ECOSYSTEM OF BAGGED GRAIN STORED UNDER NATURALLY VENTILATED WAREHOUSE: ANALYSIS AND MODELLING

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Dr. Donald Colliver, Director of Graduate Studies
ECOSYSTEM OF BAGGED GRAIN STORED UNDER NATURALLY VENTILATED WAREHOUSE: ANALYSIS AND MODELLING

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering and the College of Agriculture Food and Environment at the University of Kentucky

by

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Lexington, Kentucky
2020

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ABSTRACT OF DISSERTATION

ECOSYSTEM OF BAGGED GRAIN STORED UNDER NATURALLY VENTILATED WAREHOUSE: ANALYSIS AND MODELLING

Grain in Africa and indeed most developing parts of the world are stored in polypropylene or jute bags arranged in stacks of varied dimensions in naturally ventilated warehouses. This practice is however, associated with high postharvest losses due to poor temperature and moisture management during storage. This constitutes a major economic and food security challenge in these countries. Therefore, this study characterizes changes in moisture content and temperature occurring in a stack of bagged corn by determining the permeability of bag materials which influence moisture transfer and developing a mathematical model of heat and mass transfer which incorporates the unique physical and thermal properties of bagged corn in storage.

Water vapor transmission rate and permeability of woven polypropylene bags and jute bags increase with an increase in vapor pressure deficient of the storage environment. Water vapor transmission rate was linearly correlated with vapor pressure deficit. The development of a monitoring device capable of acquiring temperature and relative humidity data from specific locations within the stack and its deployment for field use is also discussed in terms of providing data for analyzing the bagged grain ecosystem and also for validating the mathematical model.

A comprehensive analysis of the effect of changing environmental conditions on temperature and moisture distribution as well as insect population in bagged corn is discussed. Small stacks of bagged corn (54 bags of 40 kg capacity arranged in two stacks) and a large stack (192 bags of 40 kg capacity) stored under naturally ventilated warehouses in Nigeria and US respectively were used. Generally, bagged corn temperatures followed the trends of the air temperature surrounding the bags with no differences between individual bags in the small stack. Moisture content increased uniformly in the small stacks and the warm conditions within the bags encouraged proliferation of insects, of which maize weevil *Sitophilus zeamais* was the most predominant. These contributions are unique as it marks the first time that temperature and moisture distribution in a stack of bagged grain is critically studied for the purpose of improving management.

Validation of the mathematical model was performed with experimental data from the two storage studies. There was a close agreement between the predicted and experimental data in terms of describing the temperature distribution within the stack of bagged corn, although predicted temperatures in the small stack showed higher standard errors. The average standard error between the experimental and predicted temperatures was 1.2 °C (0.8 to 2.1 °C). The average standard error between the measured moisture content and predicted equilibrium moisture content (EMC) was 1.0 percent point (0.8 to 1.1 %). The prediction accuracy of the model was improved with use of experimental values for physical and thermal properties of bagged corn. The monitoring systems and mathematical model will contribute to improved management of bagged grain in naturally ventilated warehouses.
KEYWORDS: bagged grain, food security, monitoring, postharvest losses, storage, temperature and moisture distribution

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12/20/2020
Date
ECOSYSTEM OF BAGGED GRAIN STORED UNDER NATURALLY VENTILATED WAREHOUSE: ANALYSIS AND MODELLING

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12/20/2020
Date
DEDICATION

To God the giver of all things who lifted me from a miry clay and set my feet on the solid rock.
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Although I had worked tirelessly throughout my PhD program, this dissertation, benefited from the insights and direction of several people. First, my Co-Director of Dissertation, Dr. Samuel McNeill, who has been a great help and role model for me right from the time we first met in Nigeria back in 2009 and throughout the dissertation process. I would like to thank my other Co-Director of Dissertation, Dr. Michael Montross for his insightful comments and evaluation at every stage of the dissertation process. I also wish to thank the other Dissertation Committee members, Dr Michael Sama for his assistance with the instrumentation component of this research and Dr. Ric Bessin, for providing additional insights for this work.

Special thanks to Doug Carr who spent several hours on coding and assembling the operation of the monitoring system.

I appreciate all other people and colleagues that I have meet here at University of Kentucky who have made my stay in the US worthwhile, especially John Croft of Immanuel Baptist Church, Lexington, KY and his wife, Cherry and, Tabitha their daughter.

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Now to the king of kings and the Lord of Lords who saved my life and give me inheritance among those that are being sanctified, to him alone be all the glory for this great feat.
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<thead>
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<tbody>
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<td>a</td>
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<tr>
<td>k</td>
<td>thermal conductivity (W m(^{-1}) K(^{-1}))</td>
</tr>
<tr>
<td>t</td>
<td>time during which weight change occurred (days), also present time (sec)</td>
</tr>
<tr>
<td>t+1</td>
<td>future time</td>
</tr>
<tr>
<td>x</td>
<td>material thickness (m), also actual sensor relative humidity (percent)</td>
</tr>
<tr>
<td>y</td>
<td>adjusted sensor relative humidity (percent)</td>
</tr>
<tr>
<td>A</td>
<td>area of material (m(^2)), also material dependent property for EMC equation</td>
</tr>
<tr>
<td>B</td>
<td>material dependent property for EMC equation</td>
</tr>
<tr>
<td>C</td>
<td>material dependent property for EMC equation</td>
</tr>
<tr>
<td>Cp</td>
<td>specific heat of bulk grain (J kg(^{-1}) K(^{-1}))</td>
</tr>
<tr>
<td>D</td>
<td>weight of damaged grains (kg), also mass diffusivity (m/s)</td>
</tr>
<tr>
<td>D(_{eff})</td>
<td>effective diffusivity (m(^2)/s)</td>
</tr>
<tr>
<td>Dm</td>
<td>mass diffusivity (m(^2)/s)</td>
</tr>
<tr>
<td>D(_v)</td>
<td>diffusivity of water vapor in air (m(^2)/s)</td>
</tr>
<tr>
<td>EMC</td>
<td>equilibrium moisture content (percent dry basis)</td>
</tr>
<tr>
<td>ERH</td>
<td>grain equilibrium relative humidity (decimal)</td>
</tr>
<tr>
<td>E(_0)</td>
<td>Evaporation rate (kg m(^{-2}) h(^{-1}))</td>
</tr>
<tr>
<td>Ep</td>
<td>(m(^3) of air/m(^3) of grain volume)</td>
</tr>
<tr>
<td>G</td>
<td>cumulative mass of water loss (g)</td>
</tr>
<tr>
<td>G(_W)</td>
<td>initial mass of grain (g)</td>
</tr>
<tr>
<td>G(_D)</td>
<td>Final mass of grain (g)</td>
</tr>
<tr>
<td>H</td>
<td>height of stack (m)</td>
</tr>
<tr>
<td>Lx</td>
<td>width of stack (m)</td>
</tr>
<tr>
<td>Ly</td>
<td>height of stack (m)</td>
</tr>
<tr>
<td>MCwb</td>
<td>moisture content (percent)</td>
</tr>
</tbody>
</table>
N  number of spatial elements
Nd  number of damaged grains
Nu  number of undamaged grains
Ps  saturation vapor pressure (Pa)
Pv  vapor pressure (Pa)
R  Gas constant
RH  relative humidity (percent)
$R_v$  water vapor gas constant (J kg$^{-1}$ K$^{-1}$)
T  grain temperature (°C)
Tf  floor temperature (°C)
To  initial grain temperature (°C)
Tk  grain temperature (°K)
Tkr  room temperature (°K)
Tr  room temperature (°C)
$T_{(i,j)}^n$  temperature of grain element (i, j) at t (°C)
$T_{(i,j)}^{n+1}$  temperature at future time (°C)
U  weight of undamaged grains (kg)
W  width of stack (m)
$W_g$  grain equilibrium moisture content (decimal dry basis)
$W_{g(i,j,t)}^n$  grain equilibrium moisture content of element (i, j) at time t
$W_{g(i,j,t)}^{n+1}$  grain equilibrium moisture content of element (I, j) at time t+1

Greek Symbols
$\alpha$  thermal diffusivity (m$^2$/s)
$\epsilon$  porosity of grain bed (m$^3$ of air/m$^3$ of grain volume)
$\omega$  change in partial pressure due to change in temperature at constant moisture content (Pa K$^{-1}$)
$\rho_g$  bulk grain density (kg m$^{-3}$)
$\sigma$  change in partial pressure due to change in moisture content at constant temperature (Pa)
$\tau$  tortuosity factor
CHAPTER 1. INTRODUCTION

1.1 Importance of grain storage in developing countries

Food is essential for survival of all living things and adequate and affordable food is critical in ensuring food security worldwide. Grain is the most important food component in developing countries. It plays a pivotal role in ensuring food and nutrition security in the region (Awika, 2011). The entire population of Africa, and indeed Nigeria, depends on grain for meeting the majority of their daily food requirement (IPBO, 2017).

Corn is the most important grain in the region due to its importance in providing daily calories and nutrition. According to the FAO (2010), more than 70% of farmers in the developing world produce corn in the region. This shows that, livelihood of these farmers and their families depends on ensuring adequate yield and minimal losses along the postharvest value chain to ensure that they reap the maximum benefit of their labor.

1.2 The role of grain storage in ensuring food security

According to the FAO (2006), “Food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. Thus, sufficient food has become an important index in the poverty rating of any country. While many countries in Europe and America can be said to have made tremendous progress in ensuring that a large proportion of their population have access to food in the desired quantity and quality to meet food and nutritional security, the same cannot be said of many developing countries (Aragie & Genanu, 2017; Awika, 2011; Cardoso et al., 2017). Because grains are not produced throughout the year, the surplus during harvest must be preserved for
future use. Effective grain storage is thus, an important aspect of ensuring food security, especially in developing countries where postharvest food losses are high (Adeyeye, 2017). Globally, postharvest food loss is a major constraint to the attainment of food security with almost a third of food produced being lost annually (an estimated 1.3-billion-ton worth about US $1 trillion) (Gustavsson et al., 2011). Postharvest losses have aggravated food insecurity in many developing countries especially in Sub-Saharan Africa (SSA) where many farming households also suffer loss of income and decrease in livelihood (Onyekwena, 2019; Sheahan & Barrett, 2017; Tesfaye & Tirivayi, 2018). Effective grain storage systems are key to providing a continuous food supply, fighting against chronic food insecurity, managing food crises and increasing income of food producers (Galtier, 2018).

A major challenge of food preservation and storage in warm climates and in Nigeria as a typical example is insect infestation and attacks by molds and rodents (Degri & Zainab, 2013). The environmental conditions of the country support the growth of many stored grain insect pests and molds. According to Fields (1992), stored grain insect pests will thrive in an environment with a temperature range of 25-33 °C. Equilibrium relative humidity (ERH), or water activity, within the grain bulk is important to minimize mold degradation. Spoilage occurs most readily above ERH values of 65% (Yaouba et al., 2012). These conditions are very common in tropical and sub-tropical climates. Climatic conditions in the US and Europe allow for grain to be cooled below the optimal temperature range of stored grain pests that limits losses.

In Nigeria, the weather condition varies in the different agro-ecological zones across the country. Ilorin, located in the northern part, is a semiarid climate (Figure 1.1).
The temperature is usually very warm year-round, which makes insect development a major challenge. The southern part of the country enjoys more rain and is humid for most of the year with high temperatures (Figure 1.2). These conditions predispose grain to spoilage due to mold and insects as a result of insufficient drying capacity. These conditions are partly responsible for the poor performance of metal silos, where moisture migration and condensation lead to caking of stored grains resulting in large losses. These challenges are very similar in other developing countries that have a high ambient temperature and relative humidity year-round.

Figure 1.1 Average climatic condition of Ilorin, Northern Nigeria (Altitude: 307 m)
Source: (ClimaTemps.com)
1.3 Rationale for this research

About 70% of grains produced in Nigeria are stored on-farm by farmers living in remote parts of the country without dedicated storage infrastructure (Umeh, 1994). As a result of this, the common practice is to store grains inside jute or polypropylene bags that fit within the low production levels. These bags are used for grain storage at the farm level, market level and even in warehouses. Even though these bags have been reported to offer little protection to the grains against moisture transport, the magnitude of moisture redistribution that can occur as a result of water vapor permeability of the bag materials have not been reported in the literature. Also, very little information is available in the literature on the ecosystem of grains stored in jute or polypropylene bags thus limiting management decisions on controlling insect and mold losses.
Temperature and relative humidity conditions within the bags will vary with the surrounding air due to the vapor pressure differential. In situations where high temperature and high relative humidity persist for more than a month, which is very common in tropical climates, grain will often gain moisture and become infested with insects and molds. Thus, making the grain unfit for human consumption.

Environmental control (air conditioning in warehouses) in tropical countries is too capital intensive and requires a huge quantity of energy which is beyond the reach of common farmers. Insect control using chemical protectants has thus become the traditional approach to limiting insect damage. Though this has been effective to a large extent, problems of overuse and abuse of insecticides have led to cases of pesticide resistance, grain contamination from unapproved chemicals, high chemical residues in food grains and even death in a few cases (Okoruwa et al., 2009). Aside from this, treated grains stored in bags, in most cases, are held in various structures without a monitoring system for tracking the quality of the stored product. This is due to lack of awareness of the importance of monitoring in keeping the quality of stored grains. On the other hand, the cost of monitoring devices available in the market is beyond the reach of the resource-poor Nigerian farmers. Monitoring could involve many variables including; temperature, moisture content, carbon dioxide levels, moisture condensation, surface crusting and insect population on a regular basis. Monitoring is important for early detection of grain spoilage problems, pest infestation, determination of population dynamics and evaluation of pesticide applications. Thus, there is a need for proper storage strategies as well as cost effective and efficient monitoring systems at the farm and warehouses levels to maintain
the quality of stored grain. This is will ensure effective control of insect pests and reduce losses due to mold growth.

To be able to achieve this, effective and affordable monitoring devices need to be developed for farmers, grain handlers, and warehouse managers. This will assist in the analysis of the storage conditions (temperature and moisture distribution, mold development, and insect development) of grains stored in bags. Proper monitoring systems will allow farmers and warehouse managers to decide when to re-dry or sell their grains to minimize losses due to insects and molds.

The application of predictive models as decision tools has led to improvement in the management of grain quality during storage. Predictive models have been developed for monitoring heat and mass transfer in silos (Thorpe, 1997) and grain bags (Arias Barreto et al., 2013; Gastón et al., 2009). They have also been successfully applied for monitoring grain and insect respirations as well as insect population dynamics during storage (Flinn et al., 1992; Flinn et al., 2010; Mani et al., 2001; Ochandio et al., 2017). Application of predictive models for moisture and temperature distribution in bagged-grain storage systems will be a useful tool for maintaining grain quality and preserving food supplies.
CHAPTER 2. OBJECTIVES

2.1 Project Goal

The main goal of this research is to evaluate losses in stacks of bagged maize stored in a naturally ventilated warehouse without temperature and humidity control and its dependence on the initial condition of maize and environmental conditions. The overall grain conditions (temperature and moisture content) will be predicted and validated. A sensitivity analysis of the parameters that influence storage will be conducted with the goal of effectively managing maize quality to reduce postharvest losses and provide food security.

2.2 Specific Objectives

The specific objectives of this project are:

i. To determine water vapor permeability of bag materials used for grain storage

ii. To develop a monitoring system to assess the internal environment of bagged maize stored under naturally ventilated warehouse, specifically focused on high ambient temperature and relative humidity.

iii. Measure the effects of changing ambient conditions on the moisture content and quality of bagged corn stored under naturally ventilated warehouses in Ilorin, Nigeria and Lexington, KY USA.

iv. To develop a mathematical model that predicts the heat and mass transfer in bagged corn stored in a naturally ventilated warehouse.
v. Validate the prediction model using data collected from laboratory and field trials set up under objective (iii) and determine the sensitivity of storage parameters on the predicted results.

