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Preserving quality during grain drying and techniques for measuring grain quality

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Abstract

In most years and in most countries grain is dried to safe storage moisture content using different drying systems, i.e. natural air drying, near-ambient (low temperature) drying, high temperature drying, and dryeration. During natural air and near ambient drying detrimental effects on grain quality can be avoided if drying can be completed within the allowable safe storage time which depends on the initial moisture content of grain and weather conditions. During high temperature drying detrimental effects on grain quality can be avoided if grain is not heated beyond critical temperature. If grain is heated beyond critical temperature due to dryer type or improper functioning of dryer then end use characteristics of grain can be severely affected. Dryeration combines high temperature drying with low temperature cooling and results in better quality grain than high temperature drying for the removal of the same amount of moisture. Further research is needed to develop effective control strategies to optimize dryers for grain quality, uniformity of drying, and energy efficiency. Research is also needed to develop dryers which operate quietly, discharge less pollutants, and are economic.

Key words: heat damage, grain quality, high temperature drying, near-infrared spectroscopy, machine vision, storage.

Introduction

Globally around 2.4 billion tonnes (Gt) of grains, oilseeds, and legumes (hereinafter referred to as grains) are produced annually (Faostat, 2006). The grains need to be stored safely until consumed. Safe storage of grains can be accomplished by manipulating two important physical factors: temperature and moisture content (Figure 1), provided the grains are not invaded by insects, mites, rodents, or birds (Jayas et al., 1995). Grains stored at high moisture and high temperature spoil fast (Figure 1). The spoilage can be measured by several factors including the end use of the grain. But a drop in germination, presence of visible mould, increase in free fatty acids, amount of carbon dioxide produced, or a combination of two or more of these factors are commonly used. Drop in germination seems to occur first and therefore, is considered as the most sensitive parameter. The width of zone of short-term storage and values for the axes labels for temperature and moisture content in Figure 1 are dependent on the type of grain and the factor being used to measure spoilage. For example,

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moisture content for storing wheat safely for more than a year under temperate climate is 12-13 % wet basis (w.b.) but for canola (an oilseed crop) it is 8-9 % w.b.

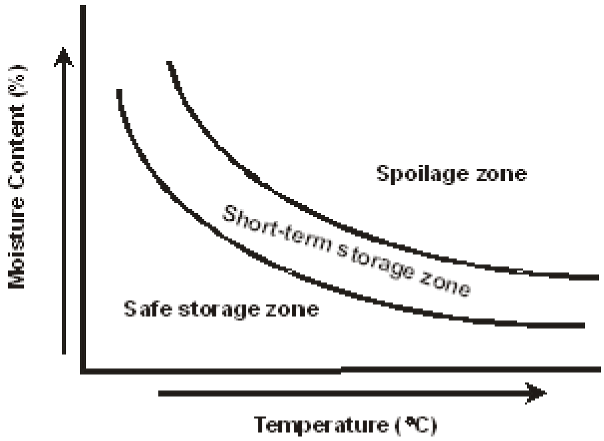

Figure 1. Relationship between temperature and moisture content for safe storage of grain.

Grains are usually harvested at a high moisture level to avoid shattering losses and to reduce the growing season where two or more crops are grown in a year. Sometimes, undesirable rain also forces the farmers to harvest the grains at high moisture level. Therefore, drying is a most common practice to artificially remove the moisture from the harvested grain to attain a moisture content for safe storage. A list of safe storage moisture contents for storing grains up to one year in Canadian prairies is given in Table 1 (CGC, 1993).

Drying of grains prevents microbial growth and slows enzymatic changes and considerably increases the storage life. It also reduces grain mass; thus, facilitating its transportation, and handling. Drying of grains is commonly accomplished by forcing air through the bulk grain at different temperature: natural (ambient) temperature, near-ambient temperature, low temperature, and high temperature. In the natural-air drying, ambient air is used without heating to remove the excess moisture from the grain. In near-ambient drying, the temperature of the ambient air is raised by 1 to 5 °C from frictional losses of the fan and motor assembly. In low temperature drying, the ambient air is heated by 5 to 15 °C using external sources of energy (e.g., electricity, fossil fuels, solar energy). In high temperature drying, air is usually heated to about 50 to 200 °C based on the initial moisture content of the grain, the end use of the dried grains, and the type of dryer. Maximum temperatures of grain during drying for different end uses are given in Table 2 (Hall, 1980). This paper briefly describes the working principles of commonly used high temperature dryers, effects of high temperature on quality changes in grain, steps to be taken to avoid detrimental effects on grain due to drying, and methods to determine grain quality factors.

