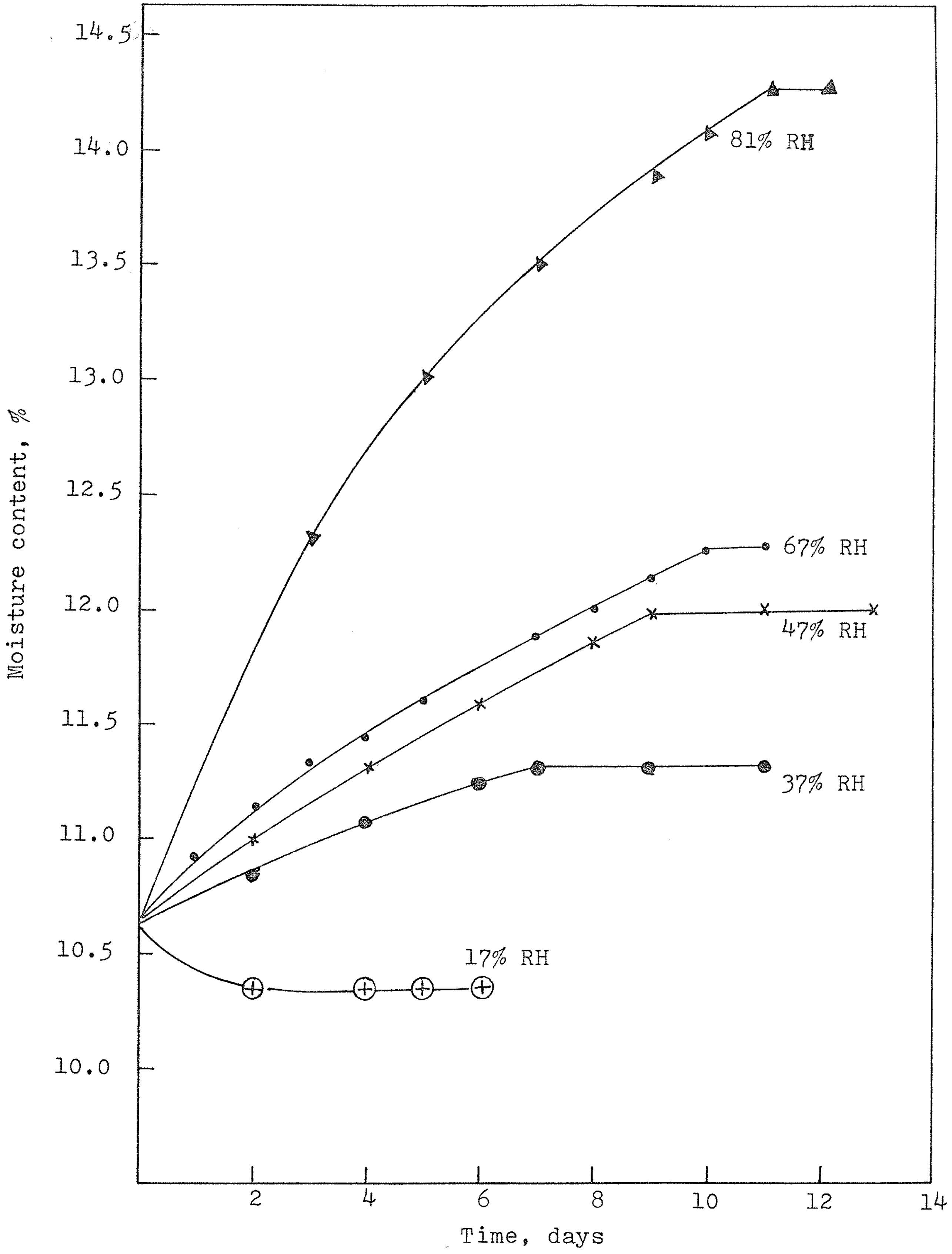

Fig. 4.1 Rate of approach to moisture equilibrium at -10° C at five relative humidities.

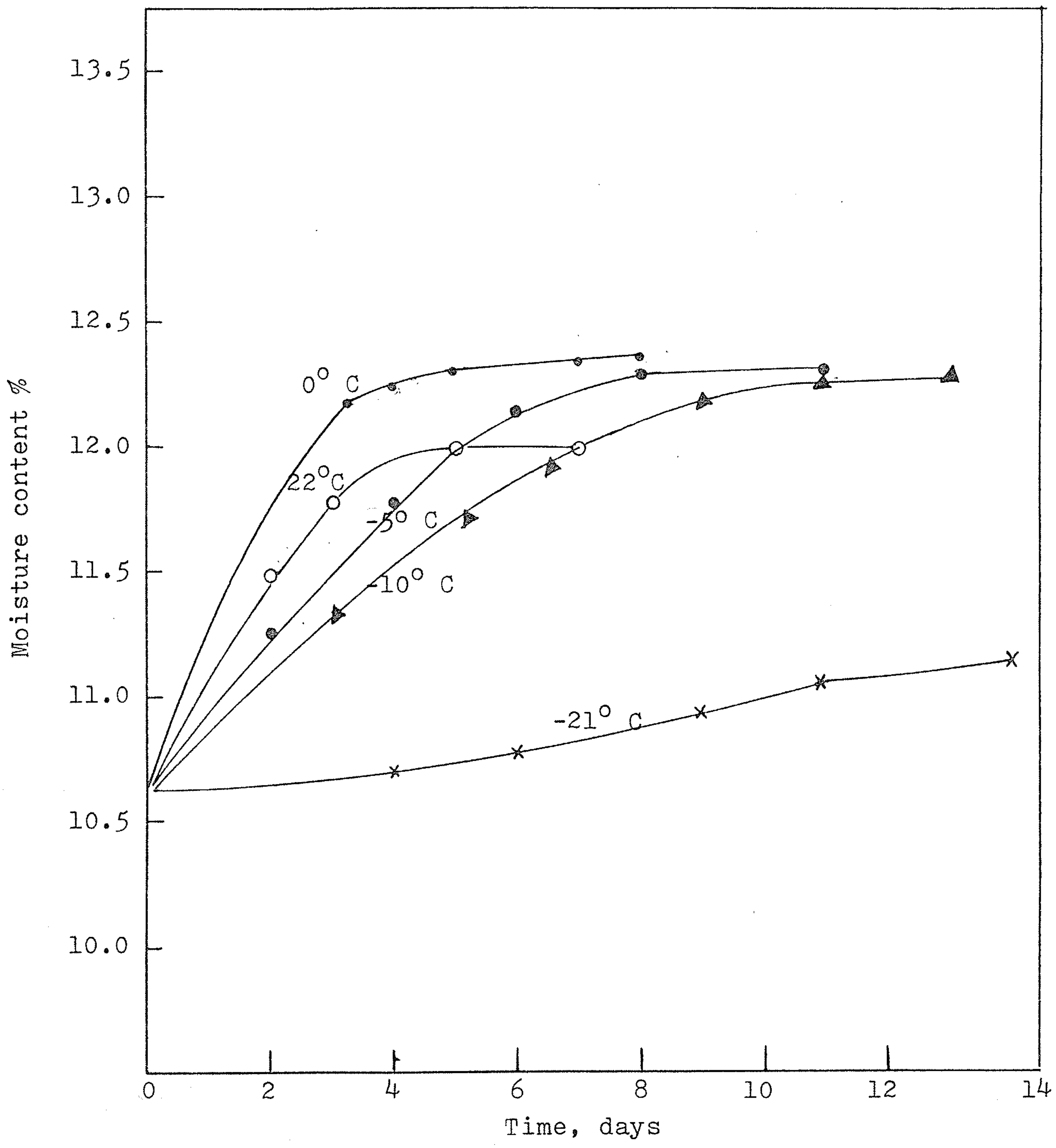

Fig. 4.2 Rate of Approach to moisture equilibrium for wheat at 67% relative humidity.

confined within the bulk of the mass of wheat. For example, temperature of grain and outside air, the extent of air circulation and size, shape and composition of container in which grain is held.

Due to the resistance of air to the duffusion of water vapor one would expect that the rate of approach to equilibrium would be slower in air than in an atmosphere having the same water vapor pressure but from which the air has been exhausted. If, however, the air is maintained in rapid motion the water vapor at the surface of the kernel will be replenished as fast as it is adsorbed and the rate of adsorption will more nearly equal that of vapor alone.

All samples attained equilibrium within 6 to 14 days, depending on atmospheric conditions to which they were exposed. Thus, time required was much less than that reported by Gane (1941) for the static period. He reported 70 to 80 days were required to reach equilibrium at 0° C.

4.2 Adsorption and Desorption Isotherms

Equilibrium moisture contents varied with temperature, relative humidity and initial moisture content of wheat (Table 4.1 to 4.3). However, it is clear that equilibrium moisture content did not increase at a uniform rate when in equilibrium with an increasing atmospheric humidity, a much greater change in equilibrium moisture content was recorded with change in relative humidity from 75 to 90% than from 45 to 65%.

Both adsorption and desorption isotherms were of the characteristic sigmoid type (Fig. 4.3 to 4.6) except for the isotherm at -21° C (Fig. 4.7). Moisture content rose comparatively at both low and high relative humidities and flattened out in the intermediate range between 30 to 65% relative humidity.

Equilibrium moisture content increased with decreasing temperature (Fig. 4.8). A comparison between the two curves at 22° C and those at 0° C shows clearly the displacement towards the higher moisture range. The effect of temperature on equilibrium moisture content was more prominent in the relative humidity range of 35 to 70%. The curves also indicate that the effect of temperature on equilibrium moisture contents became smaller as the relative humidity approached 100%.

The initial moisture content of wheat affects its equilibrium moisture content. Below 0° C the effect of initial moisture content was more distinct (Fig. 4.4 to 4.7). With a difference in initial moisture content of 5% the differences in equilibrium moisture content were smaller at low relative humidities, than at high relative humidities. For samples with an initial moisture content difference of 10% the differences in equilibrium moisture content were constant throughout the relative humidity range. The initially high moisture samples had a higher equilibrium moisture content than the initially dry samples.

The shapes of the isotherms at -21° C (Fig. 4.7) are

Table 4.1. Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at 22° C and 0° C. (All values are averages of four replications.)

Temp.	Initial moisture content	Relative humidity %											
		14		34		44		66		77		88	
C	%	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	10.6	9.8	0.1	12.0	0.4	12.5	0.1	13.0	*	14.2	*	16.3	*
22	14.8	10.6	*	13.0	0.2	13.0	0.3	13.5	*	14.5	0.1	16.4	0.1
	20.0	10.7	*	13.4	0.1	13.5	0.3	14.0	0.2	15.2	0.1	16.8	*
		13		30		49		64		80		87	
	10.6	12.5	0.1	13.7	0.1	14.1	*	14.6	0.1	17.2	0.1	19.2	0.5
0	14.8	14.2	0.1	15.0	*	15.3	*	15.5	*	16.9	0.2	18.7	0.1
	20.0	15.1	*	16.5	0.2	16.9	0.1	17.1	0.2	19.3	0.1	20.1	*

*value of standard deviation is less than 0.1.

Table 4.2. Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at -5° and -10° C. (All values are averages of four replications.)

Temp.	Initial moisture content	Relative humidity %											
		15		32		46		67		75		87	
C	%	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	10.6	11.5	*	14.0	0.1	15.0	*	14.4	*	17.4	0.1	17.7	0.1
-5	14.8	13.7	*	15.3	*	15.7	0.1	16.3	0.1	17.1	0.2	18.1	0.3
	20.0	14.3	*	16.8	0.2	17.6	0.1	18.1	0.1	20.1	0.2	20.0	*
		17		37		47		67		81		**	
	10.6	11.0	0.1	12.6	0.5	13.6	0.1	13.9	*	16.1	0.1	ND	
-10	14.8	13.9	0.1	15.2	0.2	15.6	*	15.7	0.1	16.6	*	ND	
	20.0	14.6	0.2	16.6	0.2	17.2	*	17.8	0.2	19.3	0.2	ND	

*value of standard deviation is less than 0.1.