Development of an effective monitoring system, analysis of the ecosystem of grains stored in polypropylene bags and the application of a predictive model will improve grain handling and storage practices worldwide and consequently lead to a reduction in storage losses.
CHAPTER 3. LITERATURE REVIEW

3.1 Grain production and utilization in developing countries

Cereal grains are major crops grown by farmers across developing countries due to their importance in meeting their nutritional needs and calories (Awika, 2011). Maize, rice, sorghum, millet, and wheat are the most important cereal grains grown in Africa. Although, maize, rice and wheat are the most important crops in the world, millet and sorghum are very important in providing daily calories in semi-arid parts of Africa and India (Awika, 2011). Nigeria is the largest producer of sorghum in the world accounting for about 85% of the global production (FAO, 2010).

Even though millet and sorghum have been reported to be superior to maize in terms of nutritional value and health benefits (Awika & Rooney, 2004; de Morais Cardoso et al., 2017; Taylor & Duodu, 2015), production of these two important crops have been on decline in most developing countries including Nigeria (Awika & Rooney, 2004; National Research Council, 1996). Cereals grains are mainly consumed as food in most developing countries with between 60 and 80% of the populations daily calories derived from direct consumption of these crops. This is in contrast to developed countries which only derive about 30% of calories from cereal grains (WHO, 2003). Cereal crops in developed countries also contribute indirectly to human nutrition as they are used as livestock feeds and for other industrial products.

Maize has arguably become the most important cereal grain in Africa and about 90% of it is consumed directly as food (FAO, 2018). As a result, its production has been on the rise especially in Nigeria (Figure 3.1). Although wheat is used for confectionery products, wheat production in Nigeria and Africa at large is minor in comparison to the
global production. As shown in Figure 3.1, Consequently, the country has relied on importation to meet the demands for wheat based products such as bread, biscuits and pasta (USDA, 2019). Sorghum and millet production declined sharply after 2008 with millet production hovering just about 1 MT a year.

Figure 3.1 Cereal grain production in Nigeria between 2000 and 2016 (FAO, 2018).

3.2 Grain handling and storage practices in developing countries

Grain storage in developing countries is largely influenced by low production levels, environmental conditions, and infrastructures. Due to the low production levels, harvesting is done manually while postharvest processing such as threshing, and winnowing has been mechanized to a large extent at central facilities. Farmers stored about 70% of their grains in various types of traditional storage structures (Pradhan, 2014; Sharon et al., 2014). Various types of traditional storage structures made of mud or twined straw are used as granaries in many developing countries.
Traditional methods used for grain storage at the farm and domestic level include; cribs and rhumbus, platforms, open fields, roofs, gourds, earthenware pots and fireplaces (Kamala et al., 2016; Mishra et al., 2012). Rhumbus are typically built from local materials (mud or crop stalks). This storage structure performs better in dry areas where there is no serious concern with the storage of wet grains (Figure 3.2). In the humid areas of developing countries, grain cannot be completely dried before storage. Structures that keep the stored commodity well ventilated during storage such as storage basket cribs and ventilated cribs are used (Figure 3.3). These storage practices are, however, associated with insect infestations and other forms of spoilage.

Figure 3.2 Traditional grain storage structure-Rhmbu in Nigeria
Improved grain storage systems include improved rhombus, ventilated cribs, and metal bins. Mini metal silos which hold 1 metric ton of grains has been promoted by food and agricultural organization of the United Nations (FAO) in Africa and Latin America and by the Federal Ministry of Agriculture’s Strategic Grain Reserve Agency in Nigeria (Figure 3.4). The silo is filled from the top and covered with a metal lid which can be sealed with tape to ensure the structure is airtight. Grains needed for household use are collected periodically through the spout and is resealed. Although the Federal Ministry of Agriculture under the Agricultural Transformation Agenda (ATA) distributed mini silos to
farmers across the country, the adoption rate was poor, and the idea has since been jettisoned.

Figure 3.4 Metal silos (1 mt) for distribution at Jos, Nigeria (Photo by S. McNeill, Sept. 24, 2009)

Unlike the traditional structures, the rhumbu is built on a stone support to prevent rodent attack while the cross ventilation in the crib aids drying of the grain and limits the development of molds. However, high postharvest losses and aflatoxin contamination have been reported in the traditional and improved storage techniques (Udoh et al., 2000).

Modern and commercial grain storage techniques include warehouses, conventional corrugated steel silos, and inert atmosphere systems. In the warehouse storage system, bagged grains in woven polypropylene sacks are arranged on pallets and stored in a building specifically constructed for storage purposes. In most cases the storage period is usually less than six (6) months. The walls are typically masonry with a corrugated steel roof, and no environmental control of the building environment. Metal silos are used by
government agencies, commercial farms and feed mills while the inert atmosphere storage system is still relatively new in the country, though it was first introduced over three decades ago.

The shortage in storage infrastructure in developing countries of the world has been identified as a crucial factor in reducing post-harvest losses (Hodges et al., 2010; Sheahan & Barrett, 2017). According to Kumar and Kalita (2017), effective grain storage has the advantage of contributing to increased food security without bringing more land area under cultivation by minimizing postharvest losses and enhancing marketing.

The use of polypropylene and jute bags for grain storage has been an age long practice in Africa and parts of Asia. Bag storage is popular due to advantages in handling, transportation and storage on small scales. Many of the rural roads linking farms to major towns are in a deplorable state. This makes it difficult for large tucks that transport grain in bulk to access most production areas. Apart from this, lack of specialized vehicles for transporting and handling bulk grain in cities is also a major hurdle. Furthermore, most of the grains produced by subsistence farmers with small farm holdings are stored on–farm or in their houses, thus large bagged (and bulk) storage facilities are not readily applicable (Manandhar et al., 2018).

Woven polypropylene bags, which usually hold 100 kg of grain, has become a standard unit for handling, transporting and marketing of grains at all levels. However, woven polypropylene bags do not offer protection against air and moisture migration as well as insect, rodent, and mold attacks. It has been reported that post-harvest losses in grains stored in polypropylene bags ranges between 19.2% and 47.7 % with considerable loss in seed germinability (Baoua et al., 2014; De Groote et al., 2013; Ognakossan et al.,
According to Kumar and Kalita (2017), postharvest loss in the rice value chain in Nigeria stood at about 24.9% (40% higher than what is currently recorded in most developing countries in Asia) and is estimated at about 156.2 million USD. This suggests that losses in other grains may be much higher because rice is not one of the crops that is susceptible to postharvest losses.

3.2.1 Insect infestation

Insects that attack many stored agricultural commodities, referred to as “stored-products insects” are significant in grain storage management. Stored-products pests cause serious damage to stored grains, dried root and tuber crops and have been reported to account for more than 20% of storage losses in developing countries (Phillips & Throne, 2009). Some of the common stored-products insects that are of importance are listed in Table 3.1. These losses are aggravated by inadequate storage structures coupled with poor grain management and sanitation which give the insects easy access to foods, thus encouraging their multiplication (Pradhan, 2014). Estimated postharvest losses (by dry weight) in cereal grains produced in some selected African countries are shown in Figure 3.5 (APHLIS, 2019). Postharvest loss in maize ranged between about 16% in Mali and 20% in Ethiopia. Average losses in sorghum and rice is about 12% in all the countries while average losses in millet is about 11%. The high losses in maize is not unconnected to the quantity being produced in these countries.
Figure 3.5 Estimated dry weight losses in some cereal grains in selected African countries in 2019 (APHLIS, 2019).

<table>
<thead>
<tr>
<th>Name</th>
<th>Common names</th>
<th>Crops attacked</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Sytophillus zeamais</em> (M.)</td>
<td>Maize weevil, greater grain weevil</td>
<td>Maize, dried cassava, yam chips, sorghum</td>
</tr>
<tr>
<td><em>Prostephanus truncates</em> (H.)</td>
<td>Larger grain borer, great grain borer</td>
<td>Maize, dried cassava</td>
</tr>
<tr>
<td><em>Tribolium castaneum</em> (H.)</td>
<td>Red flour beetle</td>
<td>Flour, beans, nuts, seeds</td>
</tr>
<tr>
<td><em>Rhyzopertha dominica</em> (F.)</td>
<td>Lesser grain borer, wheat weevil, grain weevil</td>
<td>Maize, wheat</td>
</tr>
<tr>
<td><em>Sytophillus oryzae</em> (L.)</td>
<td>Rice weevil</td>
<td>Rice, maize, wheat, barley</td>
</tr>
<tr>
<td><em>Sitotroga cerealella</em> (O.)</td>
<td>Angoumois grain moth</td>
<td>Maize</td>
</tr>
<tr>
<td><em>Callosobruchus maculatus</em> (F.)</td>
<td>Cowpea weevil</td>
<td>Cowpea, groundnut</td>
</tr>
</tbody>
</table>

Adapted from (Opit, 2016).

Of all the insects listed above, maize weevil is the most predominant in many of the traditional storage structures used on the farm and in markets (Holst et al., 2000). Maize weevil is a species of the beetle family Curculionidae found in all warm and tropical parts of the world (Throne, 1994). Adult maize weevil and larvae damage grains by chewing and are a serious threat to food security in the tropics. Infestation usually starts in the field.
and continues in storage (Ojo & Omoloye, 2016). Adult females chew into maize kernels and lay an egg inside the kernels and cover the hole with a mucilaginous secretion (Meikle et al., 1999). In most cases one egg is laid per kernel. Most of the adult life of the females (up to one year) is spent laying eggs (300 – 400 per female), although most of the eggs are laid within the first 4-5 weeks. Eggs are creamy white while the larvae are white, fleshy and legless. The immature stages (egg, larva and pupa) are rarely seen because they are hidden in the kernel feeding on the internal parts of the grain. This makes it difficult to detect infestation at the early stage. Adults which are usually 3 -3.5 mm long emerge from the grain leaving large holes with irregular edges on the hulls and excrete powdery white frass. Adults can live for about four to eight months (Mason & McDonough, 2012). Development time ranges from about 35 days under optimal conditions (27 °C) to over 110 days at 18 °C (Throne, 1994). However, the life cycle can be completed in 26 days at a temperature of 30 °C and relative humidity of 75% (Okelana & Osuji, 1985). The population of S. zeamais infesting stored grain at a given time depends on the initial population at harvest (especially when maize is not treated before storage), immigration of other insects into the store and the rate of multiplication of the insects infesting the grain during storage.

3.2.2 Strategies for reducing storage losses

Most of the storage techniques highlighted above are not effective in minimizing losses due to insects, molds, and rodents. Research has shown that improved handling and storage practices such as the use of metal silos and hermetically sealed bags are capable of reducing postharvest losses in food grains at all levels (Kumar & Kalita, 2017).
The most common method of controlling insects in stored grain is based on chemical control. Synthetic insecticides are applied to grains during storage to control insect pests. Although insect control using synthetic chemicals have been successful there are a number of issues, which include health hazards, environmental contamination and insect resistance (Rajendran & Sriranjini, 2008). Consequently, researchers have now focused on the new plant-based alternatives that pose limited harm to humans and livestock and are environmentally friendly.

In Africa, plant materials have also been used for the control of stored products insect. Rajendran and Sriranjini (2008) enumerated a host of plants and their extracts that have been used as a protectant against several stored products pests. Essential oils from plant extracts have also been used by other authors (Olivero-Verbel et al., 2013; Paes et al., 2012) that have shown promise. Maize weevil suppression using plant extracts have shown promising results at laboratory levels (Okonkwo & Ewete, 2000; Udo, 2005). However, research on plant-based insecticides in Africa is focused on efficacy studies, with limited data on mammalian toxicity and commercialization prospects as well as the bioactivity of the proposed phytochemicals. This clearly suggests that a lot of research is still needed in the area of biological materials for the control of stored product pests.

Another attempt which has shown a promising result is the use of inert dusts which damages the exoskeleton of insects causing them to lose body moisture and eventually die. These dusts can be obtained from finely ground stones, such as marble and dolomite and applied on grains. A more interesting approach is the use of diatomaceous earth dust (DE) a natural resource found in selected localities around the world. Nigerian derived DE has proven to be effective in the control of stored insect pest such as maize weevil (Sitophilus
zea mais) and cowpea beetle (Calosobrocus maculatus) (Nwaubani, 2006; Nwaubani et al., 2014; Otitodun et al., 2015). The main drawback of DE is that they cause an increase in bushel weight and can damage processing equipment. Environmental impacts of DE are debated which has limited the use of DE as insecticide on a commercial scale.

Recently, research efforts have focused on the use of biological control using parasitic insects to prey on stored products pest insects. Infestation of one species of stored products pest can influence the development of other species in two different ways if the environmental condition (temperature and relative humidity) is conducive and food availability is not limited. In one way, when stored cereal is infested for instance by the lesser grain borer, *Rhyzopertha dominica* (Coleoptera: Bostrichidae) a primary pest, which can damage kernels, red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae) which is a secondary pest can infest the grain causing more damage. These two species can continue to increase in population if the environment is favorable and food availability is not limited. The other form is the development of parasitoid insects which will infest grain in order to feed on the primary pests. Thus, the presence of the parasitoid pests limits the population of the primary insect pests. Increase in population of *T. castaneum* and *R. dominica* in silos in Kansas, was reported by Nansen et al. (2009). In the same study, it was reported that with the presence of the rusty grain beetle, *Cryptolestes ferrugineus* (Coleoptera: Laemophloeidae) the population of the other two species decreased. Papanikolaou et al. (2018), also reported that the population of live insects decreased in maize infested with *R. dominica* and *P. truncates* when compared with samples infested with either of the insects in single species treatment.
Adarkwah et al. (2012), studied the potential of controlling maize weevil in maize stored in jute bags using wasps. They reported that although some parasitism was observed, based on the reduction in the number of maize weevils in the bags, the activities of wasp decreased with the depth of grain. Although this area of research shows promising results, it remains an area for entomologists in the developing world to explore.

Reports of extensive research on the use Purdue Improved Cowpea Storage (PICS) bags in some countries in Africa have shown that hermetic bags are effective in reducing storage losses and maintain germinability of seeds (Amadou et al., 2016; Baoua et al., 2014; Williams et al., 2017). Additionally, its ability to limit insect attacks and mold growth makes it a superior alternative to the polypropylene bags (Darfour & Rosentrater, 2020). However, despite promising results, these technologies are yet to be fully adopted by farmers in many regions in Sub-Saharan Africa (World Bank, 2011). While the technology has performed exceptionally for safe storage of grains meant for household consumption, farmers still need a better alternative for storage of medium to large scale harvest at the aggregators and market levels for improved income (Darfour & Rosentrater, 2020). Issues identified with the use of PICS bags relative to polypropylene bags are; its small size (holding about 70 kg which is less than the standard 100 kg), the average cost of the bag (about ten-fold higher than polypropylene bags), and high skilled labor required to effectively tie the bags. The PICS bags are thus less attractive to farmers and grain aggregators dealing with thousands of bags (Nouhoheflin et al., 2017).

Conventional silos have had limited success in Nigeria and indeed most tropical countries compared to experiences in North America and Europe. This is due to the problem of moisture migration and condensation due to tropical climate and limited energy
infrastructure in most of the developing world. Unlike in the temperate and subtropical climates where aeration is effectively used to cool grain during storage, this is not achievable in the tropical climates due to lack of cold weather (Agboola, 2001). Additionally, though many of the silo complexes in Nigeria are equipped with aeration systems, the lack of dependable electricity has made them unreliable. Consequently, losses due to mold, caking and insect infestation are prevalent. Apart from this, the high initial cost has greatly deterred farmers from adopting even small (1 mt) metal silos.