Table 1. Upper limit of safe moisture contents for storing grain up to one year under Canadian prairies (Compiled from CGC, 1993).

Crop	Moisture Content[1] (% w.b.)
Wheat	14.5
Oats	14.0
Barley	14.8
Rye	14.0
Flaxseed	10.0
Canola and rapeseed	10.0
Mustard seed	9.5
Peas	16.0
Lentils	14.0
Fava Beans	16.0
Buckwheat	16.0
Triticale	14.0
Corn	15.5
Soybeans	14.0
Sunflower seed	9.5
Safflower seed	9.5

[1] For long-term storage (>1 year) in well-engineered structures, the moisture content should be 1 to 3 percentage points less than the values listed in this table.

Table 2. Maximum safe temperature (ºC) of grain during drying for various end uses (Hall, 1980).

Crop	End Use		
	Seed	Sold for Commercial Use	Animal Feed
Ear Corn	43	54	82
Shelled corn	43	54	82
Wheat	43	60	82
Oats	43	60	82
Barley	41	41	82
Sorghum	43	60	82
Soybeans	43	49	-
Rice	43	43	-
Peanuts	32	32	-

Working principles of high temperature dryers

Convective Dryers

In all high temperature dryers which use hot air to dry grain heat is mainly transferred by convection from air to grain and by conduction within grain. Air is also used to carry the removed moisture. The hot air dryers are mainly classified as batch, recirculating, and continuous-flow dryers based on the flow of grains inside the dryers (Pabis et al., 1998). In batch dryers, farmers can dry various types of grains in batches of shallow thickness by forcing air typically at an airflow rate of 125 (L/s)/m^3 to obtain faster drying. Two types of batch dryers are normally used, on-floor dryers where grains are dried on the floor and roof-type in which grains are dried on a cone-shaped perforated floor near the bin roof. A large selection of dryer assembly can be possible for these dryers however, a considerable moisture gradient is produced in the bed from bottom to top. The recirculating dryers are the advanced batch dryers with a central auger system to recirculate the grain from the bottom to the top to avoid the production of a large moisture gradient and also to unload the grains from the bin after drying. These dryers produce a uniform drying however grains are more susceptible to breakage due to continuous auguring. In the continuous-flow dryers, grain flows continuously through the dryer and there is a relative movement between the grain and drying air.

Continuous-flow dryers are usually classified into four subclasses based on the relative movement of grain and air flow: cross-, concurrent-, countercurrent-, and mixed-flow dryers. In the cross-flow dryers, grain and air move in perpendicular directions (Figure 2a). The major disadvantage of this dryer is the development of high moisture and temperature gradients across the grain column as drying proceeds, which causes stress-cracks and thus the quality of the grain deteriorates. Developments in the design of the cross-flow dryer have focused on minimizing the temperature and moisture gradients across the grain column. For this, reverse airflow cooling or drying or both, grain column inverting, slotted plenum panels and differential cross-flow drying have been evaluated and found effective to some extent. Recently, Sukup Manufacturing Company, Sheffield, Iowa developed a dryer (Figure 2b) where columns of grain cross over and this results in more uniform drying. In the concurrent-flow dryers (Figure 3a), grain and air move in the same direction. Typically most of the commercial concurrent-flow dryers have two or three concurrent drying zones separated by tempering zones and a counter-flow cooling zone. This design allows use of high air temperatures (Table 3) because hot air comes in contact with wet grain and due to evaporative cooling, grain temperatures below those given in Table 2 can be maintained.