**relative humidities above 81% were not maintained because of freezing of salt solutions.

ND: No data.

Table 4.3. Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at -21° C. (All values are averages of four replications.

Temp.	Initial moisture content %	Relative humidity %									
		17		33		**		69		**	
C		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
-21	10.6	11.9	0.4	12.2	0.1	* * *		12.6	0.1	ND	
	14.8	15.5	*	15.7	0.2	* * *		15.9	0.1	ND	
	20.0	17.8	*	18.2	0.1	* * *		18.6	0.3	ND	

*value of standard deviation is less than 0.1.

**relative humidities were not maintained because of freezing of salt solutions.

ND: No data.

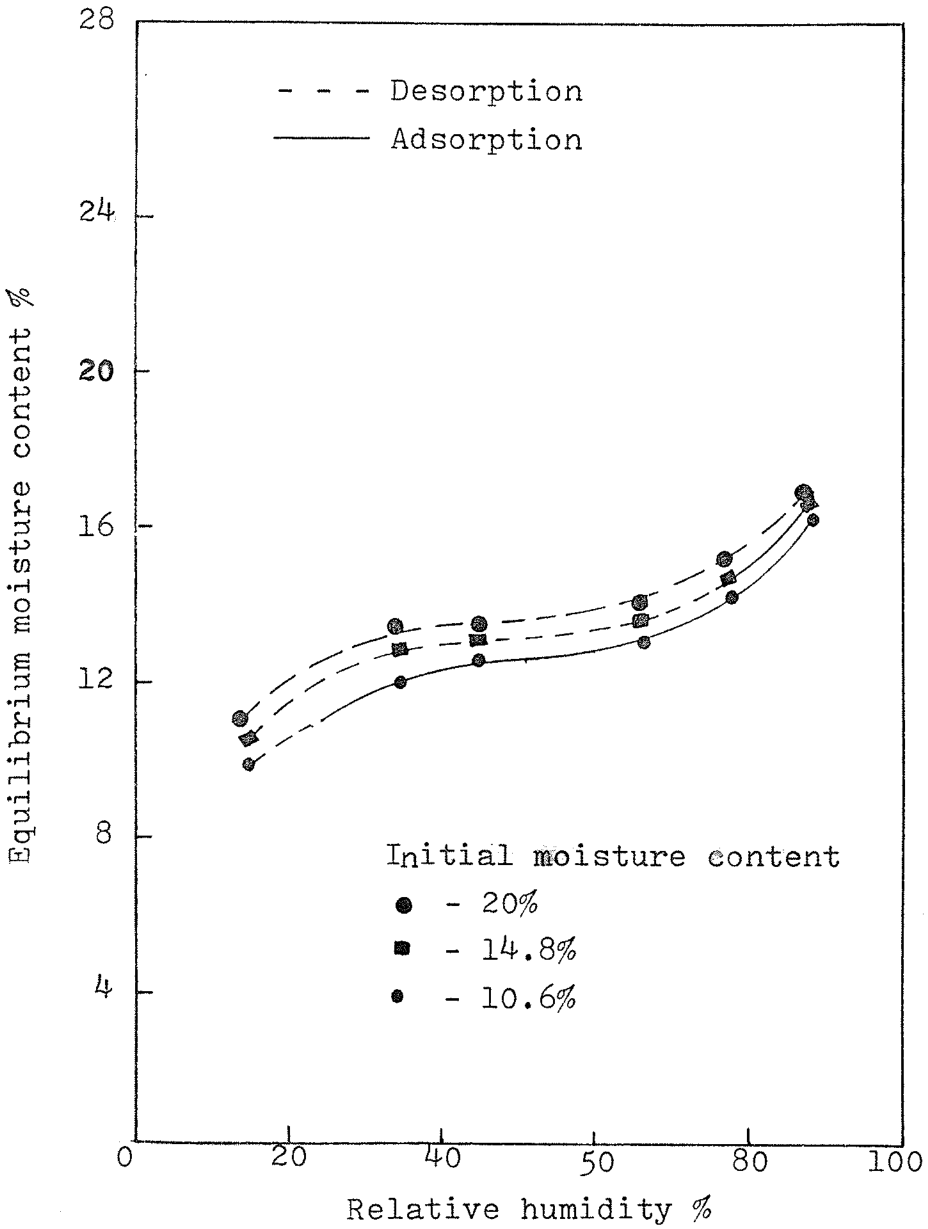

Fig. 4.3 Adsorption and desorption isotherms for wheat at 22° C

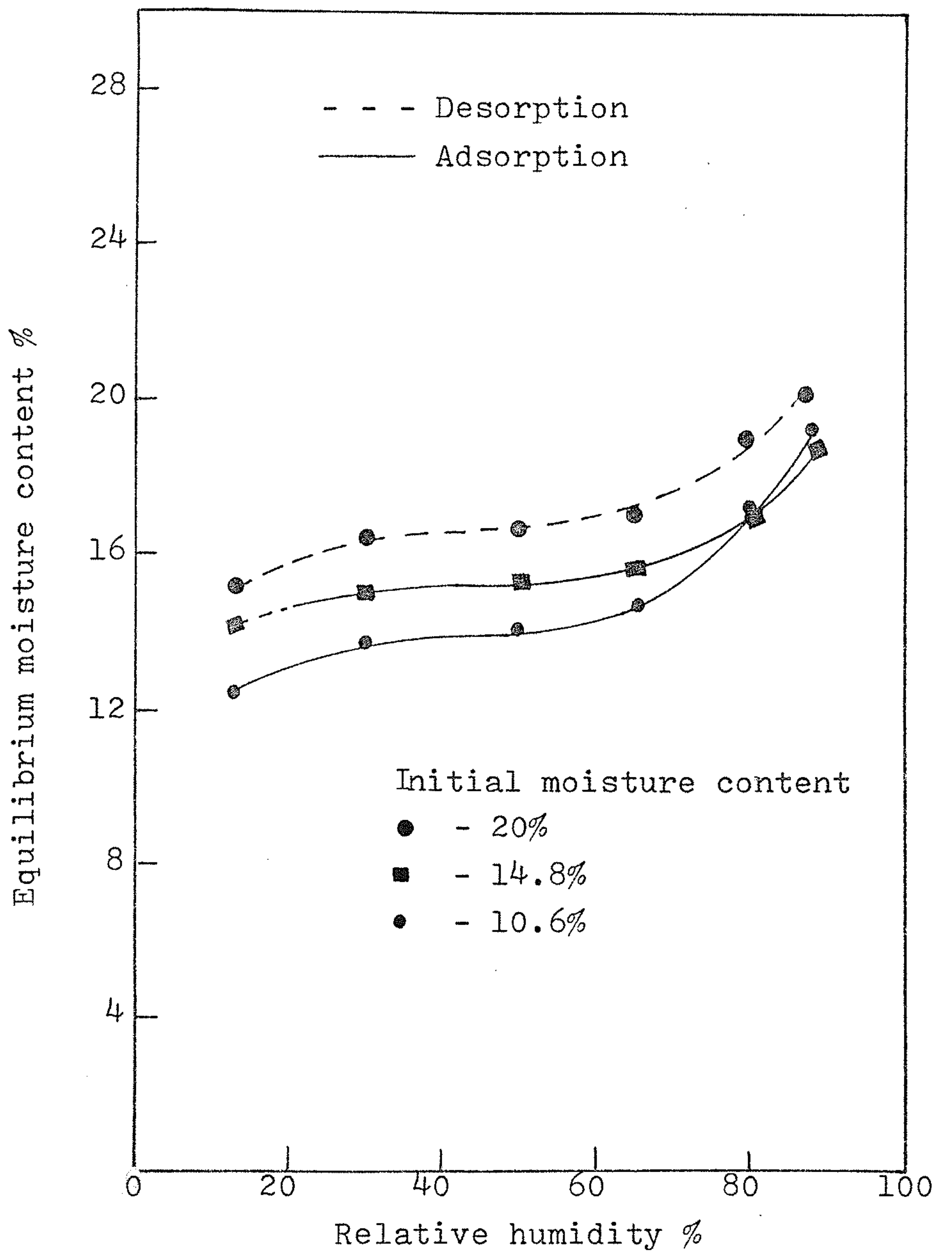

Fig. 4.4 Adsorption and desorption isotherms for wheat at 0° C

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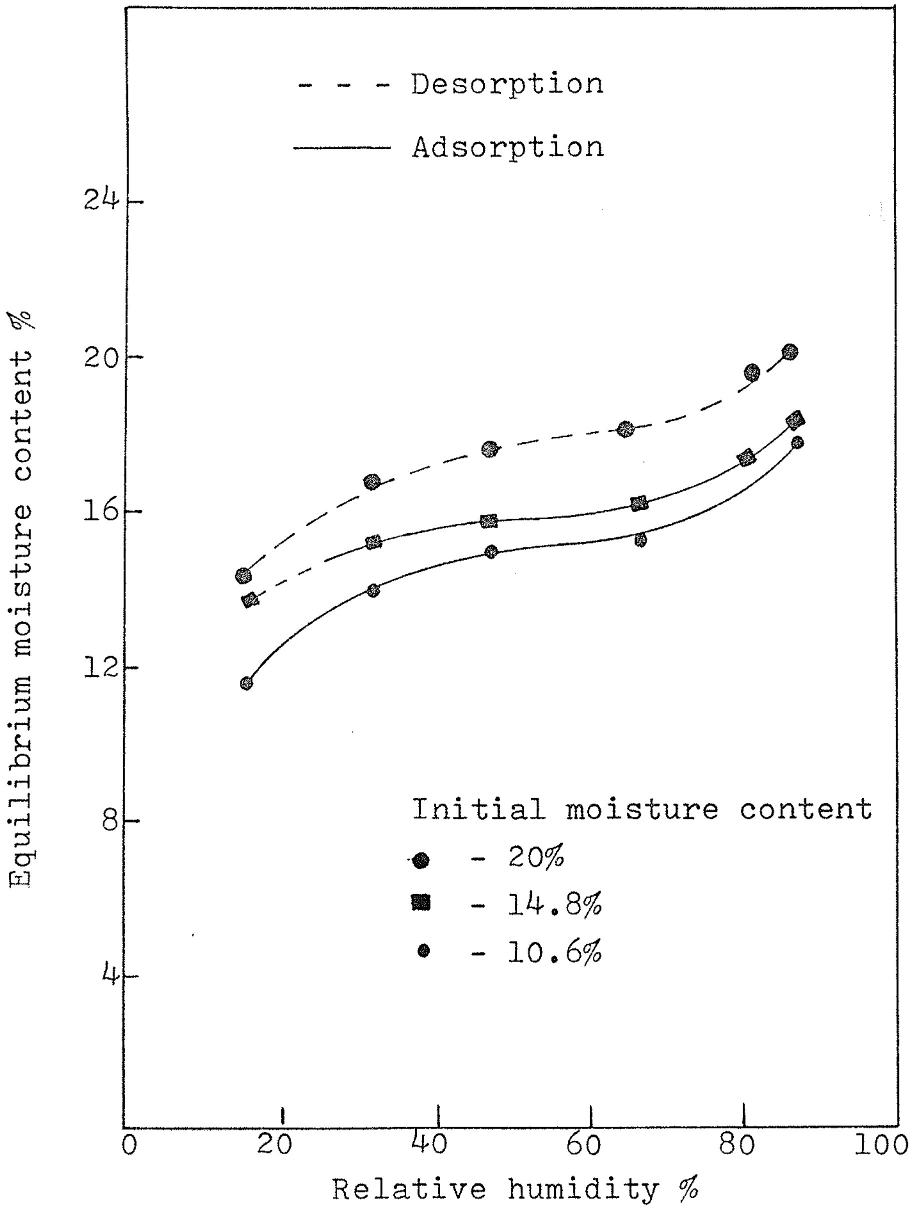