Inert atmosphere storage in conventional silos was introduced in Nigeria in the early 80s. This storage system utilizes sealed silos with a modified atmosphere where the normal atmosphere has been replaced with either nitrogen or carbon dioxide (Navarro & Calderon, 1980). This controls the activities of degradation agents in the stored commodity. As opposed to the conventional silos, the system does not require the use of synthetic chemicals. Nitrogen or carbon dioxide gas is released into the silos eliminating oxygen in the process thereby creating an inert condition within the bin. This makes it difficult for insects (at any of their life cycle stages) to survive. The airtight condition of the bin also limits moisture migration and condensation which leads to mold infestations and caking in common storage structures. According to Agboola (2001), an inert atmosphere silo was successful in controlling insect infestation and moisture migration, thus eliminating storage losses in grains. The technique is also effective for controlling beetle infestation in cowpea (Babarinsa et al., 2017) and has the potential of reducing mold and aflatoxin contaminations in grains (Escobedo-Avellaneda & Welti-Chanes, 2016; Kumar & Kalita, 2017) and preventing loss of food reserves (Janardhana et al., 1998). Despite the enormous merits highlighted above, high initial cost, lack of awareness and limited promotion by the
government has limited the use to silos operated by government agencies and a few large commercial farms and feed mills in Nigeria (Okonkwo et al., 2018).

The challenges identified in the various strategies attest to the fact that polypropylene bag storage will continue to be the most used medium for grain storage.

3.3 Impact of environmental condition on grain storage ecosystem

The components of the grain ecosystem consist primarily of the storage structure containing the stored grain and the various biotic and abiotic factors their interactions and, the external factors acting on the structure (Jian & Jayas, 2012; Navarro, 2006). The biotic factors of the grain ecosystem consists of the stored grain, insects and microorganisms while the abiotic factors include; temperature, relative humidity, wind, and solar radiation (Figure 3.6). A good understanding of the interaction among the various factors allows researchers to identify potential areas of intervention for enhancing storage. Environmental conditions change throughout the year and these changes affects the microclimate and quality of stored grains in bins, flat storage, silo bags, bags in warehouse and other traditional structures.
Figure 3.6 Components of the ecosystem of grain in a sealed bin (Navarro, 2006)

The goal of management is to limit the impact of the fluctuations in ambient environment on the stored products while at the same time taking advantage of the conditions for maintaining the quality of stored grain. For instance, in Europe and North America, during winter when the daily temperatures are near freezing, quality of stored grains are maintained at optimum. Additionally, insect pests are not active and do not impact the stored commodities. However, the situation is different in tropical climates where the weather is usually warm throughout the year. Under those conditions, high temperature and relative humidity cause moisture migration and condensation in metal silos while at the same time encouraging multiplication of insects.

Lane and Woloshuk (2017), studied the influence of changing storage environment on the microenvironment and quality of corn stored in PICs and woven polypropylene
bags. Dried grain (at 14% moisture content) samples weighing 40 kg were placed in the bags. *Aspergillus flavus* inoculated satchels and non-inoculated satchels were introduced into the bags and they were monitored for a period of three months. They reported that, though the temperature and relative humidity in the bags tracked that of ambient, PICs bags prevented a moisture content increase and insect infestation while in the moisture content and number of infested kernels increased in grain stored in woven polypropylene. Also, warm weather increases the chance of insect infestation.

However, it should be noted that, bags used in this study were arranged as single layer and were not stacked. There is a possibility of getting a different result especially for woven polypropylene bags when stacked, which is the normal practice by farmers.

### 3.4 Mechanisms of moisture movement in stored grain

Moisture transfer in hygroscopic substances such as grain is usually associated with a number of physical, thermal and at times biological processes. The physical and thermal mechanisms include liquid diffusion, vapor diffusion and thermal diffusion while the biological process is a result of respiration of the grain and insect activities which results in the release of carbon dioxide, water and energy. According to Navarro (2001), moisture transfer in bulk grain is through any of the following;

i. Diffusion of moisture through inter-particle contact, that is conduction

ii. Diffusion of moisture due to vapor gradients in the grain bulk

iii. Translocation of moisture due to convection currents
iv. Exchange of water vapor with the atmospheric air occurring at the surface of the grain.

Water can also be transferred through openings in the storage structure (leakage) or condensation occurring inside the surfaces of the silo which then falls on the grain.

Moisture transfer is driven by thermal gradients, vapor gradients, and moisture gradients. Thermal gradients develop due to seasonal variation in ambient temperature and cause moisture migration in stored grains or can cause natural convection airflows. Vapor gradients results from the differences in vapor pressure exerted by water vapor in the air surrounding the grain and the moisture in grain itself. Moisture content of stored grain increases when the vapor pressure in the intergranular air surrounding the grain is greater than the vapor pressure exerted by the moisture within the grain. Conversely, grain loses moisture when the vapor pressure exerted by its moisture is greater than the vapor pressure in the intergranular air surrounding the grain. Moisture gradient exist as a result of the differences in moisture in a grain bulk induced by thermal or vapor gradient. Therefore moisture migration can be considered as water vapor transport due to diffusion and convection with the grain moisture acting as source term (Khankari et al., 1995; Khankari et al., 1994). In non-aerated storage, convection air currents and diffusion can cause disproportionate movement of moisture which can results in grain caking, crusting and eventual spoilage (Montross & Maier, 2001). It is therefore an important task in grain storage management that acceptable temperature and moisture distribution is ensured in grain bins (Markowski et al., 2007).
In bagged grain storage systems, this phenomenon seldom occurs due to convection around the stack maintaining the equilibrium within the stack. In most cases, temperature stratification within the grain stack is not enough to induce water vapor transport. Condensation is not common due to the permeability of the bags causing water vapor to evaporate from the bags at the peripheral layers.

3.5 Grain moisture and temperature measurement during grain storage

It is important to measure grain moisture prior to storage because it plays a crucial role in its storage stability, quality and the sale weight. Grain must be stored at the appropriate moisture content usually referred to as the safe moisture content in order to maintain its quality during storage. Grain temperature is inversely correlated with its moisture content. Grain moisture content and temperature also influence the distribution of insects and fungi which causes grain spoilage (Jayas & Jeyamkondan, 2002; Navarro, 2001). However, as the temperature and relative humidity of the air in the interstitial space of the stored grain changes, the safe moisture also changes. As illustrated in Figure 3.7, while high moisture grain can be safely stored at a low temperature without serious deterioration, only low moisture grain should be stored at high temperature. Therefore keeping the temperature and the relative humidity at optimum levels ensures that grain are kept at the desired condition that guarantees good sales (Uddin et al., 2006).
Grain moisture is measured using direct methods or indirect methods. The oven drying method which is regarded as the most accurate method involves measuring weight changes in a convection oven using a standard scale (ASABE Standards, 2007). Other direct methods are based on drying using microwave or infrared technology.

Temperature cables have been used to monitor the grain condition in large storage bins. These sensors usually consist of thermocouples attached to a small diameter steel cable at predetermined intervals, with the cable attached to the roof of the bins. In some cases, relative humidity sensors have also been used in similar system. The outputs of the thermocouples and or relative humidity sensors are collected at a central location and the data can be used to predict the future condition of stored grains (Schwab et al., 1991). One of the advantages of the monitoring cables is that they are placed permanently in the bins and do not interfere with loading and unloading of the grain.
Indirect methods measure the electrical properties or chemical composition of grains and then convert it to moisture content. Most commercial moisture meters use indirect methods. Because of their simplicity, versatility, and speed of measurement they have become widely used in the field and at storage locations. The equilibrium relative humidity technique has also been successfully used in determining the moisture content of grains. This technique involves measuring the equilibrium relative humidity of the air in the interstitial spaces of grains and the temperature, then the moisture content is calculated using an Equilibrium Moisture Content (EMC) model (Chen, 2001). The availability of inexpensive sensors that can measure temperature and relative humidity with good accuracy has led to the development of various sensors that have been applied for monitoring moisture content of grain (Armstrong & Weiting, 2008), tea (Chen et al., 2014) and wood products (Tangirala et al., 2010). Although the ERH of various crops are affected primarily by the drying temperature, variety and the agro-ecological conditions (Chen, 2000), it has also been reported that the relative humidity of the air within the grain bulk has a significant effect. At a relative humidity greater than 80%, the prediction errors are large for most sensors (Uddin et al., 2006).

Chen (2001), evaluated the accuracy of a temperature and relative humidity sensor (Model Shinyei THP-B7T, Shinyei Kaisha Co., Tokyo, Japan) in measuring the EMC of corn and rough rice based on ERH technique. The manufacturers rated accuracy of the sensor was 0.5 °C and ± 3.0 % r.h. with measurement range of -10 to 60 °C and 20-95% for temperature and relative humidity, respectively. The sensor was, however, calibrated to improve its accuracy with the temperature calibrated using an ice bath and the relative humidity calibrated using several aqueous salt solutions. The sensor’s accuracy was 1%
point of the measured moisture content of rough rice and corn used in the study. Chen et al. (2014), reported that calculated EMC of the same type of sensor when used for Oolong tea was within 0.5 wb (wet basis) of the moisture content determined by oven drying method. However, relative humidity and moisture content of the material should be below 70% and 15% wb respectively for the desired accuracy to be achieved.

Ward and Davis (2013), developed a system for monitoring the internal environment in a large grain bag (silo bag, holding between 250 - 375 MT of grain). The system consisted of linear arrays of Type-T high-precision thermocouple wires (Omega Engineering, Inc., Stamford, Conn.) and humidity sensors (HM1500LF, Humirel, Inc., Chandler, AZ) attached to a food grade C-channel and installed in the silo bag to monitor the condition of corn and soybeans stored in separate bags (Figure 3.8 Monitoring grain temperature and relative humidity in silo bag. (a) silo bag with grain (b) the schematic of the monitoring unit (Ward & Davis, 2013)

b). The system adequately described the condition of the stored grain and showed that changes in temperature and relative humidity of grain internal environment significantly affected the quality of stored grains. The main challenge with the monitoring of grain condition in silo bags is the lack of rigid structure to which the monitoring system can be permanently attached. Thus, the system must be installed after the bags have been loaded with the point of insertion sealed to prevent water from entering the grain and removed before unloading to avoid damaging it. Additionally, the system is prone to rodent attack which can either damage the cables shown Figure 3.8 which will cause loss of data or they can bore through the bags.
The circumstances encountered in woven polypropylene bag systems is different than that of silo bags. In warehouse grain storage system, grains are stored in 100 kg bag with the individual bags arranged in large stacks.

![Figure 3.8 Monitoring grain temperature and relative humidity in silo bag. (a) silo bag with grain (b) the schematic of the monitoring unit (Ward & Davis, 2013)](image)

Commercial moisture meters such John Deere™, DICKEY-john™, agraTronix™ are widely used by farmers and feed millers across Europe and America. Many farmers in the developing world, however, cannot afford these systems thus limiting them to relying on their experiences in ascertaining the condition of stored grain. With this in mind, Armstrong et al. (2017), developed a low-cost probe type instrument for measuring the moisture content of grain based on the equilibrium relative humidity (ERH), which were first tested in Ghana and Nigeria in 2014. To measure the EMC of grains, the probe is inserted into polypropylene or jute grain bags where the sensor equilibrates to the grain environment, after approximately 6 minutes the moisture content is determined. As with all ERH technique-based moisture meter, it is required that the air surrounding the grain and the grain are in equilibrium for accurate measurement. The first version of the instrument produced cost about 100 USD and continuing efforts have been made to bring
the cost down. The probe is easy to use and is calibrated for most grains grown in Africa. They reported that there was a good agreement between measured moisture content and the moisture content determined by oven drying methods.

This technology is now been commercialized in Africa under the brand name “GrainMate” by a company in Ghana (Sesi Technologies, 2018). The company has made several modifications to the initial version, and it is now being sold in Nigeria, Ghana, and some East African countries where USAID has sponsored postharvest loss prevention projects. While the product has not been promoted as a moisture monitoring device, it is a valuable tool that will allow farmers and grain handlers in Africa to know the moisture content of their grains before storage (Sesi Technologies, 2018). A major challenge with the use of the EMC probe is that it can only be used for measuring moisture content of grains at a specific time and not suitable for monitoring the trend in the moisture during the entire storage period. The grain bags must be opened or pierced each time a measurement is taken when used with bagged grain, this creates openings in the bag which must be properly sealed to avoid a point of entry for insects, spoilage, and spillage.

It is therefore necessary to develop a system that is not only accurate and affordable but also with the capability of providing the temperature and relative humidity profile of bagged grain during storage.

3.6 Grain storage models

In order to maintain the quality of grain during storage and identify active deterioration the temperature and moisture content distribution and rate of change within the grain bulk must be known. Currently, this is only possible by conducting experiments during which regular measurements and samples are taken and analyzed. However, it is
expensive and time consuming (Abe & Basunia, 1996; Jia et al., 2000). With good knowledge of the physical and thermal properties of the stored grain, storage structure and the environmental condition, mathematical models allowed researchers to accurately predict grain conditions. Predictive models are very important in managing and evaluating grain storage systems. Models have been effectively applied for studying the ecosystem of grains stored in silos, and flat storage structures. Models for predicting temperature and moisture content of grains stored in silos, warehouse and silo bags abound in the literature.

Iguaz et al. (2004) modeled heat and mass transfer in rough rice under unaerated conditions. The model used the coupled effect of moisture transfer on heat transfer to predict the temperature of rough rice. Although there was good agreement between the predicted and observed temperatures, the model under-predicted the temperature at all points considered in the grain mass.

A combination of a thermodynamics model and spatial stochastic process was used to predict the interior temperatures of a cubic shaped grain storage warehouse by Wang and Zhang (2015). They incorporated changes in ambient temperature using a sinusoidal segmentation to predict the internal environment of the warehouse while a thermodynamic model was applied to the heat transmission within the walls of the warehouse. A 3-D unsteady state heat transfer was then integrated into Gaussian Markov random field with which they were able to characterize the variations in the interior temperatures in the warehouse. Changes in ambient temperature, solar radiation, and heat transmission within warehouse walls were successfully applied. The results showed that the interior temperature of the warehouse changes slowly in a sinusoidal trend with a smaller fluctuating range compared to the ambient. However, it was not clear if grains were stored
in bulk or in bags. Temperature gradients induce natural convection currents that can lead to spoilt grains, typically found at the center of bins or grain piles due to moisture migration (Jian et al., 2009).

All the previous research deals with a confined environment (silo wall) where the rate of exchange between stored grains and the ambient air is restricted to the grain having direct contact with the storage container and minimal moisture transfer. In the headspace (top of the bin between the grain surface and roof) where there is free exchange between the grain surface and the headspace. The bottom of the silo could be a plenum that would function like the headspace or concrete floor. However, in polypropylene bag storage systems, the bag material provides some moisture resistance and there is additional void space in between stacked bags resulting in a channeling effect into the stack. The warehouse environment the bags are stored in will fluctuate with the ambient conditions and will impact the storage conditions within the bag stack.

Research efforts in Nigeria have focused on the performance of silos and the impact of the changing environment on proximate composition and germinability of stored grains. Performance of silos made of different structural materials (termite mound clay, reinforced concrete and galvanized steel) under humid tropical environment have been studied (Omobowale et al., 2015). Their results showed that temperature inside the silos changes with a lag as the ambient temperature changes. Relative humidity in the silos increased during the storage period with a negative impact on the proximate composition of the stored maize. Moisture content of maize stored in termite-mound clay silo and concrete silo increased significantly after 8 months of storage. Galvanized steel silo however, had minimal moisture addition during the same period. Proximate compositions were similar
for maize stored in the 3 types of silos up to 8 months. Protein content in the termite-mound clay silo was, however, significantly lower than others. These results suggested that termite-mound clay and concrete silos are not suitable for long term grain storage under a humid tropical environment.

The effect of ambient temperature on the temperature distribution inside inert atmosphere silos filled with two cultivars of wheat grown in Nigeria was studied by Ajayi et al. (2016). They reported that the mean temperature at the center of the silo was lower than that at the top. This limits the effects of moisture migration resulting from the movement of warm air from the center of the bin to the upper part of the silo. The result suggested that the inert environment within the silo protected the stored wheat from the impact of changing environmental condition. This was confirmed by another study on storage of brown cowpea (Babarinsa et al., 2017). In both studies, there was no significant loss of quality in the commodities stored for 30 months. Even though the storage period span through wet and dry seasons, no moisture condensation was observed in the silos throughout the storage period. However, as earlier discussed, even though the system has proven to be effective, the possibility of adopting the system by farmers across the country remains uncertain.