This design also minimizes the development of the temperature gradient between the grain and the air because the grain is cooled in the counter-flow cooler and thereby reducing the formation of stress-cracks in the grain. Although the capital cost for these dryers is very high compared to the cross-flow or mixed-flow dryers but the grain quality is superior. Bakker-Arkema et al. (1977) showed that wheat dried in a commercial two-stage concurrent-flow dryer at air temperature ranging from 150 ºC to 218 ºC did not lose its baking quality. In the countercurrent dryers (Figure 3b), grain and air flow move in the opposite directions. The hot air enters at the driest region of grains and leaves at the wettest region. Therefore, drying-air temperature has to be selected such that it should be safe in terms of the end use of the dried grain. These types of dryers are frequently in-bin dryers with fully-perforated floors and air moving upward and dried grain being removed with an auger at the bottom. Because of the limitation on the air temperature, these dryers are not commonly used. In the mixed-flow dryers (Figure 4), grain is dried by a mixture of cross-, concurrent-, and countercurrent-flow processes. Grain flows over a series of alternating inlet and exhaust air ducts of different designs in different mixed-flow dryers (Pabis et al., 1998). Since grains can be well mixed in these types of dryers and not exposed to the drying air temperature for long time, the drying air temperature in the mixed-flow dryers is higher than in cross-flow dryers but lower than in concurrent-flow dryers (Table 3). Brooker et al. (1992) recommended drying air temperature range of 65-85 °C for food grains in the mixed-flow dryers. Bakker-Arkema and Maier (1995) compared an average effect of the dryer types on the drying-air temperature, the maximum grain temperature, and the percentage of stress-cracks in the corn kernels (Table 3). Similar results were obtained by Montross et al. (1999) for corn drying. They reported that the dryer type has more influence than the drying air temperature on the stress-crack development or on the breakage susceptibility.

The dryeration process or combination drying consisting of high-temperature drying and aeration is an advantageous process since grains can be exposed to the high temperature drying followed by tempering and then cooling using aeration. Stress-cracks development is reduced due to the tempering

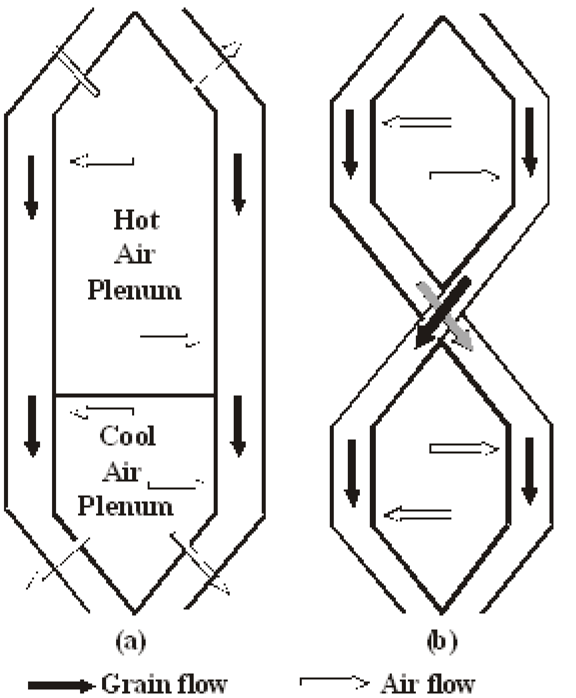

Figure 2. Schematic diagrams of different dryer designs; (a) cross-flow dryer, (b) Sukup double cross-over flow dryer.

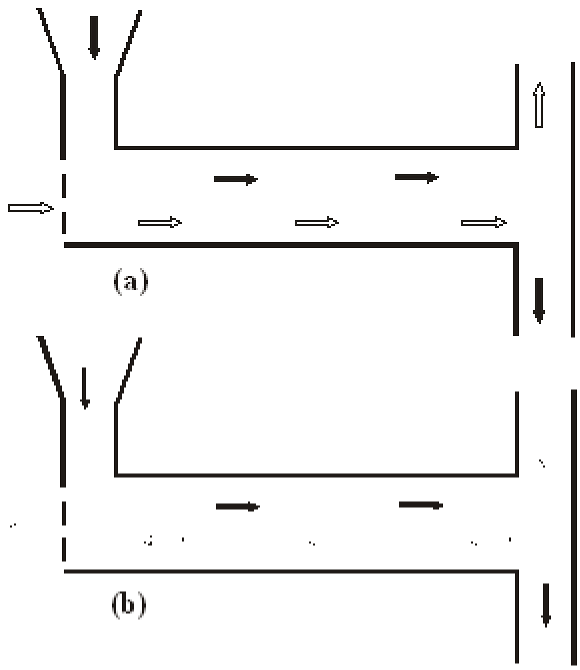

Figure 3. Schematic diagrams of different dryer designs; (a) concurrent-flow dryer, (b) countercurrent-flow dryer (refer to Figure 2 for description of arrows).