Fig. 4.5 Adsorption and desorption isotherms for wheat at -5° C

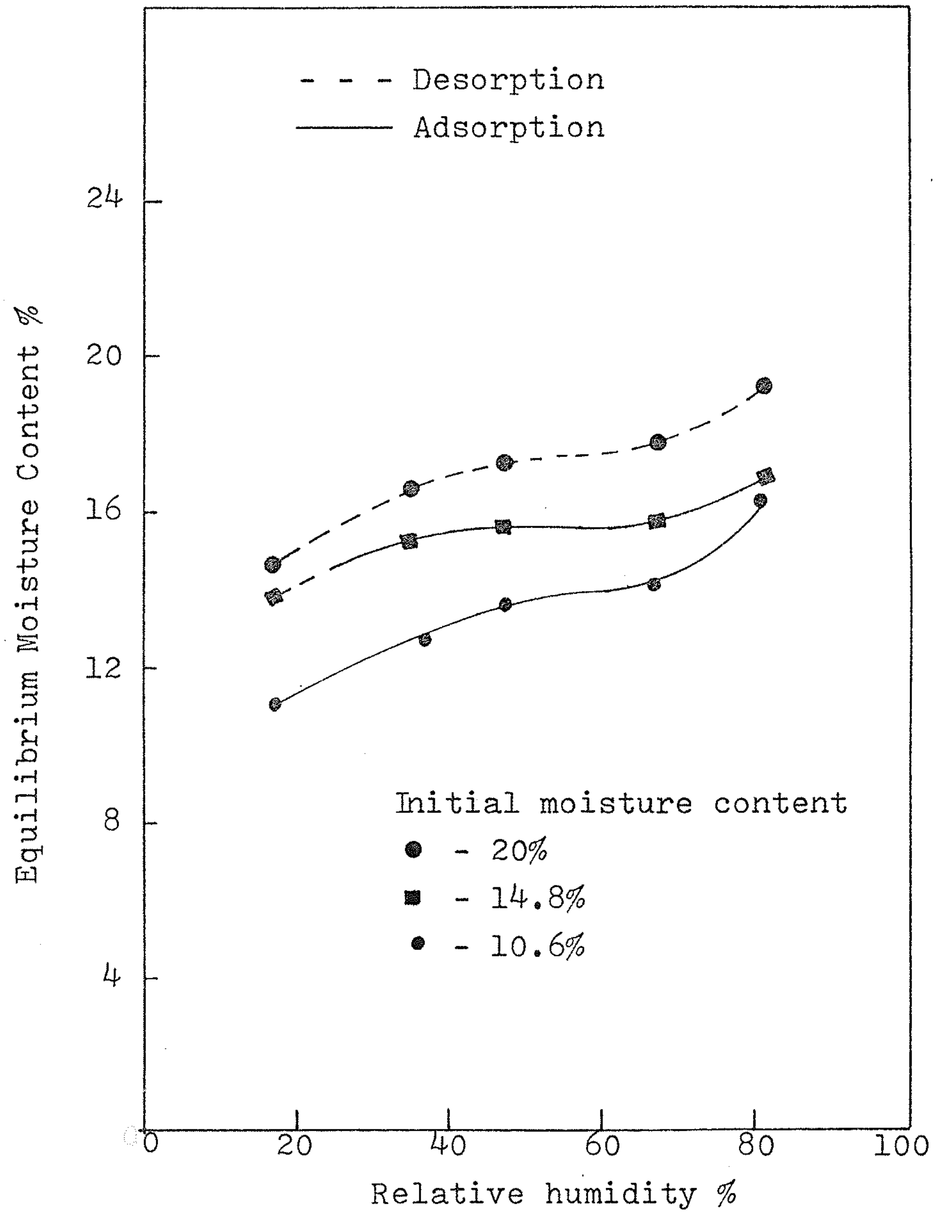

Fig. 4.6 Adsorption and desorption isotherms for wheat at -10° C

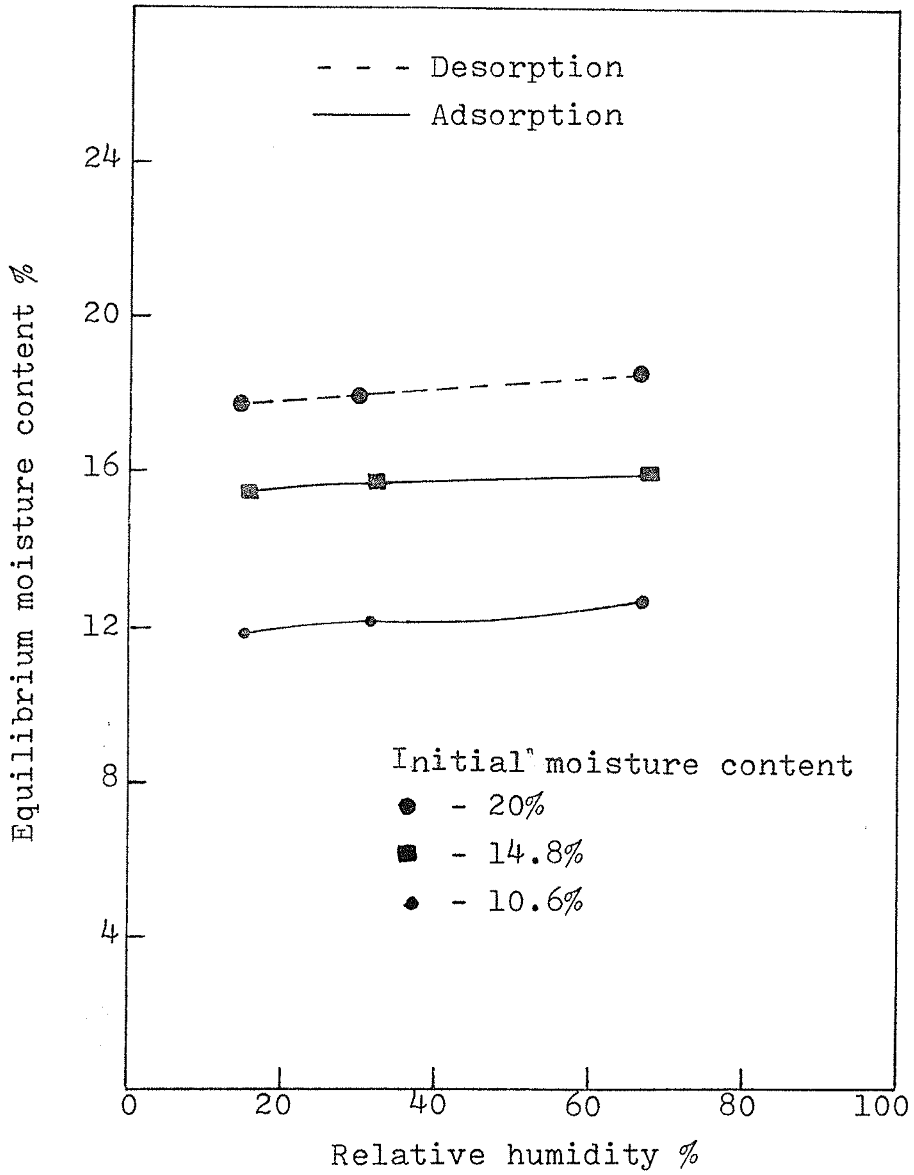

Fig. 4.7 Adsorption and desorption isotherms for wheat at -21° C

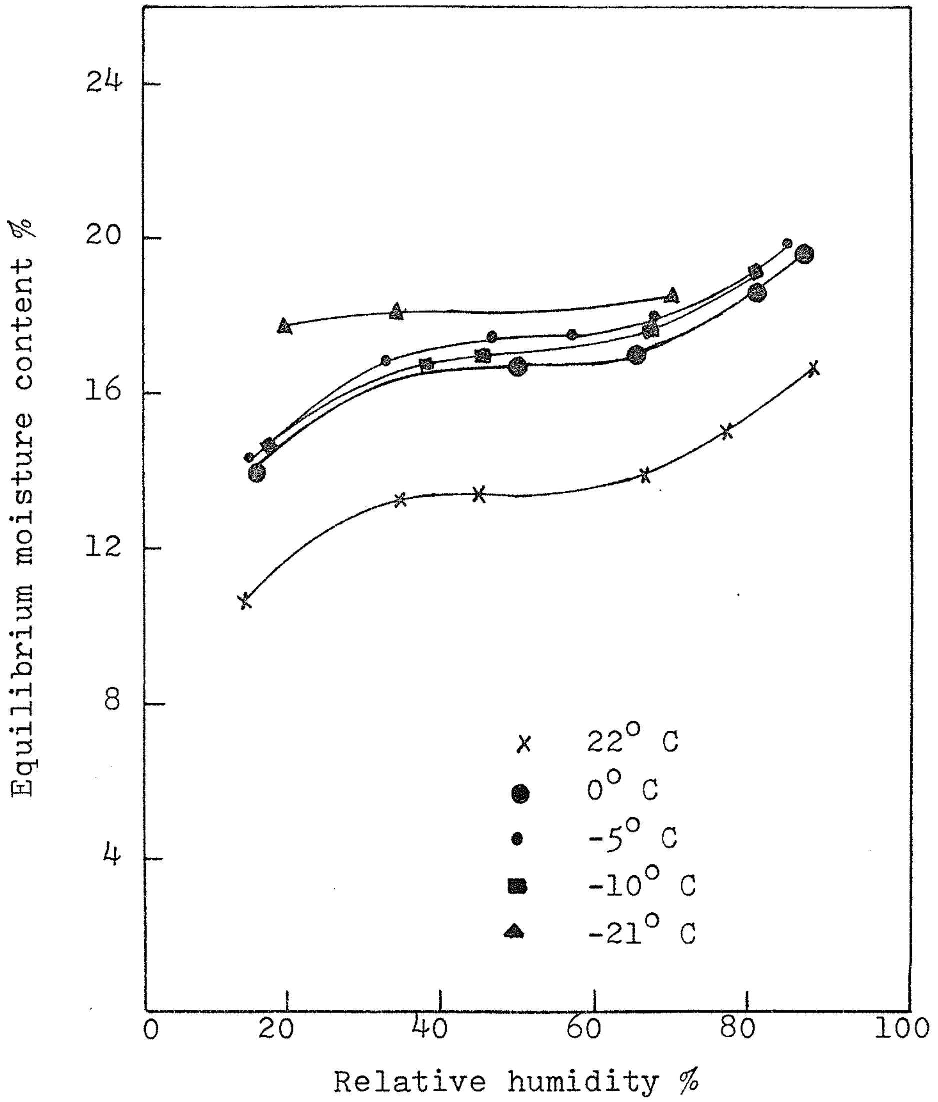

Fig. 4.8 Effect of temperature on equilibrium moisture contents of wheat (desorption)

quite different than the ones observed at other test temperatures. The equilibrium values could not be measured at the high relative humidities due to freezing of the salt solutions. This makes it impossible to predict the nature of the curve at the high relative humidities. However, both desorption and adsorption isotherms are nearly flat, and this fact implies that exchange of moisture from grain was independent of relative humidity.

The equilibrium moisture contents I determined at 0° were higher than those determined by Gane (1941) (Fig. 4.9). At relative humidities below 40% the differences in equilibrium moisture content were large. However, above 40% relative humidity my experimental values of equilibrium moisture content were in close agreement with those of Gane (1941). The deviations of the equilibrium moisture content points below 40° C could have been caused by failure of the solution to attain uniform saturation which would change the vapor pressure in the test cabinet or the relative humidity indicator could have been in error. There are other reasons to believe that these differences could have been caused by leakage of water vapor from the test cabinet, differences in kind and type of wheat and moisture content determination methods.