There have been few attempts at predicting the condition of granular material stored in polypropylene bags. A mathematical model, using forward difference in the time integration with the finite element method for the spatial distribution was used to simulate the moisture profiles of ‘gari’ (granulated cassava flakes) by Igbeka (1987). The governing equations were developed based on conservation of mass and Fick’s law of diffusion. ‘Gari’ having an initial moisture content of 10% w.b. was in hessian and jute bags (1.0 m
long and 0.6 m wide). The bags were stored under four different environmental
temperatures and relative humidity (30°C & 60%, 30°C & 75%, 35°C & 60% and 35°C
&75%) for 180 days. Moisture content values obtained from the experiment were used to
validate the model. The predicted values show good agreement with the observed values
for 90 days after which there was a serious divergent. The moisture content in the jute bag
increased significantly while there was a marginal increase in the hessian bag. This was
due to the differences in the permeability of the bag materials. Although the author pointed
out the significance of permeability of the bag materials in moisture diffusion, he failed to
state values used and how they were determined. Apart from this, values of other
parameters used in the equations were not stated which makes it difficult to verify the
submissions of the author. Although this gives a basis for predicting the moisture of grains
stored in bags, the results need to be verified. The model cannot be applied to stacks of
grain bags which is the practical situation.

3.7 Insect population models

The behaviors of many stored products insects have been extensively studied by
scientists across the world (Athanassiou et al., 2008; Jian et al., 2006). Observations
gathered from these studies have led to the development of various methods for controlling
insect activities during storage (Athanassiou et al., 2017; Fields, 1992). Various models
have also been developed to study the population dynamics of various species of insects.

Researchers have simulated the population dynamics of *S. zeamais* using
distributed delay models which is an approach that allows inferences from data obtained to
be extended in order to explain certain behavior or occurrences within the process being
modeled. Important factors in predicting insect populations are; grain moisture content,
temperature and relative humidity of the intergranular air in equilibrium with the grain.
The earliest work was reported by Dobie (1974) who carried out a laboratory assessment of the development of the stages of *S. zeamais* on selected cultivars of maize. He fitted data obtained in the studies using linear regression to express the relationships between population growth and the important environmental factors. Recent efforts have extended the outputs of the models using data from recent laboratory studies to give better predictions (Meikle et al., 1999; Throne, 1994).

*S. zeamais* population dynamic model essentially consists of regression equations describing; the relationship between progeny production and food availability, environmental factors and duration of insect development, delay process for the development of the immature stages, the survival rate, mortality rate and the overall population growth.

Throne (1994), studied the life history of *S. zeamais* on maize stored at constant temperature and relative humidities. Maize samples used for the study was collected from southeastern United states and fumigated with phosphine after which it was frozen at about -2 °C for two weeks to ensure a complete kill of all insect stages present. Maize lots were placed in 5 cages constructed from clear acrylic tubes with lids and base covered with nylon screen to allow for ventilation. Maize was equilibrated to test condition for 6 weeks. *S. zeamais* culture maintained at 25 °C and 65 – 70 % were held in cages containing maize before they were used on the test maize samples. This condition was chosen because it is close to optimum condition required for development of maize weevil. Progeny of *S. zeamais* collected from the field were added monthly to the culture to ensure that the culture is close to what is obtainable in the field. The cages were placed in boxes containing saturated salt solutions to maintain the required relative humidity over the range of temperatures used. The whole setup was put in an environmental control chamber maintained at 30 °C and photoperiod of 12:12 (L:D) hour. Maize were then infested with female weevils (2-3 weeks old). Insects were sieved from cages after 2 days with a US standard no. 6 sieve. Three weeks after females were removed, emerging F₁ progeny were
then sieved from the maize samples every 84 hours. The test was then repeated twice using 1-2 weeks old females. Duration of development was determined at temperature (10, 15, 20, 25, 30, 35, and 40 °C) over three saturated salt solutions (NaCl, NaBr, K₂CO₃) to maintain 75 -76, 53-63 and 43% relative humidity respectively.

Regression equations derived from the laboratory data are summarized as

Equation [ 3.1 ]

\[ Progeny = \alpha + \beta e^{-\gamma \text{weight}} \]  

where,

progeny is number of progeny produced, weight is weight of maize (g), \( \alpha = 40.21 \), \( \beta = -21.48 \), and \( \gamma = 0.01265 \).

The relationship between equilibrium moisture content (calculated from grain temperature and the relative humidity of the air in the intergranular space within the grain) is given by (Meikle et al., 1999)

Equation [ 3.2 ]

\[ EMC = 0.523h - 0.00967h^2 + 0.0000706h^3 \]  

where,

EMC is equilibrium moisture content, and h, is relative humidity (%).

Effects of temperature and relative humidity on duration of development was fitted (Throne, 1994) using

Equation [ 3.3 ]

\[ Duration = a + \frac{b}{T^{0.5}} + c \log_e(T) + de^{-T} + \frac{f}{h^2} \]  

where,
T, is temperature (°C), coefficients; \( a = 5546.58 \), \( b = -103275 \), \( c = 117477 \), \( d = 2.91121 \times 10^8 \), \( e = 2.71828 \) (constant) and \( f = 81979 \) and \( h \), as previously defined.

The number of egg during 24-oviposition period (fecundity) is given as

Equation [3.4]

\[
\text{Number of eggs} = \frac{a}{1 + \left(\frac{T - b}{c}\right)^2 \left[1 + \left(\frac{h - d}{c}\right)^2\right]}
\]  

[3.4]

where, \( a = 330.550 \), \( b = 28.1315 \), \( c = 3.20929 \), \( d = 94.7541 \) other terms as previously defined.

The survival of the immature stages is expressed as

Equation [3.5]

\[
\text{Survival} = a + b e^{-0.5 \left[\left(\frac{T - c}{d}\right)^2 \left(\frac{\log e (\frac{h}{f})}{g}\right)^2\right]}
\]  

[3.5]

where,

\( a = -0.124731 \), \( b = 1.14602 \), \( c = 25.04 \), \( f = 63.3030 \), \( g = 0.314531 \) and other terms as previously defined.

The index of susceptibility (which is an indication of the conduciveness of an environment for population development) under a given temperature and relative humidity is given as

Equation [3.6]

\[
S.\text{index} = e^{\left[a + b \log e (T) + \frac{c}{T^{0.5}} + \frac{d}{T^2} + \frac{f \log e (T)}{T^2} + \frac{g}{h^2}\right]}
\]  

[3.6]

where,
a = 19696.6, b= -2889.20, c= -83408.9, d= 187391, f= -235431, g = -5985.48 and other terms as previously defined.

The study showed that, oviposition of *S. zeamais* (5 females laying eggs for 48 hours over 32-256 g of maize) was not significantly affected by duration of development. However, progeny production increased with food availability. Survival of the immature stages (egg, larvae and pupa) was significantly affected by temperature but relative humidity was not a limiting factor. However, duration of development was significantly affected by relative humidity. Development time ranged from about 35 days under optimal conditions (30 °C and 75%) to over 110 days at 18 °C. Maximum fecundity corresponding to 6.65 eggs per female in 24 hours was recorded at 30 °C and 75% relative humidity with the optimum number being 3.04 eggs per female per day at 26.6 °C and 70% relative humidity. Survival from egg to adult emergence was affected by combination of temperature and relative humidity, with the lower limit at 13 -15 °C. High rates of survival were recorded from 17.5 to 32.5 °C at 75% relative humidity and from 20 to 30 °C at 57%.

Maize weevil development is greatly reduced at temperatures less than 15 °C or above 35 °C irrespective of the relative humidity. A relative humidity of less than 45% is also adjudged to be detrimental to maize weevil development at any temperature. This is very important when considering integrated pest management plans for controlling maize weevil infestation in grain stores and warehouses.

Meikle et al. (1999), simulated the population growth of *S. zeamias* in grain stored in West Africa using the equations highlighted above with some modifications. Two sets of field data were used to validate the model. The first data was collected from maize cribs in Ibadan, Nigeria. Matured maize harvested from a research farm, dehusked but not threshed was fumigated with phostoxin in 200-liter plastic drums for 3 days. The treated maize was then stored in four naturally ventilated maize crib (0.8 x 0.8 x 1m) for 9 months. Three kg of cobs held in a large nylon-mesh trap bag were set at the center of the cribs. Samples were drawn from the bag by carefully removing cobs and placing them in a plastic
Samples were collected during the first 2 months, monthly for the remaining storage period. Samples drawn were taken to the laboratory where adult insects were carefully removed, identified and counted with the cob returned to the crib. Samples were placed in one-liter jars and sieved weekly for insect emergence. The second data was collected from field trials conducted at Dogbo, Benin Republic. This experiment differed from the first in that, maize samples were replaced with adjacent samples from the crib. The simulation showed that the maximum growth rate occurred at 30 °C and about 78% relative humidity. They also noted that equation (5) derived by Throne (1994) was not stable at extreme conditions. However, it was noted by Throne (1994) that caution should be taken in extrapolating values beyond the tested range reported. The model was able to explain the effect of immigration which was lacking in Throne’s work.

Other models used coupled heat balance models to study the development of insects exposed to varying temperature during storage (Flinn et al., 1997; Flinn et al., 1992; Flinn et al., 2004). Heat and mass transfer coupled with carbon dioxide and oxygen levels of the storage environment have also been used for predicting insect activities in grain storage (Gastón et al., 2009).

Gas concentration in a storage bin has also been used to study insect infestation. Diffusion of gases into carbon dioxide and oxygen balances in a storage container were used as a basis for predicting insect activities. Arias Barreto et al. (2017), modeled carbon dioxide and oxygen balance in wheat stored in silo bags. They reported that the oxygen and carbon dioxide levels in the bag were a function of the initial moisture content and temperature of the wheat within each region of the bag. The model was further tested using soybeans. In the two experiments, the model effectively predicted gas concentration in the silo bags which correlated with insect development in the bags.

In another study, the respiration rate of soybeans under hermetic storage was modeled along with the change in oxygen concentration (Ochandio et al., 2017). The study revealed that concentration of oxygen is critical in predicting grain and insect respiration.
This is important because insects need oxygen to survive. As they carry out metabolic activities, they release carbon dioxide. Thus, the balance between the oxygen and carbon dioxide levels can reveal the level of insect activities.

A comprehensive model for predicting the grain ecosystem which incorporates heat and mass transfer, grain and insect respiration, as well as dry matter loss, was developed by (Montross et al., 2002). They studied the interdependence of these processes on grain quality. The temperature distribution due to conductive, convective heat transfer and diffusion of moisture in steel silos were also investigated and the model was used to investigate the application of aeration as an alternative pest control technique. Their results showed that with proper prediction of the ecosystem of stored grain, best management practices can be applied without necessarily using chemical control.

Although application of these models to polypropylene bag storage systems has not been reported in the literature, modeling of insect population dynamics was not carried out as part of this research due to very limited data collected. However, insect infestation in bagged corn under natural ventilated warehouse is discussed in chapter six of this dissertation.
Abstract

Polypropylene and jute bags are widely used for grain storage across the developing world. The permeability of clear polypropylene bags (PP-C), opaque polypropylene bags (PP-O) and jute bags were determined using the ASTM E96 Standard Test Methods under three temperature and relative humidity (r.h.) combinations (25 °C/65% r.h., 28 °C/75% r.h. and 30 °C/80% r.h.) that resulted in vapor pressure deficits of 1.11, 0.95, 0.85 kPa, respectively. The water vapor transfer rate (WVTR) and the interaction between water vapor permeability (WVP) of the materials were determined. WVTR ranged from 216 g m⁻² day⁻¹ for opaque material (PP-O) exposed to air conditions of 30 °C / 80% r.h. to 478 g m⁻² day⁻¹ for jute exposed to air at 25 °C / 65% r.h. WVTR decreased with vapor pressure deficit for all materials. There was no significant difference in the WVTR between the polypropylene bags (PP-C and PP-O). WVP values ranged from 4.7 x 10⁻⁵ g (m day Pa)⁻¹ to 6.4 x 10⁻⁴ g (m day Pa)⁻¹ at 25 °C / 65% r.h. for PP-O and jute, respectively. WVP of PP-C and PP-O decreased slightly as the vapor pressure deficit increased. The permeability of jute was significantly different from both polypropylene bags under these test conditions (p<0.05). The change in corn moisture content with initial moisture at 10% and 12% (wb) were investigated using mini bags constructed from the three materials. Environmental condition, initial grain moisture, and the interaction among the parameters, had a large impact on the moisture change. There was a weak positive interaction between WVP of bag materials and change in corn moisture. This study demonstrates that environmental condition is the major cause of moisture changes in corn stored in woven bags, thus adequate monitoring is required to maintain grain quality during storage.

Keywords; bagged-grain, moisture migration, postharvest losses, storage.
4.1 Introduction

Corn (*Zea mays*) is an important crop for meeting the daily food requirement in many developing countries. Starch-based grains, primarily corn, are the basis for food security in Africa providing over 20% of total calories in human diets in 21 countries and over 30% in 12 countries (Yakubu et al., 2011). Effective grain storage is an important aspect of reducing postharvest losses, especially in countries where food losses are high (30% or more), and reduced losses contribute to increased food security without bringing more land area under cultivation (Kumar & Kalita, 2017). The shortage of effective storage infrastructure in developing countries has been identified as a crucial factor needed to reduce post-harvest losses (Hodges et al., 2010; Sheahan & Barrett, 2017). The use of polypropylene and jute bags for grain storage has been an age-long practice in much of the world and will likely remain a common practice in much of the developing world at the farm and market levels (Figure 4.1).

![Figure 4.1 Bagged corn in the market](image)

Bag storage (typically 50 or 100 kg each) is popular in much of the developing
world because of its numerous advantages in handling, transportation, and storage for relatively small quantities of grain. Bulk handling of grain is limited by road infrastructure, availability of trucks, and local constraints to grain marketing. Furthermore, most of the grain is produced by subsistence farmers with small land holdings who store grain on-farm or in their houses, thus large bulk storage facilities are not readily available. Polypropylene bags, which typically hold 100 kg of grain, have become the standard unit for handling, transportation, and marketing of grains at all levels in the developing world. Even though several works have suggested that polypropylene bags do not offer barriers to moisture transfer or insect and mold infestation (Ognakossan et al., 2013), there are indications that the practice will continue for the foreseeable future.

Previous research has indicated that improved handling and storage practices, such as the use of metal or plastic silos (~1 mt capacity) and hermetically sealed bags (70 to 100 kg) can reduce postharvest losses of grain at the household and farm level. The Purdue Improved Cowpea Storage (PICS) bags (Amadou et al., 2016; Baoua et al., 2014; Williams et al., 2017) uses a double layer of sealed plastic bags to create hermetic conditions that is placed inside a woven polypropylene bag to protect the inner plastic bags during handling. Issues identified with PICS bags compared to single-layer polypropylene bags are: 1) its smaller size (holding 70 kg); 2) higher cost (about ten-fold higher than polypropylene bags); and 3) laborious effort is required to tie the three bags (vs sewing a single bag) which makes it less attractive to grain aggregators and processors dealing with thousands of bags (Nouhoheflin et al., 2017). ZeroFly (ZF) storage bags employ an insecticide-incorporated woven polypropylene outer layer and have also been used for grain storage in Africa. The advantage of the ZF bag is that it retards insect attacks on the stored grain and can easily
be sewed using either a handheld bag closer or traditionally with needles and twine (Paudyal et al., 2017). ZF bags also feature the option of a thick inner plastic liner to incorporate hermetic storage.

Permeability to water vapor and oxygen is an important indicator of the barrier properties of a packaging material because it provides information on the shelf life of products held within (Bedane et al., 2012). Permeation is a measure of the penetration of a permeate (i.e. water vapor) through the bag material that contains grain. Permeation depends on the material properties and the environmental conditions under which the materials are used. Thus, it is important to examine the influence of ambient conditions on the permeability of grain bags (Siracusa, 2012). Laboratory experiments are usually the most reliable approach for determining the permeability of the barrier materials. Measurement of permeation of packaging materials to oxygen, water vapor, and other compounds are well documented in the literature (Galić & Ciković, 2001; Hülsmann et al., 2009; Rubino et al., 2001). Effects of the storage environment on the permeability of silo bags for carbon dioxide and oxygen have also been reported (Chelladurai et al., 2016).