Table 3. The average effect of dryer type on the drying-air temperature, the maximum grain temperature, and the percentage of stress-cracked kernels in corn (Bakker-Arkema and Maier, 1995)

Dryer Type	Drying-Air Temperature (°C)	Maximum Grain Temperature (°C)	Stress-Cracked Kernels (%)
Cross-flow	80-110	80-110	70-85
Mixed-flow	100-130	70-100	40-55
Concurrent-flow	200-285	60-80	30-45

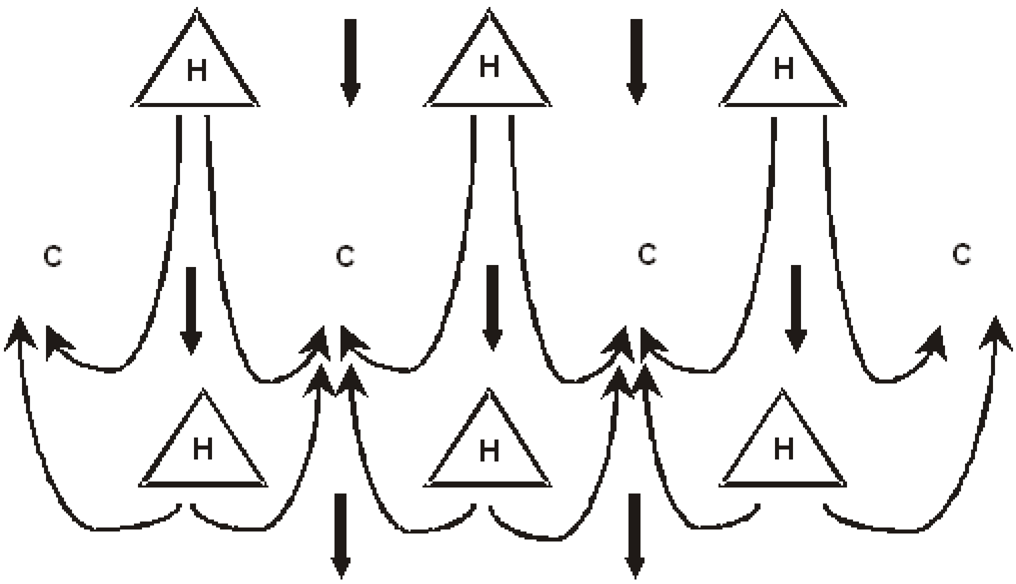

Figure 4. Schematic diagram of a mixed-flow dryer. Thicker arrows indicate grain flow, thinner arrows airflow, H hot air duct, and C exhaust air duct.

process (Cnossen and Siebenmorgen, 2000). Aeration allows maintaining uniformity in the grain temperature which helps in reducing the moisture migration inside the grain bulk due to temperature differences. It further helps in removing unpleasant odors and in venting fumigants. Dryeration process is thermally efficient than conventional drying and rapid cooling.

Dryers at the research stage

Some other kinds of dryers, currently mainly used for research on grain drying and have the potential to be used by industry, are: fluidized bed dryers, spouted bed dryers, microwave and infra-red dryers. Fluidized bed drying can produce homogeneously dried grain in a very short time because grains are suspended in a hot air moving at a high velocity (2-3 m/s). Paddy bed of 100 mm thickness can be dried using fluidized-bed dryer from 24 % to 18 % moisture in 15 min at a drying air temperature of 100 °C and an air-velocity of 2 m/s, without any adverse effects on the quality (Sutherland and Ghaly, 1990; Tumambing and Driscoll, 1991). Disadvantages of the fluidized bed dryers include high power requirements for producing the fluidization velocity. In addition, thermal efficiency of these dryers which can be increased by recycling the exhaust air, is low as compared to the conventional air dryers. The spouted-bed drying technique is almost similar to the fluidized bed technique but requires less airflow because whole grain bed is not suspended. Ghaly et al. (1973) employed a high temperature (93 ^{o}C) spouted-bed drying technique to dry wheat kernels from 17 % (w.b.) to 12 % without affecting the baking quality. In microwave drying, grains are irradiated by electromagnetic energy which generates a high thermal potential between the interior of the grain and the surrounding air so that moisture moves faster from the grain into the air. This process would minimize the air-flow requirements and a uniform drying can be achieved within a short time. However, operational cost due to high energy requirement is very high which prevents the adoption of this technology over conventional air drying systems (Radajewski et al., 1988). Further, microwave energy can significantly affect the physical and biochemical properties of grains when heated above certain critical grain temperature than that of drying air (e.g., germination capacity of wheat severely decreases at grain temperature above 60 ^{o}C) (Okazaki and Ishihara, 1980).