4.3 Hysteresis

Under most conditions the equilibrium moisture during adsorption was lower than during desorption (Fig. 4.3 to

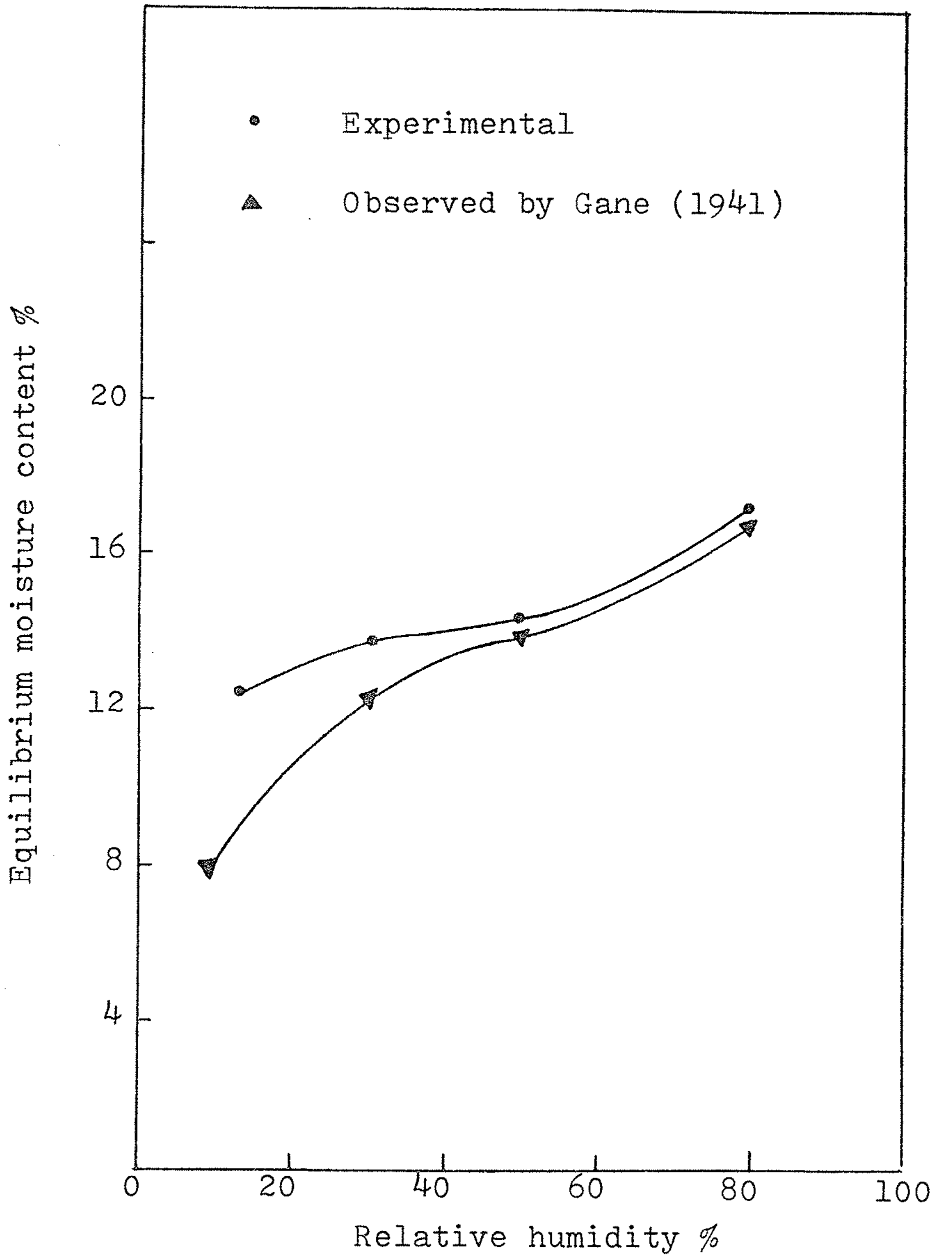

Fig. 4.9 Adsorption isotherms
for wheat at 0° C

4.7). The magnitude of the difference varies with the levels of relative humidity and temperature. The hysteresis effect was larger at low temperatures than at high temperatures. At 22° C and 45% relative humidity the hysteresis observed was 1%, which is identical to that reported by Hubbard et al.(1957), while Babbitt (1945) reported 4% hysteresis under the same conditions. The hysteresis observed in this study at 0° C, -5° C, -10° C and -21° C, are 2.5%, 2.8%, 3.4% and 6% respectively.

Above 70% relative humidity the hysteresis effect decreased for all test temperatures except for -21° C. At -21° C the hysteresis effect was constant throughout the relative humidity range (Fig. 4.7).

4.4 Low Temperature Drying

4.4.1 Weather Conditions in Manitoba

For unheated or low-temperature drying systems, drying will take place if the vapor pressure of the material is higher than the vapor pressure of the surrounding atmosphere. The equilibrium moisture content information can be used for determining the vapor pressure of the wheat. To determine the actual amount of drying possible under a given set of atmospheric conditions, a knowledge of weather data is required, because weather conditions vary the drying potential of ambient or slightly heated air from year to year and region to region. To investigate the drying potential of unheated air drying in Manitoba, 10 years of weekly average data for Winnipeg was obtained from Fraser (1978) (Fig. 4.10). For example, in the month of August (average temperature 20° C and relative humidity 70%) the air has more drying potential (equilibrium moisture content 14.0%) than in the month of October (average temperature 0° C and relative humidity 75%) because the equilibrium moisture content at this environmental condition is 19.3%.

4.4.2 Energy Consumption

Using my equilibrium moisture content data energies consumed per unit of water removed at various grain and environmental conditions were calculated. To calculate the energy consumption values the assumption is made that the drying process is adiabatic and therefore takes place at constant wet-bulb temperatures. The grain depth in deep-bed grain bin was enough so that air exhausted at conditions in equilibrium with the initial moisture content of the grain. The following conditions were assumed in the calculations:

1. Air was moved through a deep-bed of grain at the rate of $2m^3$/min-t.
2. Incoming relative humidity was 70%.
3. Initial moisture content of grain was 20%.
4. Grain depth was 2m.
5. Rise in air temperature is 1° C due to fan heat.
6. Air exhausted at conditions in equilibrium with the grain moisture and incoming air temperature.

Assuming these conditions, each condition was varied

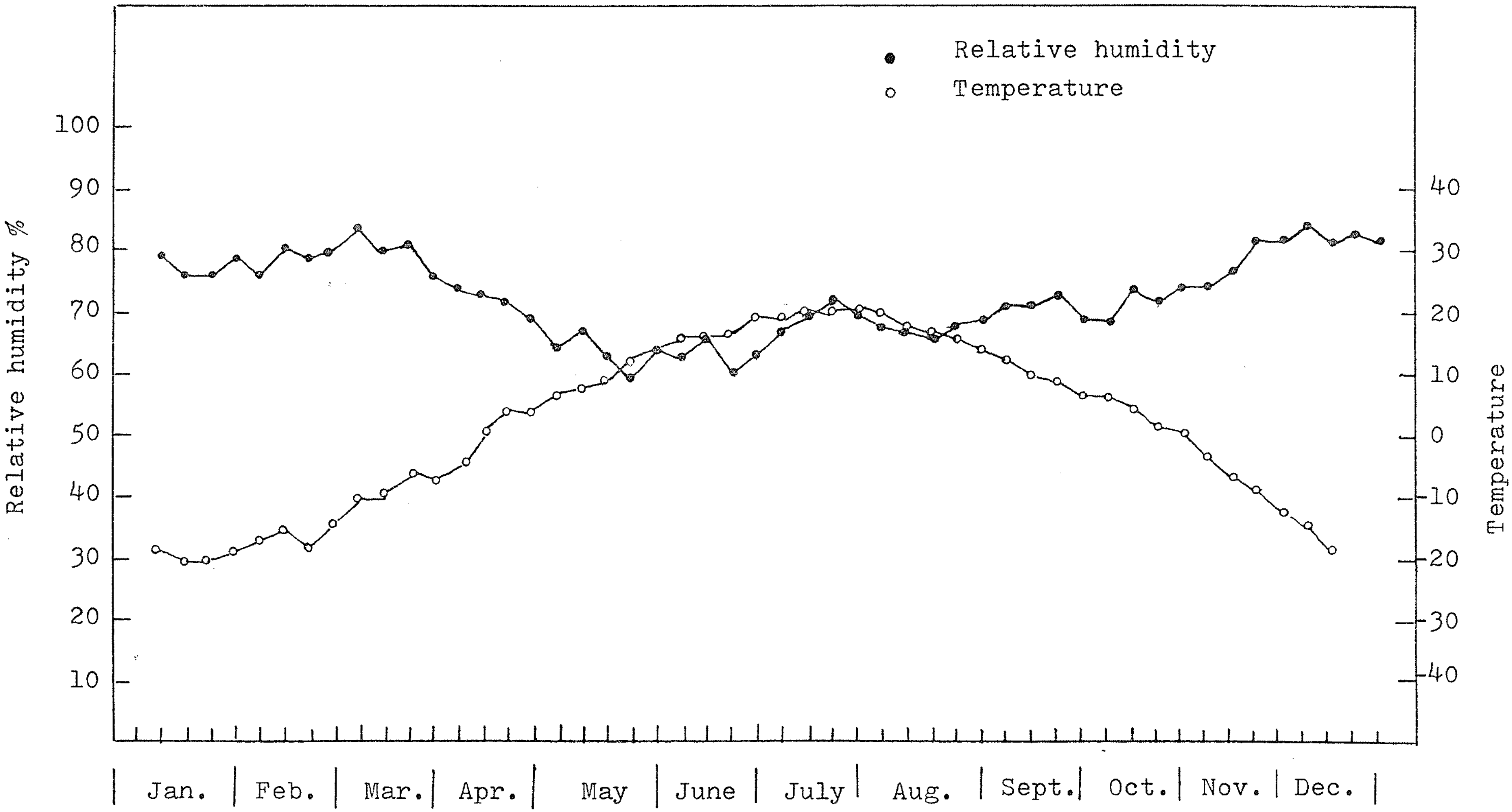

Fig. 4.10 Ten years weekly averate temperature and relative humidity data for Winnipeg, Manitoba

keeping others unchanged to predict the effect of each variable on energy consumption. The procedure used to calculate the energy required per unit of water removed is given in Appendix B.

Air flow rates affect the energy consumption in low temperature drying. Energy consumed in MJ/kg of water removed from wheat increases with increasing air flow rates (Fig. 4.11). As the temperature of the drying air decreases energy consumption for a given air flow rate increases. For Manitoba weather conditions (Fig. 4.10) the energy required to remove 1 kg of water will be about 200% (maximum) more in January (average air temperature -20° C) than in November (average air temperature 0° C), because of the low moisture carrying capacity of the air at low temperatures. To dry grain before spoilage can occur, either air flow rate must be increased or the air must be heated to a higher temperature. To keep the energy consumption minimum, it seems (Fig. 4.11) it is better to plan drying with higher air temperatures than to increase the air flow rates. Thus, drying with slightly heated air would be more feasible if it is done in April than in winter.