Grain is typically stored from three to twelve months depending on region and market demands. However, the effect of environmental conditions during storage and the influence of the bag material to moisture changes needs to be investigated. The rate of spoilage in bag storage systems will be highly influenced by the surrounding temperature and amount of moisture transported through the bag material into the grain. Quantifying the moisture transport through the bag material will aid in developing effective management strategies to limit spoilage that negatively impacts the end products such as food and feed.
Therefore, this research aims to determine the water vapor transmission rate (WVTR) of polypropylene and jute materials typically used for grain storage and to evaluate the effect of their permeability on potential moisture changes in stored corn.

4.2 Materials and methods

4.2.1 Grain storage bag materials and test dishes

Jumbo size (100 kg capacity) clear polypropylene bags (produced by Nigerian Bag Manufacturing (BAGCO), Lagos Nigeria) and jute bags were obtained from a grain merchant in the Bodija market, Ibadan, Nigeria. White, polypropylene bags with a capacity of 25 kg were obtained from a local feed store in Kentucky from an unknown manufacturer. The polypropylene bags had a thickness of 0.20 mm and the jute bag had a thickness of 1.5 mm. Fifteen units of glass dishes (Pyrex dish 4 cup/950 ml, 14.2 cm x 6.3 cm) with a surface area of 158.4 cm² were utilized. Samples were cut from the bags to fit the glass dishes and used as test films.

4.2.2 Water vapor transmission rate and permeability measurement

The wet cup method described by ASTM E96/E96M-16 (ASTM, 2016) was used to measure the WVTR of the three bag materials. The method, which provides for measuring permeance through a film utilizes low humidity on one side of the film and high humidity on the other side. The low humidity side was controlled using an environmental chamber and the high humidity side was inside the glass dish filled with distilled water and covered with test films. The wet cup test method was chosen due to its suitability for measuring WVTR through materials that act as poor barrier materials. Test films with an approximate area of 182 cm² were cut from the bag materials and their thickness obtained with a digital Vernier caliper. Distilled water (500 ml) was added to the dishes using a
graduated cylinder. An air gap of 3.0 cm was left between the water level and the surface of the bag materials to provide space for water vapor exchange. The film was attached to the top of the glass dishes with the aid of a silicone sealant. The manufacturer supplied plastic lids were sealed using silicone to the top of the dishes for the positive control, while the dishes for the negative control were left completely open. The silicone sealant was allowed to dry for approximately an hour before the dishes were transferred into the environmental chamber (Parameter Generation & Control, Black Mountain, NC) and measurements began. Set points utilized for the experiments were the following combinations of temperature and relative humidity (r.h.): 25 °C / 65%, 28 °C / 75% and 30 °C / 80%. that resulted in corresponding vapor pressure deficits of 1.11, 0.95, and 0.85 kPa, respectively, determined from ASABE (2014). The experimental set up is shown in (Figure 4.2). Sample dishes were weighed using a digital balance (OHAUS, Precision Advanced; 2,100 g ± 0.01 g) at an interval of 24 hours. WVTR was determined over 20 days under each environmental condition.

Figure 4.2 Experimental set up with glass containers in a random array with open dishes and those covered with plastic lids and bag materials (Left to right first row: PP-C, jute, covered dish, PP-O, covered dish, open dish, PP-O, and jute).
Mass of water loss was plotted against elapsed time and the WVTR was calculated from the slope of the straight line that fits the curve (ASTM, 2016). WVTR was calculated using

Equation [ 4.1 ]

\[ WVTR = \left( \frac{G}{t} \right) / A \]  \[ 4.1 \]

where;

WVTR = water vapor transmission rate, g m\(^{-2}\) day\(^{-1}\)

G = cumulative mass of water lost over the measurement period, g

t = time during which weight change occurred, days

A = Area of material (film area), m\(^2\)

\( G/t \) = slope of the straight line, g/day

The permeance (g m\(^{-2}\) day\(^{-1}\) Pa\(^{-1}\)) of the bag materials was determined using

Equation [ 4.2 ]

\[ Permeance = \frac{WVTR}{\Delta p} = \frac{WVTR}{S(rh_1 - rh_2)} \]  \[ 4.2 \]

where;

\( \Delta p \) = vapor pressure difference, Pa

S = saturation vapor pressure at test temperature, Pa

rh\(_1\) = relative humidity in the dish, decimal

rh\(_2\) = relative humidity in the environmental chamber, decimal

The water vapor permeability (WVP) was determined using equation [4.1] as described by Hu et al. (2001).

Equation [ 4.3 ]

\[ WVP = \frac{WVTR \times x \times 100}{P_s \times \Delta rh} \]  \[ 4.3 \]

where;

WVP = water vapor permeability, g (Pa day m\(^{-1}\))
Ps = saturation vapor pressure, Pa
x = thickness of the material, m

$\Delta RH = \text{relative humidity differential between environmental chamber and inside dish, decimal}$

The relative humidity differential assumed a relative humidity of 100% between the film and water surface in the glass dish and the relative humidity set using a recently calibrated environmental control chamber outside the container. The temperature of the water and temperature of the environmental chamber were assumed to be equal.

Evaporation from the negative control, open dish with no film, was compared to evaporation from an undisturbed indoor swimming pool using equation [4.2] as described by Shah (2014).

Equation [4.4]  
\[ E_0 = 0.00005(P_s - P_v) \]  
\[ [4.4] \]

where;

$E_0$ is evaporation rate, kg m$^{-2}$ h$^{-1}$

$P_v$ is the partial pressure of water vapor in the air at reference temperature and humidity, Pa

$P_s$ is saturation vapor pressure at water surface temperature, Pa

4.2.3 Moisture changes in mini-bags

Mini-bags with an average dimension of 200 mm by 135 mm were made from the previously described bag materials. Medium-density polyethylene (MDPE) 0.2 mm thickness was procured from Asake polyethylene company (Asake poly, Ilorin Nigeria) and used as a control. The mini-bags had a surface area of 0.054 m$^2$. Corn harvested from the University of Kentucky research farm was dried to 10% and 12.5% after harvest and stored under refrigeration at 5°C for approximately one week. Stored samples were taken
to the laboratory and left to equilibrate to room temperature. Samples were drawn and passed through a grain divider (Boerner divider, Seedburo Equipment Company, IL, USA) to ensure proper mixing of samples to be bagged. Triplicate samples were taken during each run to determine the initial moisture content. Each mini-bag was filled with 700 g of yellow corn and stored in an environmental chamber maintained at a temperature of 25°C ± 0.5°C and relative humidity of and 65% ± 1% (EMC1 = 13.3% wb). The bags were weighed weekly for 35 days. At the end of the storage period, the change in moisture content was calculated based on the weight gain in addition to the measurement of the final moisture content using the oven drying method (ASABE, 2017). The procedure was repeated with storage conditions maintained at a temperature of 28°C ± 0.5°C and 75% ± 1% relative humidity (EMC1 = 14.7%), and 30°C ± 0.5°C and 80% ± 1% relative humidity (EMC = 15.6%). The experimental set up with the mini-bags is shown in (Figure 4.3.).

To prevent variation that may result from the movement of the dishes and the bags into varying environmental conditions, the weighing balance was stationed in the environmental chamber throughout the experiment.

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1 EMC as averaged from the Modified Chung-Pfost and Modified Henderson equations for yellow corn (ASABE, 2007).
4.2.4 Experimental design

The experiment was set up in a completely randomized block design. WVTR measurements consisted of three replicates of clear polypropylene bag material from Nigeria (PP-C), opaque polypropylene bag material from the US (PP-O) and the jute bag (J) and two controls (an open dish and dish covered with manufacturer’s plastic cover). The mini-bag experiments consisted of three replicates of PP-C, PP-O, Jute and Polyethylene (control).

4.2.5 Data analysis

Statistical analysis was performed using SAS (version 9.4, SAS Institute, 2013). PROC GLM was used to determine the effects of the bag type and environmental condition on WVTR and WVP of the bag materials. PROC GLM was used to evaluate the average weight change and the final moisture content of corn stored in the min-bags. Significance differences in the means were determined using LSMEANS at P < 0.05.
4.3 Results

4.3.1 Water vapor transmission rate through grain storage bag materials

The water loss profile of the three bag materials and the control (open dish) under the three test conditions are shown in Figure 4.4 to Figure 4.6. Water loss from the dishes covered with the manufacturers lids was negligible throughout the measurement period so this data was not included in the results. The water in the control dish was completely evaporated after 11 days.

Figure 4.4 Average weight loss of from glass dishes covered with three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) and control (open dish) at 25°C and 65% relative humidity (VPD of 1.11 kPa). Error bars are one standard deviation with three replications.
Figure 4.5. Average weight loss of from glass dishes covered with three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) and control (open dish) at 28°C and 75% relative humidity (VPD of 0.95 kPa). Error bars are one standard deviation with three replications.

Figure 4.6. Average weight loss of from glass dishes covered with three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) and control (open dish) at 30°C and 80% relative humidity (VPD of 0.85 kPa). Error bars are standard deviations with three replications.

4.3.2 Permeability of grain storage bags

The effect of environmental conditions on the calculated WVTR, permeance and WVP of the grain storage bags is shown in Table 4.1. WVTR of the woven PP-C and PP-
O were statistically the same but significantly different (p=0.0001) from that of jute bag. Environmental conditions, or vapor pressure deficit, had a significant effect (p=0.0001) on the WVTR of the bag materials. A significant interaction (p=0.0001) also existed between bag type and environmental conditions. WVP values are the same for PP-C and PP-O materials but significantly different from jute (p=0.001). WVP values of PP-C and PP-O were not significantly affected (p=0.08) by the environmental condition. However, WVP values of jute were significantly affected by the environmental condition (p=0.02). In contrast, the published value of WVP for polypropylene sheets (not woven) has been reported to be 4.5x10^{-8} g (m day Pa)^{-1} at 38 °C and 0-90% r.h. (Morillon et al., 2002).

Water evaporation rates from the open dishes were: 0.08, 0.07 and 0.06 kg m^{-2} h^{-1} at 25°C / 65 %, 28°C / 75 % and 30°C / 80%, respectively, and follows the expected trend with vapor pressure deficit. The evaporation rate decreased with vapor pressure deficit.

Table 4.1 Effect of environmental conditions on the water vapor transmission rate and permeability of bag materials

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Condition (Temp °C/ % r.h.)</th>
<th>VPD (kPa)</th>
<th>WVTR (g m^{-2} day^{-1})</th>
<th>Permeance (g m^{-2} day^{-1} Pa^{-1})</th>
<th>WVP (g m^{-1} day^{-1} Pa^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP-C</td>
<td>25 / 65</td>
<td>1.11</td>
<td>272±1^{d}</td>
<td>0.24±0.00^{c}</td>
<td>4.9±0.0 x 10^{-5}^{c}</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>0.95</td>
<td>233±5^{e}</td>
<td>0.25±0.05^{c}</td>
<td>4.9±0.1 x 10^{-5}^{c}</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>0.85</td>
<td>216±3^{e}</td>
<td>0.26±0.03^{c}</td>
<td>5.1±0.1 x 10^{-5}^{c}</td>
</tr>
<tr>
<td>PP-O</td>
<td>25 / 65</td>
<td>1.11</td>
<td>261±2^{d}</td>
<td>0.23±0.01^{c}</td>
<td>4.7±0.0 x 10^{-5}^{c}</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>0.95</td>
<td>239±2^{e}</td>
<td>0.25±0.03^{c}</td>
<td>5.1±0.1 x 10^{-5}^{c}</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>0.85</td>
<td>226±3^{e}</td>
<td>0.26±0.04^{c}</td>
<td>5.3±0.1 x 10^{-5}^{c}</td>
</tr>
<tr>
<td>Jute bag</td>
<td>25 / 65</td>
<td>1.11</td>
<td>478±12^{a}</td>
<td>0.43±0.11^{a}</td>
<td>6.4±0.2 x 10^{-4}^{a}</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>0.95</td>
<td>374±9^{b}</td>
<td>0.40±0.10^{b}</td>
<td>5.9±0.2 x 10^{-4}^{b}</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>0.85</td>
<td>324±6^{c}</td>
<td>0.39±0.07^{b}</td>
<td>5.8±0.1 x 10^{-4}^{b}</td>
</tr>
</tbody>
</table>

Values within columns sharing the same superscript letters are not significantly different (p < 0.05; n= 27). Values are the mean ± standard deviation.
4.3.3 Weight changes and moisture content of bagged corn in storage

The effects of environmental condition and initial moisture content (nominal 10% wb) on weight changes and final moisture content of bagged corn are shown in Table 4.2. over 35 days. There was a significant weight gain (p=0.0001) in all the bags as the storage conditions changed except in the control where weight gain was negligible. Consequently, the moisture content increased with weight gain. Effects of bag type on increase in moisture content was, however, not significant but the increase was significantly affected by the environmental condition.

Table 4.2. Effect of environmental conditions on weight change in bagged corn initially at 10% wb moisture content after 35 days.

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Condition (Temp °C/ % r.h)</th>
<th>EMC (% wb)</th>
<th>Initial MC (% wb)</th>
<th>Change in MC (% wb)</th>
<th>Weight gain (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP-C</td>
<td>25 / 65</td>
<td>13.3</td>
<td>9.9±0.0</td>
<td>1.6±0.1</td>
<td>12.5±0.1</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>9.6±0.1</td>
<td>3.0±0.1</td>
<td>23.8±0.1</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>10.0±0.1</td>
<td>3.6±0.1</td>
<td>28.4±0.1</td>
</tr>
<tr>
<td>PP-O</td>
<td>25 / 65</td>
<td>13.3</td>
<td>9.8±0.1</td>
<td>1.6±0.1</td>
<td>12.6±0.1</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>9.6±0.1</td>
<td>3.0±0.0</td>
<td>24.0±0.1</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>10.0±0.2</td>
<td>3.5±0.1</td>
<td>27.9±0.5</td>
</tr>
<tr>
<td>Jute</td>
<td>25 / 65</td>
<td>13.3</td>
<td>9.9±0.1</td>
<td>1.6±0.1</td>
<td>12.8±0.1</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>9.8±0.1</td>
<td>3.1±0.1</td>
<td>24.8±0.3</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>9.7±0.1</td>
<td>3.7±0.0</td>
<td>29.7±0.4</td>
</tr>
<tr>
<td>Control</td>
<td>25 / 65</td>
<td>13.3</td>
<td>9.9±0.1</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>10.0±0.1</td>
<td>0.4±0.1</td>
<td>3.2±0.4</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>9.9±0.0</td>
<td>0.4±0.1</td>
<td>3.0±0.1</td>
</tr>
</tbody>
</table>

Values within columns sharing the same superscript letters are not significantly different (p < 0.05; n= 36).

In bagged corn with an initial moisture content of 12% (Table 4.3.), weight gains were significantly influenced by environmental condition and initial moisture content as well as the interaction among the treatments (p=0.0001). The increased in moisture content were significantly different for mini-bags stored under different environmental conditions but were the same across bag types. However, the condition of corn in all the bags

55
(including the control) remained unchanged with the temperature at 25 °C and 65 % relative humidity.

Table 4.3. Effect of environmental conditions on weight change in bagged corn initially at 12% wb moisture content after 35 days.