In infra-red drying, additional medium should be used to agitate the grain kernels to expose total surface area of the grain kernels, which further increases the cost of operation. Considering the relative disadvantages of these dryers, conventional hot air dryers are mostly used in the different grain industries.

Grain quality

Grain quality cannot be defined specifically for a particular grain. Several factors such as uniformity and soundness of the kernels, test weight, amount of foreign material in grain, breakage susceptibility are used to characterize grain quality for a particular end use of a grain type. For example, for bread wheat, milling and baking characteristics are important; for corn yield of grits and flour during dry milling and yield of starch during wet milling are important; for malting barley, germination is important; for paddy, head-rice yield is important; for pulses, quality of protein and cooking time are important; and for oilseeds, yield and quality of oil are important. Further, grain quality of individual grains vary significantly, therefore, grain quality is determined based on a representative small (1-2 kg) sample of bulk grain. Quality of grain is affected by various environmental factors during the crop production period, harvesting conditions, post-harvest conditions (e.g., drying), grain storage conditions, and transportation and handling procedures. One or more of the factors given in Table 4 can affect grain quality.

Not all of the factors given in Table 4 are important from the end-user's point of view. Some of these factors are used in grain grading standards but most are used in marketing. Office of Technology Assessment in the United States compared the grading standards of Argentina, Australia, Brazil, Canada, France and US (Anonymous, 1989) and Hulasare et al. (2003) compared grain-grading standards of the US and Canada. These two reports give further details on the grading factors used by various countries.

Effect of high temperatures on grain quality factors

Not all of the grain quality factors given in Table 4 are affected by drying. Test weight, physical damage, stress-crack susceptibility, milling and baking characteristics, oil quality, and head-rice yield can be adversely affected by improper drying using high temperature air, and the expected effect is briefly described below.

Test weight of grain is expressed as mass of grain required to fill a standard volume and is expressed as kg/hL (lb/bu). Although test weight may not be the best indicator of the end use quality but higher test weight usually implies better quality and it is easy to measure, therefore, it is used in grain grading standards. Test weight is a function of grain moisture content. Grain harvested at high moisture and dried properly gives higher test weight than field dried grain of the same moisture content. But damaged grain due to unacceptable

Table 4. Factors affecting grain quality.

Baking characteristics	Mycotoxins
Carcinogen content	Nutritive value
Contamination from birds and rodents	Oil content
Cooking time for pulses	Oil quality
Dockage	Physical damage, e.g., discoloration, breakage, shrinkage
Foreign material content	Protein content
Head-rice yield	Protein quality
Insect infestation	Seed germination
Milling quality	Stress-crack susceptibility
Moisture content	Test weight
Mold content	

heating gives lower test weight (Brooker et al., 1992).

Physical damage, e.g. breakage, discoloration or shrinkage are very important issues associated with the drying of grain to maintain acceptable quality standards. The high speed of drying in the heated-air dryers may cause damage to the grain kernels. Interior or exterior stress cracks develop in the grain kernels due to the creation of temperature and moisture gradients during drying which causes an adverse effect on oil or starch recovery (Watkins and Maier, 2001). Head-rice yield is reduced due to increased stress cracks and yellowing of rice is more due to improper drying (Cnossen and Siebenmorgen, 2000). High temperature of oilseeds results in darker oil causing an increase in refining cost. Brooker et al. (1992) classified stress cracks as single, multiple, or checked with two or more intersecting cracks. Montross et al. (1999) showed that number of these cracks for corn dried in mixed-flow, cross-flow and 3-stage concurrent-flow dryers were different (Table 5). In a cross-flow dryer, the breakage susceptibility of corn is high near the air inlet of the grain column (Table 6) and increases with a decrease in the average final moisture content to which corn is to be dried (Table 7). Stress-cracking is not prevalent in the small grains (e.g, wheat, barley, oats, and rapeseed) (Nellist and Bruce, 1995). Removing moisture from grain in small increments, tempering grain or both reduce stress cracks.