Energy consumed in MJ/kg of water removed increases with increasing relative humidity of the incoming air (Fig. 4.12). Energy consumption increases rapidly above 80% relative humidity, and the effect is prominent at lower temperatures. At low relative humidities the rate of moisture removed is fast because of the large vapor pressure

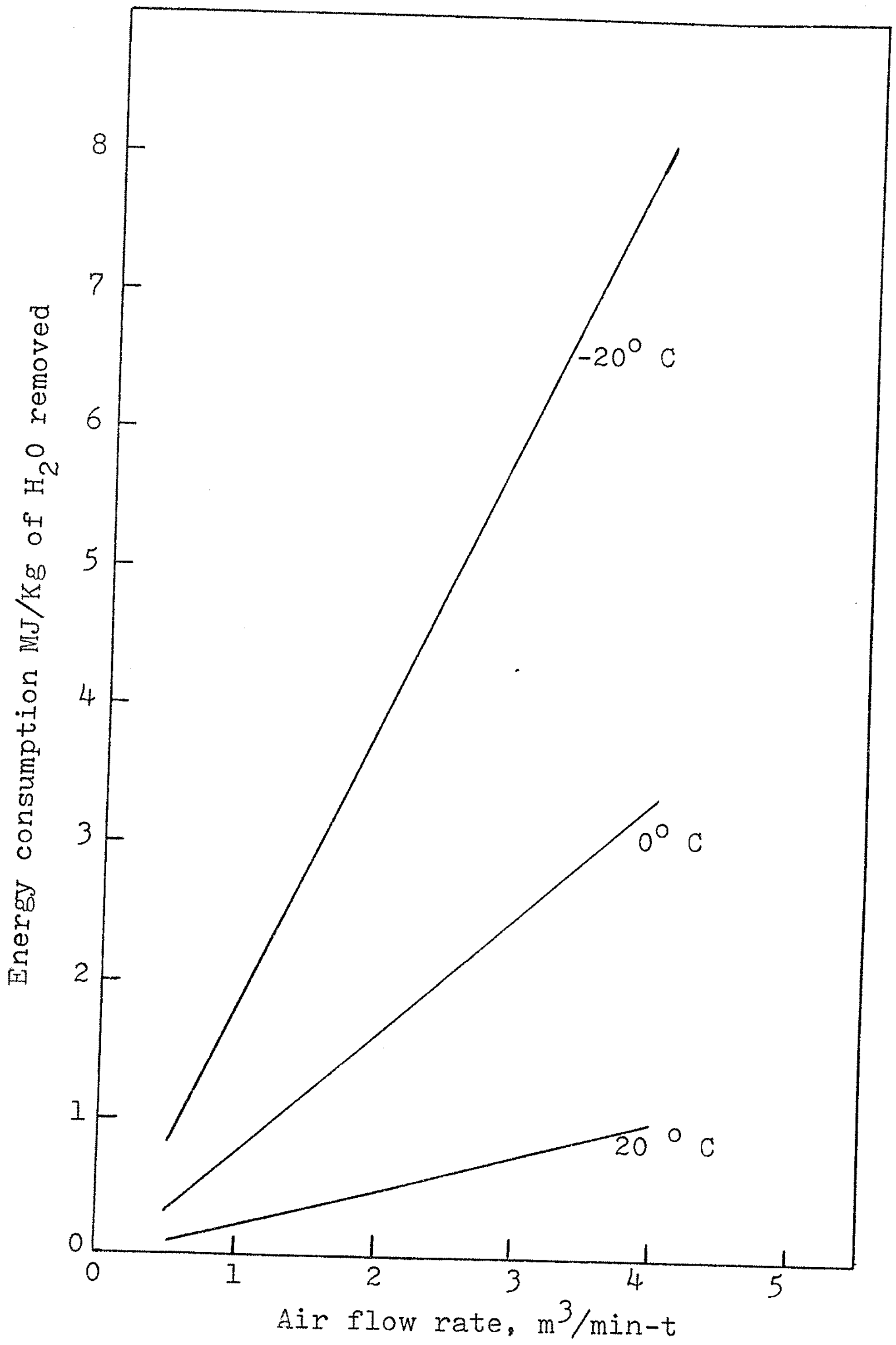

Fig. 4.11 Effect of air flow on energy consumption. (Air relative humidity 70%, grain depth 2 m, initial moisture content 20%, heat added 1° C (fan heat), air exhaust in equilibrium with grain moisture content.)

differences between the grain moisture and the water in the surrounding air. At higher relative humidities this vapor pressure difference decreases reducing the rate of moisture movement from the grain. When the vapoe pressure of grain moisture and surrounding air become equal or when the equilibrium condition is reached, drying ceases. Thus, to remove the desired amount of moisture more drying time will be required with air of high relative humidity than with air of low relative humidity, resulting in more power required, and thereby more energy consumption.

At -20° C air with 100% relative humidity can remove only a small amount of moisture due to fan heat added to the drying air. Because of extremely low moisture carrying capacity of the air, energy consumed increased to 44 MJ/kg, while at 20° C and 100% relative humidity it is only 2.5 MJ/kg. At 0° C drying air exhausts at 90% relative humidity in equilibrium with 20% moisture grain, therefore there would be an increase in moisture content of wheat with 100% incoming relative humidity. Thus in Manitoba drying in April (average air temperature 0° C and 75% relative humidity (Fig. 4.10), can save 60% energy compared with drying in January (average temperature -20° C and 80% relative humidity).

Energy consumption varies with initial moisture content of the grain. Lower the moisture content, the higher will be the energy consumed (Fig. 4.13). At moisture contents below 20% energy consumption increases. Energy consumption increased 33% from 0.75 to 1.0 MJ/kg when initial moisture content decreased from 18 to 16% at 20° C. It should be noted that the energy consumption values are for the removal of water at the given moisture content and not the average values for removal of water from the initial moisture down to the safe storage moisture level.

At -20° C the curve does not go below 20% initial moisture content because at 18.5% moisture content air exhausts in equilibrium with 65% relative humidity (Fig. 4.7). Therefore, there is little moisture removal with incoming air of 70% relative humidity, even though fan heat is added to the air. Further, it should be noted that above 20% moisture content the energy consumption curves are level. This is due to the fact that drying air will remove moisture until it comes into equilibrium with the initial grain moisture. Once the air has reached equilibrium, further moisture removal ceases. For example, at -20° C and 70% relative humidity, air exhausts at 100% relative humidity in equilibrium with 20% initial moisture content. Therefore, for given drying conditions the amount of water removed at moisture contents of 20% and above would be the same. The energy consumed to remove a unit of water from grain at moisture contents above 20% is constant.

Depth of grain in a grain bin affects the energy consumption. With increasing grain depths, energy consumption increases (Fig. 4.14). As the grain depth is increased, total resistance to air flow increases because of

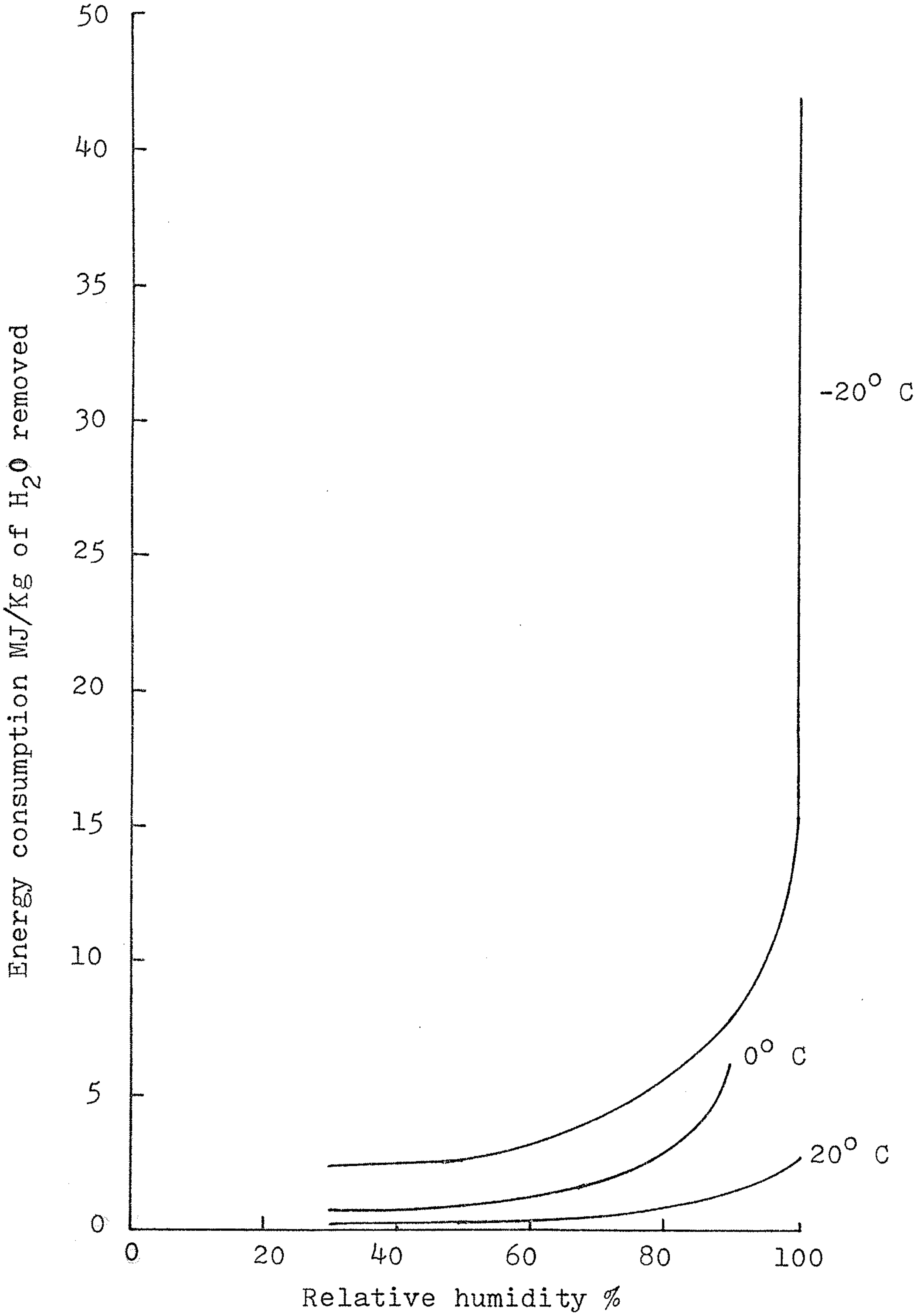

Fig. 4.12 Energy consumption at different relative humidities (air flow 2 m^3/min-t, grain depth 1 m, initial moisture content 20%, air exhaust in equilibrium with grain moisture content; heat added 1° C (fan heat)).