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Condition (Temp °C/ % r.h.)</th>
<th>EMC (% wb)</th>
<th>Initial MC (% wb)</th>
<th>Change in MC (% wb)</th>
<th>Weight gain (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP-C</td>
<td>25 / 65</td>
<td>13.3</td>
<td>11.8±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>11.5±0.1</td>
<td>1.0±0.0</td>
<td>8.1±0.1</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>12.3±0.2</td>
<td>1.8±0.1</td>
<td>14.8±0.2</td>
</tr>
<tr>
<td>PP-O</td>
<td>25 / 65</td>
<td>13.3</td>
<td>11.9±0.1</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>11.7±0.1</td>
<td>1.0±0.1</td>
<td>8.0±0.0</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>12.2±0.1</td>
<td>1.8±0.2</td>
<td>14.4±0.8</td>
</tr>
<tr>
<td>Jute</td>
<td>25 / 65</td>
<td>13.3</td>
<td>11.8±0.1</td>
<td>0.0±0.0</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>11.7±0.1</td>
<td>1.1±0.1</td>
<td>8.5±0.1</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>12.2±0.1</td>
<td>2.0±0.1</td>
<td>16.3±0.3</td>
</tr>
<tr>
<td>Control</td>
<td>25 / 65</td>
<td>13.3</td>
<td>11.8±0.0</td>
<td>0.1±0.1</td>
<td>0.7±0.2</td>
</tr>
<tr>
<td></td>
<td>28 / 75</td>
<td>14.7</td>
<td>11.8±0.0</td>
<td>0.1±0.1</td>
<td>0.0±0.0</td>
</tr>
<tr>
<td></td>
<td>30 / 80</td>
<td>15.6</td>
<td>12.4±0.1</td>
<td>0.2±0.1</td>
<td>1.6±0.1</td>
</tr>
</tbody>
</table>

Values within columns sharing the same superscript letters are not significantly different (p < 0.05; n= 36).

4.4 Discussions

The influence of environmental conditions on the final weight gain and moisture content of bagged corn is presented by the initial MC (Table 4.2. and Table 4.3.). With an initial moisture content of 10% (Table 4.2.), there was a significant weight increase over the 35-day storage period. As expected, storage environments with a higher EMC had a higher weight gain and a corresponding increase in moisture content. There was no statistically significant difference in the two polypropylene materials, although the environmental conditions had a significant effect on weight gain. With jute bags, the weight gain was similar to the polypropylene bags at the driest environmental condition (EMC of 13.3%) but was significantly higher than the polypropylene bags at the more humid
conditions (EMC of 14.7% and 15.6%). This would be expected since the driving force for moisture addition (EMC differential) was larger. On average, the corn moisture increased by 1.6, 3.0 and 3.6 percentage points in polypropylene bags from an initial moisture content of 10.0% when exposed to environmental conditions with an EMC of 13.3%, 14.7% and 15.6%, respectively. The corresponding moisture increase in jute bags was 1.6, 3.1 and 3.7 percentage points.

With corn at an initial moisture content of 12% (Table 4.3.), there was no weight gain in both polypropylene and polyethylene (control) bags when exposed to air at 25°C / 65% r.h. (EMC of 13.3%). In comparison, there was a marginal increase in the weight gain in jute bags at these environmental conditions, but this did not result in a measurable change in moisture content. The low magnitude of the weight gain under these conditions was due to the initial moisture content and environmental conditions being very close to equilibrium. The weight gain of corn stored in the two polypropylene bags increased significantly as the EMC increased, however there were no differences between the two polypropylene materials. Interestingly, jute bags had a statistically similar weight gain to the polypropylene bags with conditions of 28 °C / 75 % r.h. (EMC of 14.7%). Although the weight gain at 30 °C / 80 % r.h. (EMC of 15.6%) was statistically different from polypropylene bags at the same condition. The average moisture increases in polypropylene bags from 12.0% was 0.0, 1.0 and 1.8 percentage points when exposed to environmental conditions with an EMC of 13.3%, 14.7%, and 15.6%, respectively. In jute bags, the corresponding values were 0.0, 1.1, and 2.0 percentage points, respectively.

Corn moisture in the control samples (polyethylene) remained unchanged under an environmental condition with an EMC of 13.3%. However, the moisture content increased
marginally under the more humid condition (EMC of 14.7% and 15.6%). The average moisture increase in polyethylene bags was 0.4 percentage point for corn with an initial moisture content of 10% wb (Table 4.2.), while the average increase was only about 0.2 percentage point for corn with initial moisture content of 12% (Table 4.3.). This was expected because MDPE is a better barrier to moisture transfer than the other materials. The marginal change in moisture seen in the polyethylene may be connected to the tightness of the sealing and also the fact that polymer materials do not serve as “absolute barriers” against water vapor as pointed out by Gajdoš et al. (2000). The overall statistical analysis showed that the moisture change is influenced by the bag type, environmental condition and initial moisture content, as well as the interactions among the parameters. These observations are driven by the vapor pressure difference between the air and grain. These results support the findings from previous research where the moisture content of grain stored in woven polypropylene have been reported to increase or decrease as a result of the change in environmental conditions in which the bags are stored (Lane & Woloshuk, 2017; Likhayo et al., 2018).

As shown in Figure 4.4 (at 25°C and 65 % r.h. that represented the highest VPD of 1.11 kPa) the slope of the curve for the control (open dish) was very steep compared to the bag materials. This was expected as water freely evaporates from the dish without restriction thus an evaporation rate of 37 g of water per day was recorded. This was followed by the jute bag with an average water loss of 7.5 g/day. PP-C and PP-O bags with average water losses 4.3 and 4.1 g/day, respectively. The observed differences in the magnitude of water loss are related to the bag materials. Jute material is visually porous and not as tightly woven as polypropylene thus having an average water loss rate almost
double of polypropylene at equivalent environmental conditions. The observed trend is similar to those reported in previous studies where moisture gain increased linearly with time through polyurethane and polymeric packing materials (Schwartz et al., 1989; Zeman & Kubik, 2007). A similar trend was also observed in polylactic acid and chitosan blends films where the moisture loss was linear with time (Teo & Chow, 2014).

As vapor pressure deficit decreased, the average water loss rate decreased. When the condition was changed to 28°C and 75% r.h. the slope declined due to the decrease in VPD (Figure 4.5). The average water loss reduced to 26, 6.0, 3.6 and 3.8 g/day for the control, jute, PP-C and, PP-O samples, respectively. A further reduction in slope was observed at 30°C and 80% r.h., the lowest VPD level tested, with an average water loss of 24, 5.3, 3.5 and 3.6 g/day, respectively (Figure 4.6).

Evaporation rate from the open dishes under the selected environmental conditions are comparable to available data from the evaporation of water from an undisturbed indoor pool with the obtained values showing very marginal differences at 28°C / 75% r.h. and 30°C / 80% r.h. This suggests that the observed trends are due to the properties of the materials.

WVTR of the polypropylene materials decreased as the vapor pressure deficit decreased (Table 4.1). Changing the chamber’s condition from 25°C / 65% r.h. to 28°C / 75% r.h. reduced the VPD from 1.11 to 0.95 kPa, or 14.4%. WVTR for the PP-C and PP-O materials decreased by 14.3% and 8.4% but were not statistically different. Similarly, changing the environmental conditions from 28°C / 75% r.h. to 30°C / 80% r.h further reduced the VPD from 0.95 to 0.85 kPa or 10.5%. This resulted in a decrease in the WVTR from PP-C and PP-O bags by 7.3% and 5.4%, respectively, but they were not statistically
different. The polypropylene bags were from different manufacturers but behaved similar
and the WVTR varied with VPD as expected.

Significant differences were observed in the WVTR from jute bags. At all three
VPD levels, the WVTR was significantly higher than the WVTR from the polypropylene
bags. Decreasing the VPD from 1.11 to 0.95 kPa reduced the WVTR from 478 to 374 g
m⁻² day⁻¹, a decrease of 21.8%. A further reduction in the VPD from 0.95 to 0.85 kPa
resulted in a 13.4% decrease in the WVTR. The WVTR decreased linearly with the
decrease in VPD (Figure 4.7) with r² values of 0.992, 0.999 and 0.995 for PP-C, PP-O and
jute, respectively. For 1 kPa increase in vapor pressure deficit, the WVTR increased by
597, 218 and 135 g m⁻² day⁻¹ for jute, PP-C and PP-O, respectively. The PP-C and PP-O
have intercepts of 28.58 and 111.16 g m⁻² day⁻¹, respectively while jute bag has a negative
intercept of 187.74 g m⁻² day⁻¹. This is in contrast to the findings of Chen et al. (2014), who
reported that WVTR of BOPP materials tested at a 10 °C to 40 °C increased linearly with
relative humidity but the values increased exponentially as the temperature increased.
While the linear relationship can be attributed to the influence of relative humidity on vapor
pressure deficit the decrease in values cannot be attributed to either of the two parameters
due to their main effects and interaction effects on barrier properties of the tested materials.
Figure 4.7 Effect of vapor pressure deficit on water vapor transmission rate values of three bag materials (jute and two types of polypropylene bags, PP-C and PP-O) when held at 30 °C/80% r.h. for 35 days.

A jute bag would be considered a highly permeable film and there are potential measurement errors in WVTR in highly permeable films. High water vapor fluxes can lead to a relative humidity less than saturation leading to an underestimation of the WVTR in highly permeable films (Hu et al., 2001). There is a dependency of permeability on temperature and relative humidity that has also been reported by Togashi and Hara (2011), where an increase in the coefficient of permeability of polypropylene film was observed as temperature and relative humidity increased. Similar results have also been reported for some high barrier plastic materials where the values of the parameters increase with temperature due to the corresponding increase in partial pressure (Hülsmann et al., 2009; Schwartz et al., 1989). The analysis presented here focused on VPD so the influence of
temperature and relative humidity on WVTR could not be isolated.

In relating the WVP of the bags with the change in MC, the statistical analysis showed a weak positive correlation (p=0.07) between the two parameters, which may be connected to the interaction effect of other parameters that were considered in this study. This points to the fact that, although the permeability of the bag materials may influence moisture fluxes into the bags, the storage environment drives the magnitude of the observed changes. Although the PP-O and PP-C bags behaved similarly, there are other factors that would influence the selection of bags at the market level. Clear bags are more desirable by consumers because they can easily notice grain damage and the presence of insects, frass, mold and/or foreign materials.

4.5 Conclusions

This study has shown the effect of water vapor transmission rate (WVTR) in common bag materials at three environmental conditions. The permeability of two polypropylene bag materials (PP-C and PP-C) and their performance under the test conditions were identical. This implies that the moisture change of grain stored in the two types of bags would likely behave similarly.

The permeability of bag materials and their performance is largely affected by the ambient condition with the effects more pronounced in jute bags. This study has provided useful information on the interaction of WVTR of storage bag materials and environmental conditions on the process of moisture flux into bagged grains. A considerable amount of moisture can be transferred from the ambient air in storage warehouses to stored grain as the environmental condition changes depending on the initial moisture of the grain.

It is, however, necessary to extend the investigation to cover prevailing
environmental conditions typically found where grain storage in bags is being practiced and preferably using full size bags (100 kg) to match field/market conditions. The study also confirms that woven polypropylene and jute bags offer minimal protection against moisture changes in stored grain. Thus, adequate monitoring is paramount to prevent quality deterioration where little or no environmental control is being practiced when storing bagged grain.
CHAPTER 5. DEVELOPMENT OF A MONITORING SYSTEM TO ASSESS THE INTERNAL ENVIRONMENT OF BAGGED GRAIN IN STORAGE

Abstract

Most farmers in African countries store grain on farm using polypropylene bags due to their availability and low production levels. These bags are also used at local markets and for storage at small and large warehouses. Little published information is available on the temperature and moisture change of grain stored in these bags even though high losses are observed. Commercially available portable moisture meters (John Deere™ and DICKEY-john™) are expensive and not suitable for providing real-time information on the condition of bagged grain during storage. A monitoring system was developed to assess the internal environment of bagged grain stored in warehouses. The system consisted of eight on-board integrated temperature and relative humidity sensors (Sensirion, Model SHT35) connected to a custom Arduino-based data acquisition system. The data acquisition system recorded a time stamp, temperature and relative humidity at a user-specified interval onto a microSD card. Sensors were calibrated in an environmental control chamber at 33%, 55% and 75% RH and a temperature of 10°C, 25°C and 40°C with an average offset of 3.7% RH and 0.3°C, respectively. The system was used to monitor conditions of bagged corn in Ilorin, Kwara State, Nigeria and bagged paddy rice in Tede, Oyo State, Nigeria from May 3, 2019 to September 9, 2019. The equilibration time of the system was five minutes. Recorded air temperatures within the warehouse at Ilorin varied between 23°C and 33°C while the relative humidity varied between 64% and 82%. In Tede, air temperatures in the warehouse ranged between 23°C and 33°C, and the relative humidity varied from 68% to 84%. Bagged corn and paddy temperatures varied between 27°C and 31°C and 24°C and 32°C, respectively. Relative humidity in the bags varied between 54% and 68% in corn and 61% to 84% in paddy. Average monthly temperatures recorded at various locations in the warehouse were significantly different (p<0.05).
Temperature of bagged corn differed significantly (p<0.05) from that of the air surrounding the stack. Equilibrium moisture content of bagged corn and paddy increased by 1.1 and 1.4 percentage points (wb), respectively, during storage. The system acquired valuable data for describing the conditions inside the warehouses and the internal environment of bagged grain. This system would help warehouse managers make informed decisions to reduce storage losses.

Keywords: Grain bag storage, moisture, temperature, monitoring, loss management.

5.1 Introduction

Moisture content and temperature are primary factors for maintaining the quality of grain during storage. To ensure that grain is kept in good quality during storage, the temperature and the relative humidity must be uniformly maintained at appropriate levels for the desired storage period. Low temperatures are desirable to minimize insect activity, while a low equilibrium relative humidity (ERH) within the grain bulk is important to minimize mold degradation (Navarro, 2001). Stored grain insect pests thrive in a temperature range of 25°C to 33°C (Fields, 1992) and mold spoilage occurs most readily at ERH values above 65% (Yaouba et al., 2012). A major challenge of food preservation and storage in Africa is insect infestation and attacks by molds and rodents (Degri & Zainab, 2013), which thrive in the prevailing environmental conditions throughout the year. Therefore, accurate and timely measurement of temperature and relative humidity within a stored commodity is important in order to maintain product quality.

Traditionally, the moisture content of grain is determined by using standards based on convection oven methods (ASABE Standards, 2007). However, non-destructive, rapid indirect methods which are based on the electrical properties or chemical composition of grain have also been used in commercial moisture meters. Temperature cables have been
used for monitoring the condition of bulk grain in bins with sensors located at regular intervals (Schwab et al., 1991). The ERH technique, which involves measuring the temperature and relative humidity of the air in the interstitial spaces of grain and calculating the moisture content using an equilibrium moisture content (EMC) model have also been successfully used for determining grain moisture content (Chen, 2001). The ERH technique has been enhanced by the development of low-cost sensors with integrated temperature and relative humidity sensing capabilities with improved accuracies. This has opened additional opportunities for measuring stored grain conditions. Integrated ERH/temperature sensors are capable of replacing temperature monitoring cables that are widely used in farm and commercial bins in the U.S. (Armstrong et al., 2012).

Temperature and humidity sensors with varying accuracy and specifications have been developed and applied to monitoring agricultural commodities during transportation (Danao et al., 2015) and storage (Armstrong & Weiting, 2008; Armstrong et al., 2017a; Armstrong et al., 2017b; Chen et al., 2014; Chen, 2001). Uddin et al. (2006), developed an EMC meter using a miniaturized digital temperature and relative humidity sensor (model SHT75, Sensirion AG, Zurich, Switzerland). The accuracy of the sensor to predict EMC of wheat was examined and found to predict the moisture content with a small error (0.25% to 0.65% MCdb) with relative humidity between 20% to 70% for the three EMC equations used (modified Henderson, modified Chung-Pfost and Oswin). However, as relative humidity increased above 70%, the prediction error increased significantly regardless of the EMC model used. This shows the dependency of EMC on the ERH of the air in the interstitial space within the grain bulk. Similar sensors from the same manufacturer have also been used by other researchers to determine EMC of grain in storage. Danao et al. (2015), used a relative humidity sensor (model SHT15, Sensirion AG, Stäfa, Switzerland) to monitor temperature and relative humidity of soybeans in trucks during transport to storage in Brazil. Data obtained showed that the accuracy of the sensors were within the manufacturer’s typical specification of ±0.3°C and ±2% RH (for relative humidity less than...
In another study, the SHT75 sensor was used to monitor temperature and relative humidity in high moisture red winter wheat (Gonzales et al., 2009). EMC was calculated from the temperature and relative humidity data using the Chung-Pfost equation and moisture content (MC) was determined from grab samples using the oven-drying method. The results showed that the EMC was linearly correlated with measured MC with no significant difference. However, a very wide variation existed in the percent difference between calculated EMC and measured MC that ranged between 0 and 11.1%. This suggests that caution is needed when using these sensors for moisture measurement where high accuracy is required.