Milling process separates the grain components for further processing into usable products. For example, milled wheat flour is used in baking. Too high temperature of wheat kernels can cause denaturation of the gluten proteins which adversely affects the baking quality. The major quality criterion for wheat is loaf volume which is decreased if wheat is heated beyond safe temperature. Walde et al. (2002) have indicated that microwave drying of wheat kernels before grinding can reduce power consumption in the milling operations.

Excessively high temperature kills the germ and results in reduced germination capacity. Poor germinating seeds have detrimental effects on their end uses (e.g., in malting of barley or for

Table 5. Average type of stress cracks and stress cracked percentage of corn dried in three types of dryers (Montross et al., 1999).

Dryer types	Single (%)	Multiple (%)	Checked (%)	Stress-cracked (%)
Cross-flow	3.4	38.6	45.8	87.8
Mixed-flow	8.0	32.5	25.0	65.5
3-Stage Concurrent-flow	5.8	27.1	19.7	52.6

Table 6. Grain temperature, moisture content, and breakage susceptibility at different locations in grain columns of a conventional cross-flow dryer after drying corn without cooling from 25.5 % to an average of 19 % (w.b.) at 110 ºC (Brooker et al., 1992).

Distance from Air Inlet (cm)	Grain Temperature (ºC)	Moisture Content (% w.b.)	Breakage Susceptibility (%)
1.25	102	10	48
7.50	78	20	11
13.75	51	24	10

seed purposes). Safe drying temperature can be decided based on the initial moisture content of the grain and the residence time in the dryer. Recommended drying temperature range to maintain seed viability is about 38-43 °C (Table 2). Seed damage usually occurs when grain temperature exceeds the critical grain temperature. The highly moist kernels can retain their viability when dried in a concurrent-flow dryer even at a higher temperature drying since the kernels do not reach the high temperature.

Control strategies

Grain drying has significant effects on the quality of grains (e.g., head yield of rice, cracking of corn, milling and baking qualities of wheat, and oil content from oilseeds). To maintain the grain quality after drying and to maximize throughput at optimal energy efficiency, different control strategies have to be adopted for the operation of different dryers. In near-ambient air drying, amount of airflow needed to dry grain depends on grain type, grain volume, harvest date and initial moisture content of grain. The airflow can be controlled using simple on-off switch based on the time of the day to more sophisticated systems taking into consideration the progress of drying and the changing weather conditions (Ryniecki et al., 1993a,b; Epp et al., 1997). Since intermittent airflow can cause severe increase in the dry matter loss, continuous airflow is recommended until the drying front reaches the surface of the grain bed after which airflow can be controlled to maintain the grain moisture content.

In high-temperature dryers, several parameters such as grain discharge rate, drying air temperature, airflow rate, and grain temperature at the dryer discharge affect the target moisture content. Altering the grain discharge rate is a commonly used practice to effectively control the moisture content of the grain. Measurement of discharge grain temperature is also used for controlling grain dryers. Care, however, must be exercised so that the temperature sensor is not exposed to wind or to solar radiation. Exposure of the sensor to wind will decrease the sensed temperature and could result in over drying of grain whereas exposure of the sensor to solar radiation could stop drying early. In-line moisture sensors which can accurately sense the moisture of hot grain would be the best way to control the dryers but such sensors are not yet available. Therefore, in the high temperature dryers, effective heater control is an essential design consideration. Different dryer control systems are explained by Brooker et al. (1992). A model predictive controller for industrial cross-flow grain dryers has been developed by Liu and Bakker-Arkema (2001) for better accuracy and stability. There is an increasing demand to optimize the dryer control strategy to achieve effective drying with efficient energy use considering variable environmental conditions. Computer simulations of different grain drying models play a significant role in optimizing the dryer control strategy with efficient drying. Grain drying is usually accomplished either in a thin-layer or in a deep-bed. Various semi-theoretical and empirical models describing the thin-layer (a single grain kernel or one layer of grain kernels or a polylayer of many grain thickness) as well as the deep-bed (more than 20 cm deep) drying process for

Table 7. Effect of the average final moisture content on breakage susceptibility of 25 % moisture content (w.b.) corn dried in a conventional cross flow dryer at 110 ºC (Brooker et al., 1992).