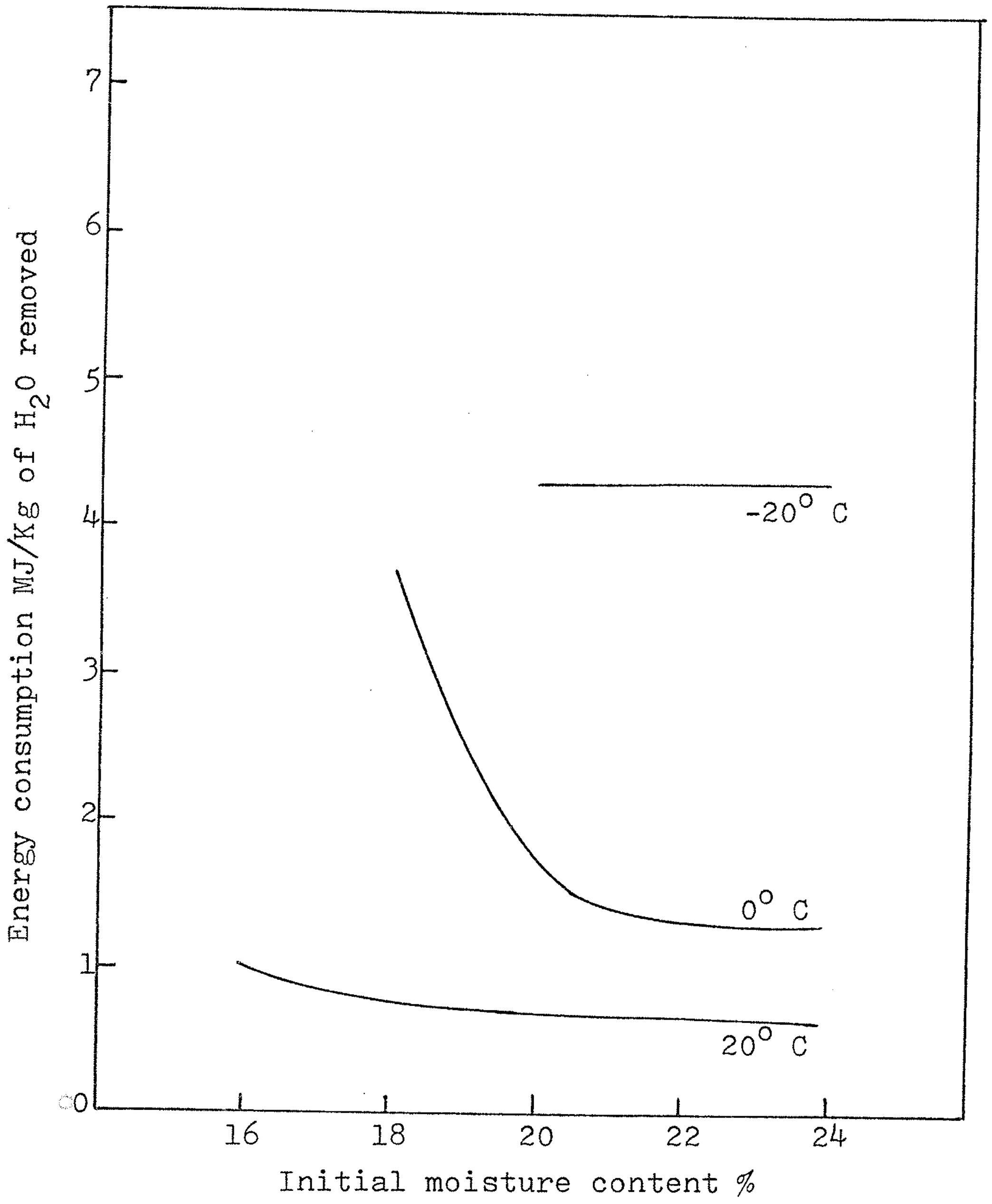

Fig. 4.13 Effect of initial moisture content of wheat on energy consumption. (Air relative humidity 70%, grain depth 2 m, air flow 2 m^3/min-t, air exhaust in equilibrium with grain moisture content, heat added 1° C (fan heat)).

two factors, both the resistance per metre depth and the product of depth times resistance increase. This results in more power being required thereby, and more consumption in energy per unit of water removed. Energy consumption increased by 130% from 4.3 to 9.9 MJ/kg, when grain depth increased from 2 to 3 m at -20° C air temperature, while at 0° C it increased by 125% from 1.7 to 3.8 MJ/kg for the same increase in grain depth.

Raising the air temperature by a few degrees can reduce the energy consumption (Fig. 4.15). In low temperature drying fan energy is always consumed, but temperature of ambient air passing through the fan may be raised by 1° C due to the fan heat. This rise in temperature reduces the relative humidity of the incoming air by 5 to 6%, thus increasing the moisture absorbing capacity of the drying air. This can result in about 33% maximum saving in energy consumption compared with no heat added to the drying air. Supplemental heat can be added using electrical heaters in the drying system. If 5° C temperature rise is desired, only 4° C will have to be added because 1° C would be added by fan heat. To add this supplemental heat over ambient air temperature, electrical energy will be consumed in addition to the fan energy. Thus, total energy will be fan energy plus the electrical energy consumed to raise the air temperature. By adding 20° C supplemental heat to ambient air at -20° C, the amount of water removed increased 10 times for a given air flow volume. However, due to the

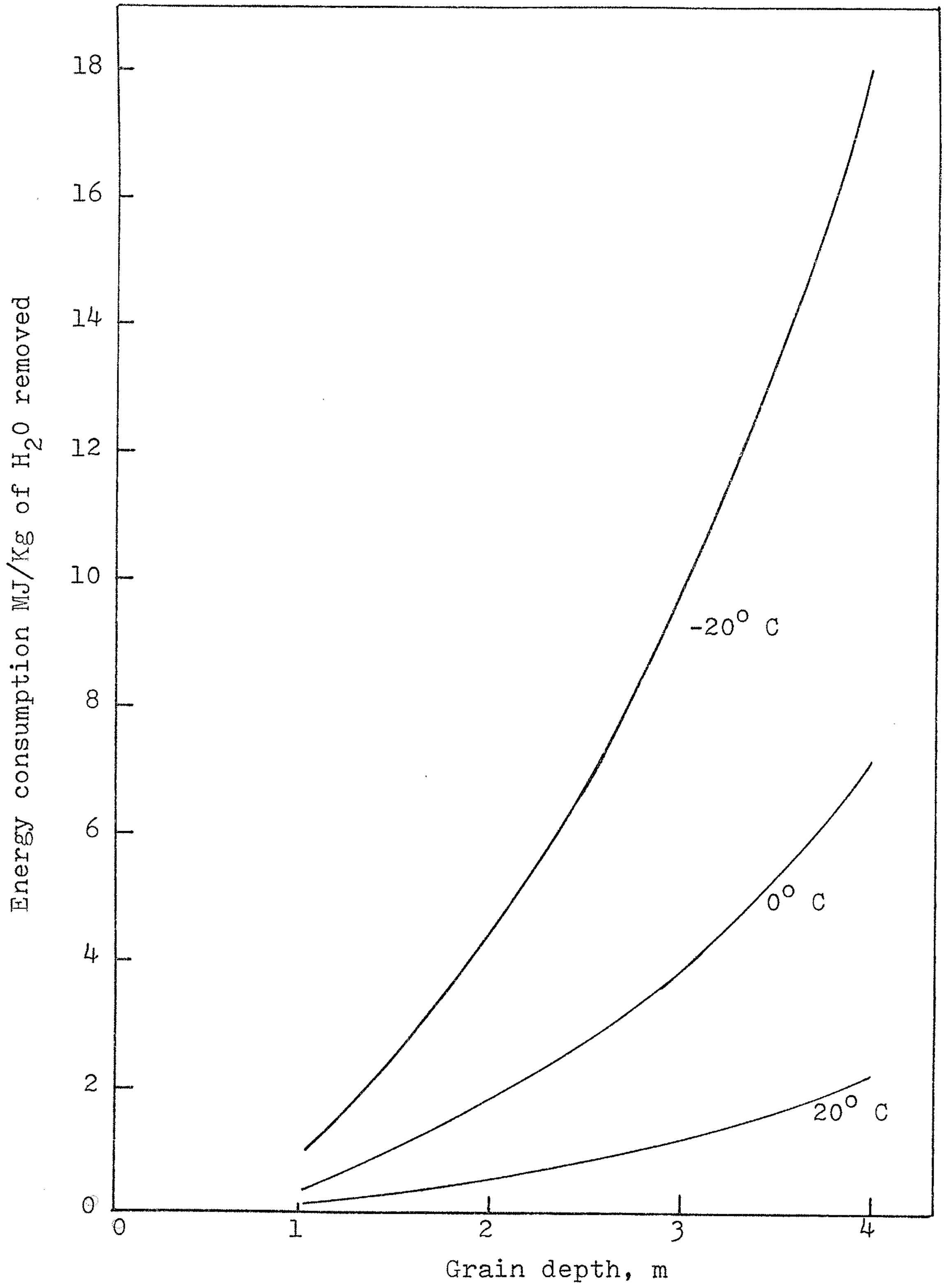

Fig. 4.14 Effect of grain depth on energy consumption. (Air relative humidity 70%, air flow 2 m^3/min-t, initial moisture content 20%, air exhaust in equilibrium with grain moisture content; heat added 1° C (fan heat)).

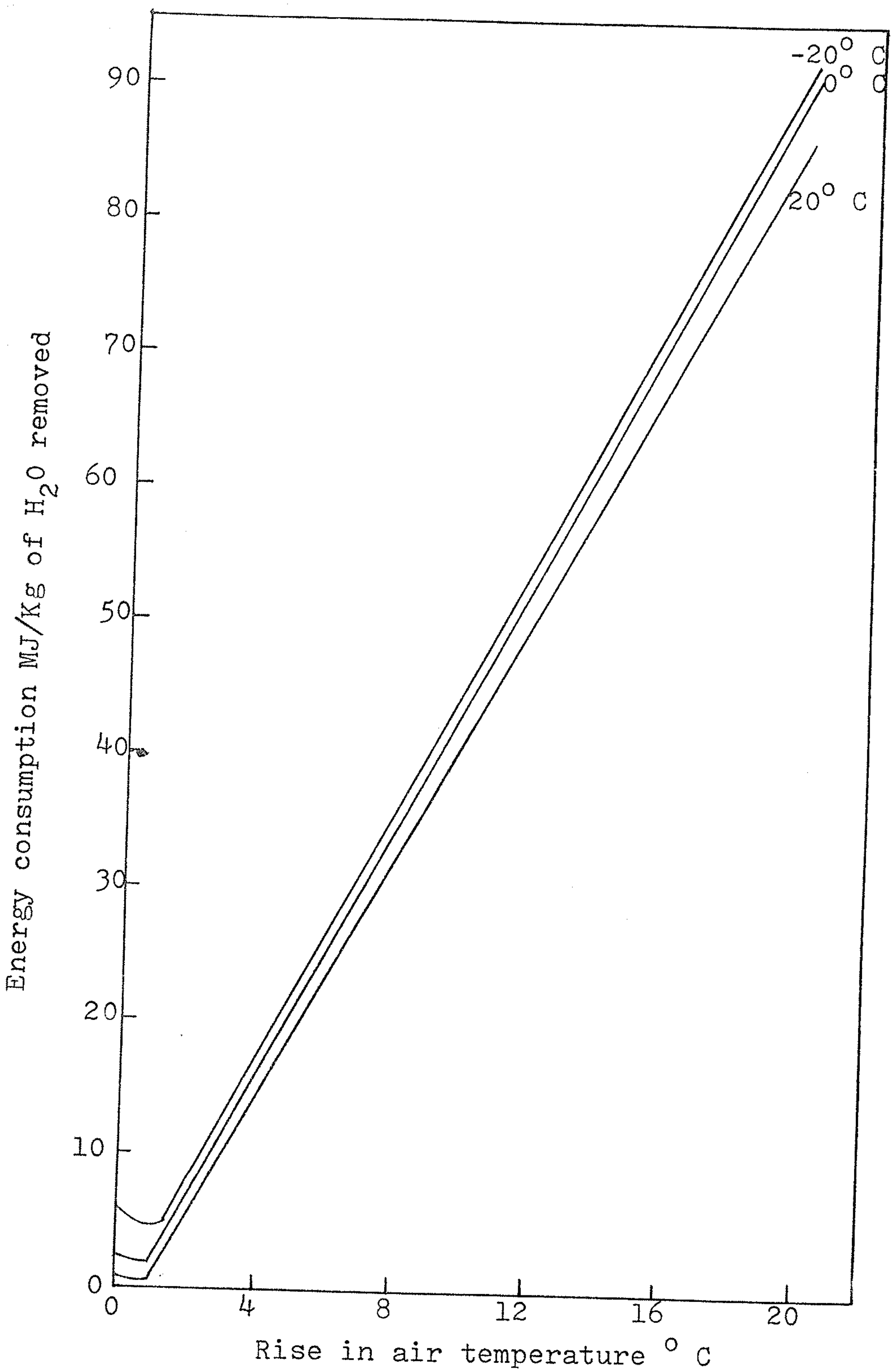

Fig. 4.15. Effect of heat added to ambient air on energy consumption. (Air relative humidity 70%, grain depth 2 m, air flow 2 m^3/min-t, grain moisture content 20%, air exhaust in equilibrium with grain moisture content.)

large quantity of heat required to raise the air temperature, there is a sharp rise in energy consumption. It should be noted that the incoming air temperature has little effect on energy consumption for different levels of supplemental heat.