Ward and Davis (2013), developed a system to monitor the internal environment in large silo bags (3 m in diameter or larger and 100 m long). The system consisted of linear arrays of Type-T high-precision thermocouple wires (Omega Engineering, Inc., Stamford, Conn.) and humidity sensors (HM1500LF, Humirel, Inc., Chandler, AZ) attached to a food grade C-channel and installed in the silo bag to monitor the condition of corn and soybeans stored in separate bags. The system adequately described the condition of the stored grain and showed that changes in temperature and relative humidity significantly affected the quality of stored grains.

In Africa, most farmers store grain in polypropylene bags due to limited production and minimal infrastructure (Manandhar et al., 2018). In most cases, grain conditions are not monitored during storage. Consequently, average losses of 20-30% have been reported in grain stored in polypropylene bags with considerable loss in seed germination (Kumar & Kalita, 2017). Losses as high as 50% have also been reported in corn stored for three months in polypropylene bags (Costa, 2014).

Armstrong et al. (2017b) developed a low-cost probe type instrument for measuring the EMC of grain based on the SHT75. Known as the post-harvest loss (PHL) meter, it consisted of a 75 cm long steel probe with a perforated tip at the end, a SHT75 sensor located inside the probe and connected to a four-conductor RJ-11 wire, which runs through
a wooden handle at the closed end and plugs into a hand-held user interface. The probe can be inserted into a grain bag and the moisture content determined after the sensor equilibrates with the grain environment, usually after about 6 minutes. The instrument has a low initial cost (~$100 USD), is user friendly and calibrated for many grains grown in Africa. The PHL meters were tested in USDA projects in Ghana and Nigeria in 2014 and 2016, respectively. In Nigeria, the moisture meter was used together with the John Deere Moisture Check Plus (Model SW8120, AgraTronix Streetsboro, Ohio, USA), and the GAC (2100-Agri Grain Analysis Computer, DICKEY-john Corp., Auburn, III, USA) to measure the moisture content of bagged corn in storage. Ajao et al. (2018) compared the accuracy of the sensors. The PHL meter had a mean percent difference of 1.64% MCwb compared to the oven-drying method. The John Deere meter was less accurate than the PHL meter (percent difference of 2.34% MCwb), while the GAC was most accurate with a percent difference of 1.08% MCwb. A company in Ghana has adopted this technology for commercialization and have a product branded “GrainMate” which is now being sold in Ghana and Nigeria (Sesi Technologies, 2018). However, a few challenges have been identified in the use of the PHL moisture meter, namely that it can only measure moisture content at specific times, which is like manual sampling used in the warehouse or receiving centers. Thus, the equipment is not suitable for remotely monitoring changes in grain temperature and moisture during the entire storage period. Apart from this, opening or piercing grain bags to take measurements compromises the structural integrity of the bags and creates openings which can allow entry for insects.

As reported by World Bank (2011), the low adoption rate of low-cost moisture meters especially in Africa has made monitoring of grain quality ineffective. A system that is accurate, robust and inexpensive is required by farmers and warehouse managers in developing countries to ensure adequate monitoring of the condition of bagged grain in storage.
The objective of this research was (1) to design a system that could monitor the temperature and relative humidity of bagged-grain (The system was intended as a tool to study the effects of a warm, humid environment on the internal environment of bagged grain stored under a naturally ventilated warehouse) and (2) test the system in naturally ventilated grain warehouses in Nigeria.

5.2 Materials and methods

5.2.1 Monitoring system

In developing the monitoring system, a breadboard prototype was first built to establish the performance characteristics and reliability of the system before embarking on fabricating a rugged version that was used in the field.

The hardware of the prototype consisted of; an Arduino-based microcontroller (HUZZAH32 ESP32 Feather Board, Adafruit Industries) with an attached real-time clock (RTC) and microSD card interface (Adalogger FeatherWing, Adafruit Industries), eight digital temperature and relative humidity sensors (SHT35, Sensirion AG, Stäfa, Switzerland), and an I²C multiplexer (TCA9548A, Texas Instruments) for allowing multiple sensors with the same address to communicate using a single I²C bus (Figure 5.1). Components were connected on a prototyping breadboard.

The microcontroller was programmed with the Arduino 1.8.9 Integrated Development Environment. Standard Arduino programming libraries were used to enable communication and control of the microcontroller’s I²C and SPI buses, which interfaced with the RTC, microSD card, I²C multiplexer and the SHT35 sensors. The ClosedCube (GitHub, 2019) library was used to poll the SHT35 sensor data over the I²C bus. Temperature and relative humidity data were combined with a timestamp provided by the RTC and written to the microSD card at a predefined time interval. The components of the prototype units are presented in appendix A1 (Table A.1).
5.2.2 Field monitoring system

The ruggedized system consisted of all the main components used in the prototype. However, the breadboard and wires were replaced with a custom designed printed circuit board (PCB) (Figure 5.2) and sensors were connected through an enclosure using bulkhead connectors (T4141012041-000, TE Connectivity AMP Connectors, Switzerland). The temperature/relative humidity sensor was housed in a waterproof/dust proof metallic shell cover of 60 mm length and 10 mm diameter attached to a 3 m long cable (TR03L, RCZTH, Electronics for the World, AliExpress, China) that was powered by a 5V USB power supply. The connectors were soldered directly to the PCB and served to mount the PCB inside the ABS/PC enclosure (NBF-32210, Bud Industries, Willoughby, OH, USA) (Figure 5.3). A power switch and USB Type-A connector were mounted on the side of the
enclosure to selectively turn the system on and supply external power, respectively. Four units of the boxes were developed and tested in two grain warehouses. The components of the ruggedized grain monitoring system are presented in Appendix A2 (Table A.2 to Table A.4) while the renderings of the PCB are shown in Figure A.1 to Figure A.7.

Figure 5.2 PCB top (left) and bottom (right) views showing copper and silkscreen layers.
The sensors were calibrated in an environmental chamber at the University of Kentucky Department of Biosystems and Agricultural Engineering. Temperature settings of 10°C, 25°C and 40°C were used. Relative humidity was controlled using three saturated salt solutions: magnesium chloride, magnesium nitrate and sodium chloride (VWR, Radnor, PA, USA) for nominal relative humidity levels of 35%, 55% and 75%, respectively. For each salt solution, a saturated mixture was created by adding distilled water to a given quantity of anhydrous salt in glass jars, following ASTM E104 – 02 standard (ASTM, 2012). Prepared salt solutions were then transferred into the environmental control chamber with the temperature set at 10°C. Sensors were passed through a rubber stopper inserted into the glass jars – leaving a gap of about 2.5 cm between the surface of the solution and the tip of the sensors (Figure ). The stoppers were tightly covered with paraffin film to ensure a sealed condition was maintained within the glass jars. The calibration system was allowed to equilibrate for 2 hours before data collection began with readings taken at 30 s intervals. Sensor readings were averaged over 15 minutes.
after successive readings stabilized to less than a 5% change in temperature and relative humidity. This procedure was repeated at 25°C and 40°C.

Figure 5.4 Sensor calibration system showing the probes in the aqueous salt solution jars (from left to right - magnesium chloride, sodium chloride and magnesium nitrate)

5.2.4 Response time

The response time of the sensors was evaluated by placing corn conditioned to 13.5% MCwb at an initial temperature of about 20°C in glass jars. The sensors were passed through a rubber stopper into the jars. This was set up in an environmental chamber set at 25°C and 75% relative humidity, and sensor data were recorded at 30 s intervals for 15 minutes. This procedure was repeated three times and the average values recorded by the sensors were plotted. The procedure was also carried out with corn conditioned to 11.5% MCwb. Response time was defined as the average time taken for sensor reading to stabilize under constant temperature and relative humidity.

5.2.5 System installation and field tests

The monitoring systems were installed in two different warehouses to measure temperature and relative humidity distribution in bags and the surrounding air in the warehouse. Two units were deployed in a small warehouse located on the campus of Nigerian Stored Products Research Institute (NSPRI) headquarters Ilorin, Kwara State, Nigeria, which is in the Savannah agro-ecological zone. The other two units were deployed
in a large warehouse facility owned by Oyo State Agricultural Development Project (OSADEP) located at Tede near Shaki in Oyo State, Nigeria, which is in the rain forest agro-ecological zone. The rationale for choosing these locations was to compare the effect of the differences in the climatic conditions on the internal environment of the warehouses and how this impacted grain moisture.

Corn purchased in a market in Ilorin was cleaned and re-bagged into fifty-four bags of 40 kg (88 lbs.) size. Sensor probes were placed in selected bags which were then sewn using a handheld sewing machine (Two Lion GK-26-1 A, China). The bagged corn was stored in the warehouse in two small stacks having 27 bags each arranged 3 by 3 by 3. Probes were placed in bags (bag), in between bags (bag space), at the air vent to the building (ambient) and in the void under the pallet (floor) (Figure 5.5.) to monitor the condition of the entire storage ecosystem. The ambient sensor was shielded from radiation and was mounted slightly outside of the warehouse. Each probe was tagged with a label showing their specific locations and plugged into the control box, which were placed in secured locations within the warehouse. The units were energized and date, time, temperature and relative humidity data were recorded at 1-hour intervals. Data were downloaded from the microSD card once per week. The integral battery was recharged once every two weeks during data retrieval and continued to supply power to the unit so there were no interruptions in data acquisition. The data acquisition period lasted from May 3 to September 9, 2019.

The second setup consisted of a large stack of 100 kg (220 lbs.) bagged paddy rice stored in a large warehouse arranged in 25 wide x 16 deep x 11 high sacks. Sensors were installed on one end of the stack (due to inability to rearrange the bags, because the paddy was already in storage for about two months). Also, samples were not drawn from the bags for moisture analysis. Temperature and relative humidity data were collected from May 7 to September 9, 2019.
Figure 5.5. Side view of the warehouse showing the positions of the sensors.
5.2.6 Moisture measurement and equilibrium moisture content calculation

About 200 g samples were taken at random from selected bags of corn during re-bagging and analyzed for initial moisture content. Random samples were also taken from the bags at the end of the storage period in September. The samples were analyzed for moisture using AOAC standard method for determination of moisture content of ground sample (AOAC, 2005).

Moisture content of stored grain was calculated using the modified Henderson equation (ASABE Standards, 2017)

Equation [5.1]

\[
EMC = \left( \frac{-\ln(1 - rh)}{A(T + C)} \right)^{1/B} \tag{5.1}
\]

where;

EMC = moisture content, dry basis decimal
rh= relative humidity of interstitial of air (decimal)
T = grain temperature (°C)

The estimated parameters of adsorption data for shelled corn A, B and C are 4.6715E-5, 1.9704 and 82.205, respectively (Chen & Morey, 1989). For paddy, the constants A, B, C are 3.33806E-5, 2.2464 and 77.922, respectively (Reddy & Chakraverty, 2004).

EMC values were converted to wet basis using

Equation [5.2]

\[
MC_{wb} = \frac{100EMC}{(100 + EMC)} \tag{5.2}
\]

where;

MC\(_{wb}\) = moisture content, % wet basis
EMC = Equilibrium moisture content calculated from Equation [5.1].

5.2.7 Data analysis

Calibration slopes and offset of the sensors were determined by performing linear regression in SigmaPlot 13.0 (Systat Software, Inc., San Jose California USA, 2014). Effect of bag position on calculated average monthly MC\(_{wb}\) of stored corn and paddy were determined using the mixed procedure in SAS (version 9.4, SAS Institute, 2013). Storage period (in months) was treated as the repeated measure while MC\(_{wb}\) was treated as the dependent variable.

5.3 Results and discussions

5.3.1 Sensor calibration results

The manufacturer’s specified accuracy for the SHT35 sensors was ±0.1°C and ±1.5% RH under the test conditions. Temperature readings showed marginal differences of ±0.2°C for all the sensors. The intercept for the regression between measured RH of the sensors and humidity fixed points for the saturated salt solutions ranged between 3.2% and 4.1%, with an average value of 3.7%. The slopes for all sensors were unity with standard deviations less than 0.04. The RH readings were therefore adjusted using (Danao et al., 2015).

Equation [5.3]

\[
y = \left(\frac{1}{b}\right)x - \left(\frac{a}{b}\right)
\]  

[5.3]

where;

\(y\) is the adjusted RH reading (%), \(x\) is the actual sensor RH reading (%), \(a\) is the slope, and \(b\) is the average value of intercept of the calibration line. Raw data obtained for each sensor, the humidity fixed point of saturated salt solutions used and the plot showing the regression of the data are presented in appendix A3.
5.3.2 Equilibration time for the sensors

Figure 5.6 shows changes in T and RH for 13.5% corn initially at room temperature (approximately 20°C) after placing in the environmental control chamber set at 25°C. The plots (average for eight sensors) indicated an initial rapid progression towards equilibrium within the first 2 min. The values slowly approached equilibrium afterwards, with the readings stabilizing after 5 min. The average temperature change was less than 5% after 4 min and 30 s., while the average relative humidity change was less than 5% after 5 min and 30 s. Thereafter, the standard deviations of the eight sensors ranged from 0.31°C to 0.44°C for temperature and 1.44% to 1.84% for RH. Similar trends were observed for other storage conditions.

Since the sensors stabilized after 5 min, the system will adequately measure T and RH in bagged grain where the conditions change much more slowly. The performance of the sensors under the test conditions were similar to those reported by (Armstrong et al., 2017) where sensors were inserted into bulk corn of different moisture content to determine the response time. The authors suggested that the sensors would require at least 6 min to equilibrate with the ambient air before accurate readings could be taken.

Figure 5.6. Sensor readings for T and RH with 13.5 MC (%wb) corn samples at 25 °C (n=3). Error bars are one standard deviation with three replications.
5.3.3 Temperature measurements in warehouses

Data collected by the monitoring system showed that variations existed in the daily average temperature within bagged corn and the surrounding air within the warehouse. Figure 5.7 shows the temperature distribution in the two warehouses. In Ilorin, the maximum ambient temperature recorded was 32.9°C on May 5 and the minimum was 23.7°C on June 27. During this period, corn temperature reached 30.9°C after about 6 days of storage and decreased to 26.9°C on June 27. Similar trends were observed in Tede where paddy was stored. Ambient temperature was highest on May 23 at 33.4°C while the lowest value, 24.1°C was recorded on August 5. Paddy temperature reached 28.8°C on May 23 and reduced to 24.7°C on August 11. Temperature generally decreased over the storage period until about mid-August, then increased slightly towards the first week of September.

![Graph](image1.png)

Figure 5.7. Average daily temperatures within the bags, under the pallet (floor) and at the eave (ambient) of the two warehouses.

Analysis of the temperature within the bagged corn (bag), air spaces surrounding the bags (space) and the air beneath the pallets (floor) shows that average temperature at the various locations were significantly different (p<0.05) over the storage period. The air beneath the pallets (floor) was cooler than the air surrounding the grain bags. However,
there was no significant interaction between the temperature at various positions and the storage period.