Final Average Moisture Content (% w.b.)	Breakage Susceptibility (%)
18	11
15	18
13	27
11	39

specific grains have been reviewed and compared (Jayas et al., 1991; Cenkowski et al., 1993; Pabis et al., 1998; Parde et al., 2003; Ghosh et al., 2004).

Measurement of degrading factors

The measurement methods of various quality degrading factors have been standardized and adopted by several countries (CGC, 1993; Jayas and Cenkowski, 2006). With the advancement in new technologies, researchers have been trying to use different equipment for effectively measuring the grain quality parameters. Most of the grain quality inspection throughout the world is currently done by the visual inspection and thus is inherently subjective. Only a limited number of factors, for example test weight, moisture content, protein and oil content, amount of dockage, loaf volume can be measured objectively. But measurement of some of these factors is very time consuming such as flour yield, loaf volume, head-rice yield. Therefore, there is a need for automated grain quality inspection equipment which can measure the end use quality quickly on a consistent basis.

The development of near-infra red (NIR) system for measuring moisture, protein and oil content in grains has made the measurement of these quality factors objective (Kawamura et al., 2003; Martens et al., 2004) and has been adopted by the industry. The NIR spectroscopy has replaced the chemical intensive Kjeldahl method for the protein quantity measurement in many countries. For proper functioning of the NIR system, large amount of reference data from different growing regions should be used for calibration. Once properly calibrated, it is a rapid technique requiring small sample size. NIR spectroscopy is also being investigated for measuring hardness and vitreousness of grain kernels, grain color classification, identification of damaged grain, detection of insect and mite infestation, and detection of mycotoxins (Singh et al., 2006). Machine vision system along with statistical or artificial neural network classifiers for pattern recognition are being investigated to determine varietal purity, class identification, impurities or foreign matters, grain kernel morphology, grain discoloration, stress cracks, insect damaged kernels (Shatadal et al., 1995; Majumdar et al., 1996, 1999; Crowe et al., 1997; Luo et al., 1997, 1999; Nair and Jayas, 1998; Jayas et al., 2000; Wan, 2002; Jadav and Jindal, 2001; Brosnan and Sun, 2002; Wang et al., 2003; Visen et al., 2003; Paliwal et al., 2003). This list of references is not exhaustive. Soft X-ray systems are being investigated for quantifying stress cracks, hidden insect infestation by internal feeders, insect damaged kernels, and sprouted kernels (Karunakaran et al., 2003a,b; 2004a,b). Transmitted light systems are used for quantifying stress cracks in grains. Susceptibility of breakage during grain handling can be measured with hardness testers.

Although grain dryers have been developed over several decades and are used around the world, there is still a need to further improve the dryers. For example, theoretically the mixed-flow dryers should give more uniform final moisture content but it is not the case in practice (Table 8). This could be because dryers are not designed

Table 8. Average moisture content, kernel moisture-content range, and standard deviation of corn dried in 1994 (compiled from Montross et al., 1999).

Dryer Type	Drying-Air Temperature (°C)	Inlet Moisture Content (% w.b.) Average	Inlet Moisture Content (% w.b.) Range	Outlet Moisture Content (%w.b.) Average	Outlet Moisture Content (%w.b.) Range
Cross-flow	90	21.8	11.0-34.5	13.9	8.0-30.5
Mixed-flow	125	19.3	10.5-33.0	15.7	8.5-33.5
Concurrent-flow (3-stage)	275,220, 225	21.8	11.0-34.5	16.4	8.0-33.0

as they should be for airflow distribution and for dryer control. Further research and better understanding of drying process is needed. Unfortunately, most agricultural engineering programs, at least in Canada and United States, are moving away from grain drying research because funding for such research is not easy. There is a need for the grain industry to come forward to work with academic community to further research in this area.

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