It appears, from my results, that to keep energy consumption low, the most suitable time for ambient air drying is in the spring. Although some drying is achieved in winter, the high energy consumption makes the drying system non-feasible. As ambient air temperature drops below 0° C the rate of energy consumption increases sharply. Treidl (1974) suggests that the best time for ambient drying in Manitoba is in spring, and the drying potential of the air to remove moisture decreases slowly in October, with a sharp decrease in November. Simulated results (Fraser, 1978) of ambient air drying suggests that ambient air drying is feasible if the drying is scheduled in the first week of April and continued in spring. The energy consumption values reported in this study are in close agreement with the values reported by Fraser (1978) for a given set of conditions. For example, at -20° C my energy consumption values are 1.84 MJ/kg and 1.7 MJ/kg at 0° C, while for the same conditions Fraser (1978) reported 1.8 and 2.0 MJ/kg respectively.

5. SUMMARY AND CONCLUSIONS

Equilibrium moisture contents of wheat were determined experimentally for both adsorption and desorption isotherms. Desired relative humidities were maintained in the vapor-proof wooden cabinets by using saturated salt solutions. The cabinets were placed inside the environmental chamber, in which temperatures ranging from -21° to 22° C were controlled.

With the experimental data theoretical calculations were performed to predict the energy consumptions for various grain and weather conditions in low temperature drying. The following conditions were assumed in these calculations:

1. Air flow rate 2 m^3/min-t;
2. Incoming air relative humidity 70%;
3. Initial moisture content of wheat 20%;
4. Grain depth 2 m;
5. Rise in air temperature by 1° C due to fan heat;
6. Air leaving at conditions in equilibrium with the grain moisture content and incoming air temperature.

To predict the effect of each variable on energy consumptions each condition was varied while keeping the others constant.

Based on the experimental and theoretical studies the following conclusions are drawn:

1. Equilibrium was reached slowly at low temperatures and low relative humidities.
2. Below 0° C (except -21° C) both adsorption and desorption isotherms are of the characteristic sigmoid type as is usually observed at 20° C and above.
3. At -21° C the isotherms are independent of relative humidities in the range of 15 to 70%.
4. Hysteresis exists between adsorption and desorption of water by wheat. It is relatively large at low temperatures. As temperature increases, hysteresis decreases.
5. At the highest initial moisture content of wheat the equilibrium moisture content is the highest.
6. Energy consumptions varies directly with the air flow rates.
7. Above 80% relative humidity energy consumptions increase rapidly.
8. As the initial moisture content of grain increases, the energy consumption per unit of water removal at that moisture content decreases, but energy consumption increases with increasing initial moisture content to dry the grain to safe storage moisture level.
9. Energy consumption increases four times if the grain depth is doubled.
10. If the fan heat is not utilized to raise the air

temperature, 33% more energy than expected will be required.

11. As the air temperature drops below 0° C, energy consumption increases rapidly.
12. The most suitable drying season with ambient air in Manitoba is in spring.

6. SUGGESTIONS FOR FUTURE STUDY

1. Experiments should be conducted to verify the predicted results of energy consumption values in low temperature drying.
2. Using the equilibrium moisture content data from this study, it is suggested that mathematical models for low temperatures be developed.
3. The verification of the models should be done at low temperatures.
4. Optimum cost in low temperature drying should be investigated for a wide range of grain and weather conditions in Manitoba.

REFERENCES

Ayerst, G. 1965. Determination of the water activity of some hygroscopic food materials by dew-point method. J. SCI. FOOD AGRIC. 16:71-78.

Babbitt, J. D. 1949. Observations on the adsorption of water vapor by wheat. CAN. J. RES. 27:55-78.

Baxter, J. F. and R. H. Hahn (ed.). 1977. Agricultural engineers year book. AM. SOC. AGRIC. ENG. St. Joseph, Mich., U.S.A.

Becker, H. A. and H. R. Sallans. 1956. A study of desorption isotherms of wheat at 25° C and 50° C. CEREAL CHEM. 33:79-91.

Bosin, W. A. and H. D. Easthouse. 1970. Rapid method for obtaining humidity equilibria data. FOOD TECHNOL. 24(10):113-115.

Breese, M. H. 1955. Hysteresis in the hygroscopic equilibria of rough rice. CEREAL CHEM. 32:481-487.

Brockington, S. F., H. C. Dorin and H. K. Howerton. 1949. Hygroscopic equilibria of whole corn. CEREAL CHEM. 26:166-173.

Bushuk, W. and I. Hlynka. 1960. Weight and volume changes in wheat during sorption and desorption of moisture. CEREAL CHEM. 37:390-398.

Carr, D. S. and B. L. Harris. 1949. Solutions for maintaining constant relative humidity. IND. ENG. CHEM. 41:2014-2016.

Chung, D. S. and H. B. Pfost. 1967. Adsorption and desorption of water vapor by cereal grains and their products. TRANS ASAE (AM. SOC. AGRIC. ENG.) 10:552-575.

Chen, C. S. 1969. Equilibrium moisture curves for the biological materials. AM. SOC. AGRIC. ENG. St. Joseph, Mich., U.S.A. Paper No. 69-889.

Clayton, R. E., S. M. Stewart and A. Farms. 1976. Experiences with low temperature corn drying in south-western Ontario. CAN. SOC. AGRIC. ENG., School of Engineering, University of Guelph, Guelph, Ontario, Paper No. 76-107.

Coleman, D. A. and H. C. Fellows. 1925. Hygroscopic moisture of cereal grains and flaxseed exposed to atmospheres of different relative humidity. CEREAL CHEM. 2:275-278.

Cook, W. H., J. W. Hopkins, and W. F. Geddes. 1935. Rapid determination of moisture in grains. CEREAL CHEM. 12:230-235.

Day, D. L. and G. L. Nelson. 1965. Desorption isotherms for wheat. TRANS ASAE (AM. SOC. AGRIC. ENG.) 8(2): 293-297.

Dean, J. A. (ed.). 1970. Handbook of chemistry. McGraw-Hill Book Co., New York, 11(10):68-71.

Foster, G. H. 1953. Minimum air flow required for grain drying with unheated air. AGRIC. ENG. 34(10): 681-684.

Fraser, B. M. 1978. Solar grain drying in Canada, a simulation study. Unpublished MSc thesis, Dept. of Agric. Eng., University of Manitoba, Winnipeg.

Gane, R. 1941. The water content of wheat as function of temperature and relative humidity. J. SOC. CHEM. IND. 60:44-48.

Gur-Arieh, C., A. I. Nelson and M. P. Steinberg. 1965. A method for rapid determination of moisture adsorption isotherms of solid particles. J. FOOD SCI. 30(1): 105-110.

Hall, C. W. 1957. Drying farm crops. Edward Brothers, Inc., Ann Arbor Mich., U.S.A. 33 pp.

Hart, J. R. 1964. Hysteresis effects in mixture of wheat taken from the same sample but having different moisture contents. CEREAL CHEM. 44:601-606.

Haynes, B. C. 1961. Vapor pressure determination of seed hygroscopicity. TECH. BULL. 1229, U.S. Dep. Agric., Agric. Res. Serv. ARS (Ser).

Henderson, S. M. 1952. A basic concept of equilibrium moisture. AGRIC. ENG. 33:29-31.

Hodgeman, C. D. (ed.). 1960. Handbook of chemistry and physics. Chem. Rubber Pub. Co., Cleveland, U.S.A. 42nd edition:1694:1705.

Houston, D. F. 1952. Hygroscopic equilibrium of brown rice. CEREAL CHEM. 29(1):71-76.

Hubbard, J. E., F. R. Earle and F. R. Senti. 1957. Moisture relation in wheat and corn. CEREAL CHEM. 34:442-443.

Instruction Manual, Relative humidity and temperature indicator Model 400C. General Eastern Corporation, Mass., U.S.A.

Karon, M. L. and M. E. Adams. 1949. Hygroscopic equilibrium of rough rice and its fractions. CEREAL CHEM. 26(1):1-12.

Moysey, E. B. and D. H. Wilde. 1965. Drying grain with unheated air. CAN. AGRIC. ENG. 7:12-13.

Moysey, E. B. 1969. Refrigeration of damp grain with natural air. CAN AGRIC. ENG. 11(1):12-3 & 22.

Pichler, H. J. 1957. Sorption isotherms for grain and rape. J. AGRIC. ENG. RES. 2(2):159-165.

Pixton, S. W. and S. Warburton. 1971. Moisture content-relative humidity equilibrium of some cereal grains at different temperatures. J. STORED PROD. RES. 7: 261-269.

Roberts, A. C., W. E. Muir and H. A. H. Wallace. 1978. Natural air drying of corn in Manitoba. Paper No. NCR 78-3003, presented at the 1978 North Central Region meeting of ASAE and CSAE, Saskatoon.

Robertson, D. W., A. M. Lute and R. Gardenar. 1939. Effect of relative humidity on viability, moisture content and respiration of wheat. J. AGRIC. RES. 59(4):281-291.

Rockland, L. B. 1960. Saturated salt solutions for static control of relative humidity between 5° C and 40° C. ANAL. CHEM. 32(10):1375-1376.

Shedd, C. K. 1953. Resistance of grains and seeds to air flow. AGRIC. ENG. 34:616-619.

Shier, G. R., R. C. Miller and W. A. Junnila. 1943. Forced ventilation of high moisture grain. AGRIC. ENG. 24:381-385.

Shove, G. C. 1967. Potential energy use in low temperature grain conditioning. ASAE (AM. SOC. AGRIC. ENG.) St. Joseph, Mich., U.S.A. Paper No. 67-302.

Shove, G. C. 1971. Low temperature drying of shelled corn. AGRIC. ENG. 52:372-373.

Shove, G. C. 1972. Transient low temperature deep-bed drying. ASAE (AM. SOC. AGRIC. ENG.) St. Joseph, Mich., U.S.A. Paper No. 72-323.

Shove, G. C. 1973. Low temperature drying. University of Illinois grain conditioning conference proceedings.

Shove, G. C. 1974. Low temperature drying of shelled corn. Paper presented at the grain conditioning conference, University of Illinois, Urbana-Champain.

Treidl, R. A. 1974. Corn drying in Canada using ambient air. CAN. AGRIC. ENG. 16(2):96-102.

Tuite, J. and G. H. Foster. 1963. Effect of artificial drying on hygroscopic properties of corn. CEREAL CHEM. 40:630-637.

Wexler, A. and S. Hasegawa. 1954. Relative humidity temperature relationship of some saturated salt solutions in the temperature range of 0° to 50° C. J. RES. 53(1):1926 pp.

Wilson, R. E. and T. Fuwa. 1922. Humidity equilibria of various common substances. J. IND. ENG. CHEM. 14: 913-918.

Young, J. H. and G. L. Nelson. 1967. Research of hysteresis between sorption and desorption isotherms of wheat. TRANS ASAE (AM. SOC. AGRIC. ENG.) 10: 756-761.

Young, J. F. 1967. Humidity control in the laboratory using salt solutions, a review. J. APPL. CHEM. 17: 241-245.

APPENDIX A

EXPERIMENTAL DATA OF EQUILIBRIUM MOISTURE CONTENT OF WHEAT

Table A.1 Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at 22° C

Initial moisture content %	10.6				14.8				20.0			
Relative humidity %	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4
14	9.7	9.8	9.8	9.8	10.8	10.6	10.6	10.6	10.7	10.8	10.7	10.7
34	11.5	12.3	12.2	12.0	12.7	13.1	12.9	13.0	13.5	13.4	13.2	13.3
44	12.6	12.4	12.5	12.7	13.2	13.2	12.6	13.2	13.0	13.6	13.6	13.9
66	13.0	13.0	13.0	13.0	13.4	13.5	13.5	13.5	14.0	13.8	14.3	14.1
77	14.2	14.2	14.3	14.1	14.5	14.6	14.6	14.5	15.2	15.2	15.0	15.1
88	16.3	16.3	16.3	16.3	16.2	16.4	16.4	16.4	16.9	16.8	16.9	16.7

*Rep. 1-4 indicates replication numbers from 1 to 4.

Table A2. Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at 0° C

Initial moisture content %	10.6				14.8				20.0			
Relative humidity %	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4
13	12.6	12.4	12.5	12.6	14.2	14.2	14.3	14.2	15.2	15.2	15.2	15.1
30	13.8	13.7	13.8	13.7	15.0	15.0	15.0	15.0	16.5	16.5	16.7	16.6
44	14.0	14.1	14.0	14.0	15.3	15.2	15.3	15.2	16.9	16.9	16.9	16.8
64	14.6	14.7	14.5	14.6	15.5	15.4	15.5	15.5	17.0	17.0	17.4	17.0
80	17.2	13.3	17.2	17.4	16.8	16.6	17.1	16.8	19.2	19.4	19.3	19.3
87	19.0	18.9	19.9	18.9	18.5	18.7	18.7	18.8	20.0	20.0	19.9	19.9

Rep. 1 to 4 indicates replication numbers from 1 to 4.

Table A3. Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at -5° C

Initial moisture content %	10.6				14.8				20.0			
Relative humidity %	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4
15	11.5	11.5	11.5	11.5	13.7	13.7	13.7	13.6	14.2	14.4	14.3	14.3
32	14.0	14.0	14.0	14.0	15.3	15.2	15.2	15.2	16.7	16.6	17.0	16.9
46	15.0	15.0	15.0	15.0	15.8	15.8	15.7	15.6	17.5	17.6	17.6	17.6
67	14.4	14.4	14.4	14.4	16.3	16.3	16.5	16.3	18.0	17.9	18.2	18.1
79	17.4	17.5	17.4	17.3	17.2	17.0	17.0	17.0	20.2	20.0	20.0	20.4
87	17.7	17.6	17.6	17.9	18.0	18.0	17.9	18.5	20.1	20.1	20.1	20.0

Rep. 1 to 4 indicates the replication numbers from 1 to 4.

Table A.4. Equilibrium moisture contents (%) of red spring wheet (cultivar, Neepawa) at -10° C

Initial moisture content %	10.6				14.8				20.0			
Relative humidity %	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4
17	11.1	11.1	11.0	11.1	13.8	14.0	13.8	13.9	14.6	14.5	14.9	14.7
37	11.8	12.9	12.9	13.0	14.8	15.3	15.3	15.3	16.7	16.3	16.8	16.7
47	13.6	13.7	13.5	13.5	15.5	15.6	15.6	15.6	17.2	17.2	17.2	17.2
67	13.8	13.8	13.8	13.8	15.8	15.5	15.6	15.9	17.7	17.6	18.0	17.5
81 **	16.2	16.1	16.1	16.0	16.6	16.6	16.6	16.5	19.0	19.5	19.4	19.4

*Rep. 1 to 4 indicates the replication numbers from 1 to 4.

**No relative humidity was maintained above 81% because of freezing of salt solution.

Table A6. Equilibrium moisture contents (%) of red spring wheat (cultivar, Neepawa) at -21° C

Initial moisture content %	10.6				14.8				20.0			
Relative humidity %	Rep.1*	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4	Rep.1	Rep.2	Rep.3	Rep.4
17	12.0	12.1	12.0	11.3	15.6	15.5	15.5	15.5	17.8	17.8	17.8	17.9
33	12.3	12.0	12.2	12.3	15.7	15.7	15.8	15.4	18.4	18.2	18.0	18.2
69	12.6	12.6	12.5	12.7	16.0	16.0	15.9	15.8	18.6	19.3	18.9	18.5
**												

*Rep. 1 to 4 indicates the replication numbers from 1 to 4.

**No relative humidities above 69% were maintained because of freezing of salt solutions.

APPENDIX B

ENERGY CONSUMPTION CALCULATIONS IN LOW TEMPERATURE DRYING

APPENDIX B

Sample Calculations

This section includes a typical calculation procedure used to calculate energy consumption in low temperature drying.

1. Fan Power

The following relation is used to calculate the fan power:

$$\text{Fan power} = \frac{\text{Total air flow x Total pressure}}{60\text{xFExME}} \qquad (B.1)$$

where:

Fan power = kW,

Total air flow = m^3/min,

Total pressure = kPa,

FE = Fan efficiency, 0.6 (assumed), and

ME = Motor efficiency, 0.8 (assumed).

To calculate total air flow rate in one set of conditions, two variables, grain depth, 2 m; air flow rate, 2 m^3/min-t; and constant 5 m bin diameter were assumed. Thus the grain fill in the bin is:

$$= (5 \text{ m x } 5 \text{ m x } 3.14 \text{ x } 2 \text{ m})/4 \qquad (B.2)$$

$$= 39.27 \text{ m}^3$$

To convert the grain volume into grain mass:

$$= 39.27 \text{ m}^3 \text{ x } 0.75 \text{ t/m}^3 \qquad (B.3)$$

$$= 29.45 \text{ t of wheat}$$

Total air flow rate:

$$= 29.45 \text{ t} \times 2 \text{ m}^3/\text{min-t} \qquad (B.4)$$

$$= 58.9 \text{ m}^3/\text{min}.$$

The total pressure of the fan is the sum of static pressure and velocity pressure. The velocity pressure in the low temperature drying is negligible due to low air velocity. The grain drying systems are designed on the basis of static pressure. The static pressure for the given air flow rate and depth was determined from the chart given by Shedd (1953). The static pressure values used in these calculations are 30% more than those given by Shedd to compensate for the packing effect and high moisture grain conditions. Thus, for an air flow rate of 2 m^3/min-t and 2 m grain depth the static pressure is 0.55 kPa.

Substituting the value of total air flow rate and static pressure in (B.1):

$$\text{Fan power} = \frac{58.9 \text{ m}^3/\text{min} \times 0.55 \text{ N/m}^2}{60 \text{ s/min} \times 0.6 \times 0.8} \qquad (B.5)$$

$$= 1.12 \text{ KW}$$

$$\text{Power required in 1 h} = 1.12 \text{ kW} \times 1 \text{ h}$$

$$= 1.12 \text{ kWh}$$

Energy consumed in 1 h fan operation is:

$$= 1.12 \text{ kWh} \times 3.6 \text{ MJ/kWh} \qquad (B.6)$$

$$= 4.07 \text{ MJ}.$$

2. Amount of moisture Removed from Wheat

The amount of water removed by the air under the given weather conditions is determined from the psychrometric

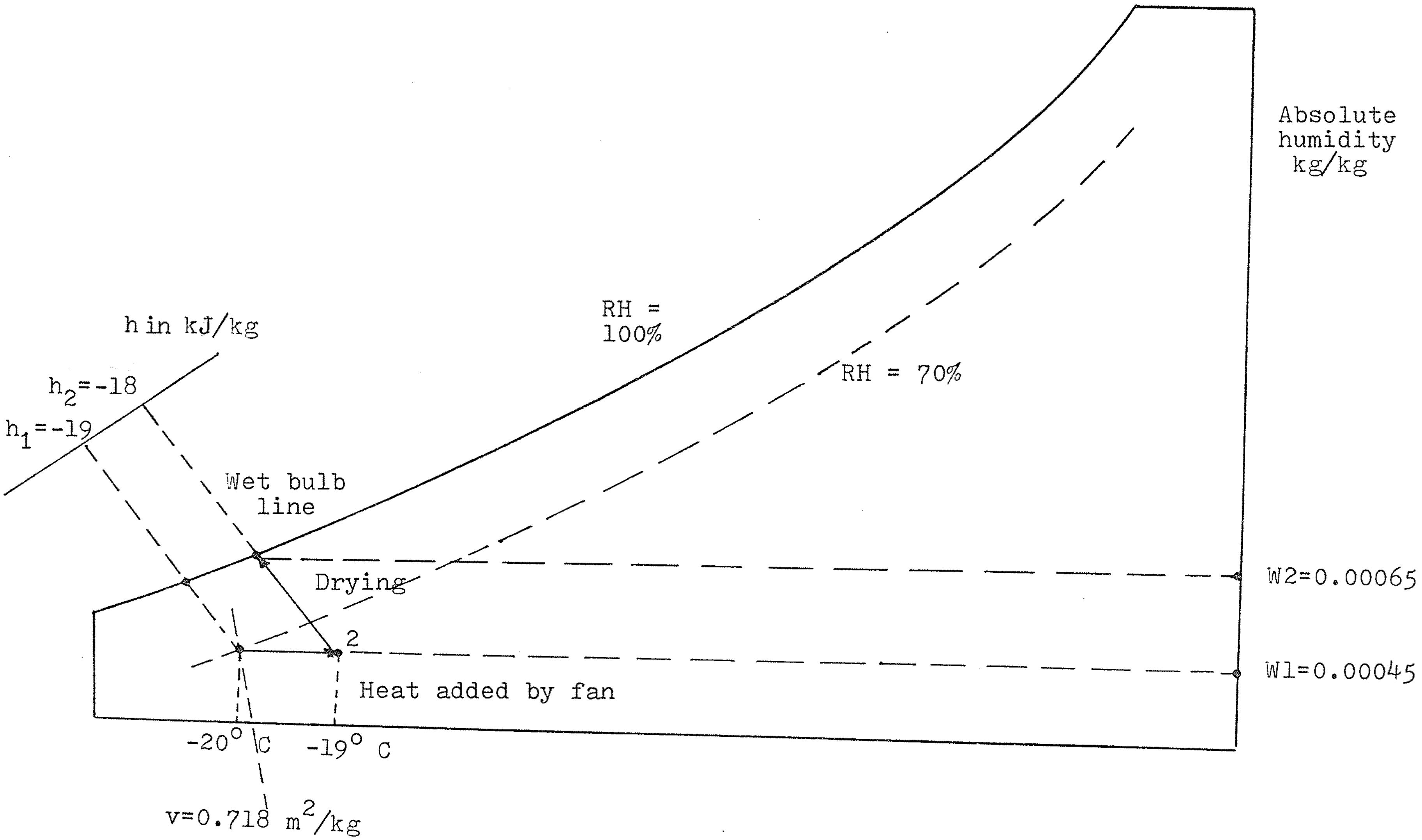

Fig. B.1 Illustration of the use of the psychrometric chart to determine amount of water removed for given conditions.

chart (Fig. B.1). State points 1 and 2 in (Fig. B.1) represent the air properties before and after heat is added by the fan motor. The specific volume of the inlet air is 0.718 m^3/kg. The inlet air relative humidity is 70%, initial moisture content of wheat 20%, and the exhaust air has a relative humidity in equilibrium with the grain moisture content (in this case, 100% relative humidity). The humidity ratio of the air before it passes through the grain is 0.00045 kg/kg of dry air. After it has passed through the grain mass the humidity ratio has increased to 0.00065 kg/kg of dry air. The amount of moisture removed from the grain is (0.00065-0.00045) kg/kg or 0.0002 kg/kg of dry air.

The mass flow rate of air from (B.4) is:

$$= 58.9 \text{ m}^3/\text{min} \times 60 \text{ min/h} \times 1 \text{ kg}/0.718 \text{ m}^3 \qquad (B.7)$$

$$= 4922.0 \text{ kg}$$

Thus, the amount of moisture removed from grain in 1 h is:

$$= 4922.0 \text{ kg} \times 0.0002 \text{ kg/kg} \qquad (B.8)$$

$$= 0.98 \text{ kg.}$$

Then the energy consumed to remove 1 kg of water from wheat is calculated using (B.7) and (B.9) values, thus:

$$= 4.03 \text{ MJ}/0.98 \text{ kg}$$

$$= 4.2 \text{ MJ/kg.}$$