Figure 5.8 shows the average daily temperature of bagged corn and paddy at three different positions: top, center, bottom, and the ambient air. Bagged corn temperature responded slowly to changes in ambient conditions as indicated by the higher temperature recorded in the bags during the first four weeks of storage. After the fourth week, corn temperatures followed the ambient air temperature with a lag and a damped amplitude. Corn temperature at the center of the stack (bag that is completely covered by other bags) was highest in the first six weeks of storage. This is due to the insulating properties of grain causing heat to be retained. Consequently, it took more time for the bag at the center to cool down. After six weeks, the temperature of the bag at the center decreased and tracked the temperature changes in the top bags for the remainder of the storage period. The temperatures of bagged corn in the various positions in the two stacks were not significantly different (p<0.05). The stacks were small and a significant temperature gradient between the bags was not observed. However, if the average monthly temperatures were considered, they were significantly different. This was expected because of the changes in weather conditions between May and August. A slightly different trend was observed in the bagged paddy where temperatures at the three locations within the stack can be clearly distinguished from the bags on the bottom that remained at a lower temperature during the storage period. Bags in the center were generally warmer than bags on top.
This demonstrates that farmers should bag grain in a cool and shady environment to minimize the initial temperature of grain considering the long period required for bagged grain to cool within the stack. This initial heat buildup can pose problems, especially in large stacks having several bags that are shielded from the ambient environment. The observed trends are similar to sinusoidal curves in grain bins and silo bags where the temperature of the grain at the peripheral layer follows the ambient with a lag and dampened amplitude (Wang & Zhang, 2015).

Figure 5.9 shows the average daily relative humidity distribution in the warehouses. In Ilorin, the lowest ambient RH was 53% on May 5 and the highest was 82% on July 5. The corresponding lowest ambient RH in Tede was 63% on May 23 and the maximum was 74% on August 18. The average relative humidity levels in interstitial spaces of the bagged corn ranged between 60% and 67% while that of bagged paddy ranged between 64% and 76%.

The relative humidity in the bags increased during the storage period at both locations. The same trend was observed for the three locations in the stack – top, center
and bottom. Relative humidity in bagged corn located at the center of the stack was slightly higher than the bags at the bottom and on top. However, in bagged paddy, the relative humidity in the bottom bags was higher than the bags at the middle and on top. This contrasting observation is likely due to the size of the stack and the specific properties of corn and paddy.

Figure 5.9. Average daily relative humidity levels in bagged corn and paddy stored in naturally ventilated warehouses.

5.3.4 Calculated EMC

The initial moisture content for corn as determined by the AOAC methods ranged from 10.5 % to 10.9 % and the final moisture content was between 11.5 and 12.1 %, an increase between 0.5 and 1.6 percentage points. Table 5.1. shows the average predicted monthly MCwb for stored corn and paddy after applying Eqns [5.1 & [5.2] for the observed temperature and RH conditions. Note that the calculated moisture content increased during the storage period. The average increase in MCwb for bagged corn in the top, center and bottom positions were 1.0, 1.0 and 1.1 percentage points, respectively. The predicted corn moisture content increase compared favorably to the measured moisture content increase. Predicted moisture increases in bagged paddy were 1.3, 1.6 and 1.4 percentage points in
the top, middle and bottom, respectively. The moisture increase was expected since the initial moisture content was low, and the relative humidity increased during the storage period. Bagged corn and paddy adsorbed moisture from the warm, humid air surrounding the bags and the MC\textsubscript{wb} increased during the storage period. However, the observed trend was similar irrespective of the position of the bags.

Table 5.1. Changes in predicted MC (% wb) values of corn and paddy during the storage period for different positions in the stack.

| Storage period | EMC (% wb) | | | | | |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                | Corn      | Paddy     |            |            |            |            |            |            |            |
|                | Top       | Center    | Bottom     | Top        | Center     | Bottom     | Top        | Center     | Bottom     |
| May            | 11.8\textsuperscript{c} | 12.1\textsuperscript{b} | 11.4\textsuperscript{d} | 11.5\textsuperscript{d} | 11.2\textsuperscript{d} | 12.0\textsuperscript{c} |
| June           | 12.0\textsuperscript{c} | 12.4\textsuperscript{b} | 11.7\textsuperscript{d} | 12.0\textsuperscript{c} | 12.0\textsuperscript{c} | 12.6\textsuperscript{b} |
| July           | 12.5\textsuperscript{b} | 12.8\textsuperscript{b} | 12.1\textsuperscript{b} | 12.3\textsuperscript{b} | 12.4\textsuperscript{b} | 12.9\textsuperscript{b} |
| Aug            | 12.8\textsuperscript{a} | 13.1\textsuperscript{a} | 12.5\textsuperscript{b} | 12.8\textsuperscript{a} | 12.8\textsuperscript{a} | 13.4\textsuperscript{a} |

Analysis of the average monthly EMC showed that the calculated values differ significantly (p<0.05) with respect to month and location in the stack for both grains. In corn (small stack), there was no significant change in MC\textsubscript{wb} after the first two months of storage at all positions. A significant change in MC\textsubscript{wb} was recorded between July and August for the bags in the top and center of the stack but not in bottom bags. A possible reason for this result was the relatively small mass of grain stored in the warehouse and possible differences in the initial moisture content of corn in individual bags.

In bagged paddy, the moisture changed significantly with the storage period for bags at the top and center of the stack. This increase was more pronounced due to the sensor location at the end of the stack. There was no significant difference in the calculated moisture in the bottom bags for June and July. The effect of position on moisture content in the bagged grain during storage is not clear from the data obtained. More data is required to explain the observed changes in moisture content with respect to the position of the bags.
The small temperature gradient observed in the two warehouses is an indication that moisture change in bagged grain was not driven by temperature gradients but rather vapor pressure of the air surrounding the bags. This phenomenon has been reported to cause spoilage of upper layers in horizontally stored bulk corn (Joffe, 1958) under tropical climates and crust formation at the center of piles in flat storages under cold climates (Jian et al., 2009).

5.4 Conclusions

The monitoring system developed was effective in measuring temperature and relative humidity levels in warehouses and within stacks of bagged grain. The system had a short response time, with the capability of recording stable data after about five minutes. The condition of bagged grain can be effectively monitored over the storage period using this system without opening the bags which was a big improvement over currently available moisture meters. Data collected were used to estimate the EMC of stored grain which was an indication of moisture changes and storability. The system provided a better understanding of the effect of varying ambient conditions on the internal environment and moisture changes of bagged grain stored in warehouses. Vapor pressure gradient between the air and grain is more likely to contribute to moisture transfer under the observed conditions due to negligible temperature gradients in the stack. Temperature and EMC data from the system will be useful for developing appropriate models that will aid effective management of bagged grain. This will help warehouse managers to better manage insect and mold problems and hopefully reduce postharvest losses. The system can be scaled to suit a particular warehouse capacity and as such will ease the adoption rate by various stakeholders. With additional cost reduction through economies of scale, farmers and grain storage facility managers in Africa should be able to afford the system.
CHAPTER 6. IMPACT OF STORAGE ENVIRONMENT ON THE MICRO-CLIMATE AND GRAIN QUALITY IN POLYPROPYLENE STORAGE BAGS

Abstract

Polypropylene bags (100 kg capacity) are used by farmers in many African countries for handling, marketing, and storage of grain. Though high postharvest losses have been reported in polypropylene bag storage systems, most of the reported losses are estimates from experimental studies where small quantities of grain are placed in bags with all surfaces exposed which is different from the usual practice of arranging bags in stacks. This study investigated the effects of warehouse temperature and relative humidity at two locations (Ilorin KW, Nigeria and Lexington KY, USA) on corn (initially at 10% and 14% moisture content wet basis, respectively) in polypropylene bags arranged in a small (KW) and larger stack (KY). A monitoring system having multiple measurement points located under the roof and pallets, air spaces between bags and inside selected bags provided the temperature and relative humidity profile within the warehouse and the micro-climate of selected bags from May 3 to Sep 9, 2019 at Ilorin (four months) and Dec 8 to Sep 28, 2020 at Lexington (ten months). Temperature and relative humidity in the warehouse at Ilorin ranged between 23-31 °C and, 60-82% and from -1 to 26 °C and 39-95% respectively, at Lexington. EMC of bagged corn was determined by the modified-Henderson equation and increased by 1.2% and 0.5% (wb), at Ilorin and Lexington, respectively. Insect damaged kernels in Ilorin and percent weight loss due to insect damage ranged between 7-24% and 0.1-18% respectively, after four months of storage. There was a significant difference in the number of insects present in bags at different layers in the stacks. Warm weather encouraged the multiplication of insects in Ilorin. Minimal insects were found in corn stored in Lexington. The results demonstrated that monitoring could help to prevent deterioration due to moisture and insect activities in bagged grain.
6.1 Introduction

Grain is the most important staple in the whole of Africa forming the bulk of their diets (Awika, 2011). It is the basis for food security in Africa because it provides over 20% of total calories in human diets in 21 countries, and over 30% in 12 countries (Yakubu et al., 2011). Of all the cereal crops grown in Africa, corn is the most important in terms of nutrition and calorific value (Nuss & Tanumihardjo, 2010). About 67% of total corn production in the developing world comes from low and lower-middle-income countries thus stressing the significant role of corn in the livelihoods of millions of poor farmers in Africa (FAO, 2010). Postharvest losses (during transportation, storage, processing, and marketing) of grains in Africa is estimated to be about 30% (Hodges et al., 2010). Storage losses account for about 80% of the estimated numbers. Grain storage in Africa is affected by insect infestation and attacks by molds and rodents (Degri & Zainab, 2013). Insects and molds thrive in most African countries due to the prevailing hot humid weather (Fields, 1992; Yaouba et al., 2012). An investigation into grain handling in Nigeria and in some other part of Sub-Saharan Africa show that about 70% of harvested grains are stored by farmers in their homes (in jute or polypropylene bags) or farms using traditional storage structures such as cribs, rhumbus (woven thatch structures), and roofs (Kamala et al., 2016; Umeh, 1994). The use of inefficient storage technologies and poor postharvest management practices have been identified as a major problem in Sub-Saharan Africa (Adejumo & Raji, 2007). Even though grain yield has increased over the years, the inability to store grains properly still constitutes a major problem for food security in Sub-Saharan Africa (Adegbola et al., 2011). Because storage is an integral part of the grain value chain, an effective storage mechanism can minimize postharvest losses and enhance marketing (Adeyeye, 2017).

Grain is mostly stored in polypropylene bags and arranged on pallets in naturally ventilated warehouses across many rural communities in Africa and Southeast Asia. Bag
storage has been a long-time practice with jute bags and more commonly now, polypropylene bags holding between 80 and 120 kg of grain are the standard means of handling, marketing, and storage. A good explanation for this trend is the existence of predominantly small-scale farmers with an average farm holding of about 1.5 hectares (FAO, 2010). Thus, grains are stored in polypropylene bags that fit within the low production levels. Other factors that have allowed the continuation of bagged grain storage systems include poor road infrastructure, high cost of modern storage technologies, and the segregated marketing system that limits grain aggregation and bulk trading (Smale, 2011).

This storage practice is, however, associated with insect infestations and other forms of spoilage (Kamala et al., 2016; Ognakossan et al., 2013). Because of the vulnerability of bagged grains to insect attacks, they are mostly used in conjunction with insecticides. However, despite the effectiveness of insecticides, cases of abuse, grain contamination, and pesticide resistance have given rise to serious concerns among farmers, processors, and consumers (Okoruwa et al., 2009). Polypropylene bags do not prevent air and moisture movement in ventilated warehouses as the grain condition often deteriorates with rapid changes in the environment in which they are stored (Lane & Woloshuk, 2017a).

Moisture content and temperature are the most important factors in ensuring the storage stability of crops including grains. The common rule of thumb is that grain should be stored at a low moisture content and low temperature. Thus, to maintain the quality of stored grains proper monitoring is required because the condition of stored grain changes with the prevailing weather conditions. According to Abe and Basunia (1996), the condition of stored grain can only be known by getting temperature and moisture content data at various points in a grain bulk over the storage period. This is achieved by collecting samples from the bags and analyzing the samples to make decisions. However, this approach is not efficient, and it only reflects the condition of stored grain at the time of sampling. The need for monitoring has led to the development of various devices with temperature and relative humidity data acquisition capabilities that allows for grain
moisture and temperature to be monitored during storage (Armstrong et al., 2017; Gonzales et al., 2009; Ward & Davis, 2013). However, many farmers and grain aggregators in Africa do not have access to such devices, thus making monitoring very difficult or impossible.

PICs bags have been introduced to Africa as an alternative to the polypropylene bags to reduce postharvest losses in grain storage (Amadou et al., 2016; Baoua et al., 2014; Williams et al., 2017). However, despite the tremendous positive results that have been reported with the use of PICs bags many farmers are constrained to using woven polypropylene bags for storing grains (Nouhoheflin et al., 2017). It is therefore important for researchers to continue to study woven poly-propylene bag storage systems to improve them.

One of the causes of grain spoilage during storage is moisture migration and redistribution resulting from convection currents arising from temperature differential in bulk grain. According to Khankari et al. (1994), the phenomenon is driven by a gradient in the partial pressure of water vapor which causes water vapor to diffuse from the warmer region to the colder region in a grain bulk. The magnitude and rate of this diffusion is a function of, average moisture content of the grain in storage, size of storage, length of the storage period, and differences in ambient and grain temperature (Joffe, 1958). It has been reported that insect activities in stored grain can also contribute to this phenomenon due to the correlation between insects and temperatures.

Even though many studies have reported high postharvest losses in grain stored in woven polypropylene bags (Baoua et al., 2014; Lane & Woloshuk, 2017a), it is important to note that most researchers reported losses from single layers of bags or minimal number of layers. A typical example of such arrangements is shown in Figure 6.1, where small bags were used and not arranged in stacks and, as a result, more than 80% of the bag surface area was exposed to the room air conditions.
For instance, Lane and Woloshuk (2017a) in their study used only three bags and there was no indication of how the bags were arranged. This arrangement is however different from what is common in the field or warehouse where bags are arranged in stacks with successive layers interlocked which limits the number and size of air channels depending on the tightness and size of the stack. Because grain is a good insulator, it is counter-intuitive to expect the microclimate of single bags of grains or those arranged side by side to be representative of those arranged in large stacks. A recent study showed the effect of integrated pest management (IPM) techniques on the quality of corn stored in 4 different markets in Nigeria (Ala et al., 2020). The experimental setup contained bags in layers, (three layers of 100 kg polypropylene bags of corn using traditional storage practices and 4 layers of 100 kg polypropylene bags of corn stored using IPM techniques). They reported that using IPM can significantly lower insect population in bagged grain and has the potential of reducing the pressure of using insecticides to control insect infestation in bagged grain storage system. Although the temperature and relative humidity of the store houses were monitored, temperature and humidity within the grain were not monitored during storage. Thus, the study was unable to establish the magnitude of the changes in grain condition and correlation with insect population. This effort showed that while researchers continued to promote the use of PICs bags to replace woven polypropylene
bags entirely in the future, proper monitoring of the condition of bagged grain and the use of IPM techniques can help reduce insect damage in bagged grain in the immediate term.

Therefore, the objective of this research was to continuously monitor temperature and relative humidity in bagged corn and evaluate the impact of temperature and relative humidity changes in grain warehouses on the microclimate and insect population in bagged grain stored under two different climatic conditions.

6.2 Materials and methods

6.2.1 Sample preparation

6.2.1.1 Experimental set up in Ilorin, Nigeria

Woven polypropylene bags were procured from a produce market in Ilorin, Kwara State, Nigeria. Corn used for the experiment was procured in February 2019 from a local market in Oke-Oyi, Ilorin East Local government area of Kwara state, and transported to the Nigerian Stored Products Research Institute campus in Ilorin. The average weight of the bagged corn was 85 kg. Bags were arranged on pallets and fumigated by placing 1 Phostoxin® pellet per 100 kg of grain. The bags were aerated on the fifth day by removing the plastic sheet and opening all windows and doors for natural air movement. The bags were then mixed by filling a new bag with about 25 kg, then shaken together then new bags were filled with 40 kg of thoroughly mixed grain. A total of 54 bags were filled. A temperature and relative humidity monitoring system developed as a part of this project was placed in selected bags to record the condition of air within the bag stack and recorded hourly. The bags were sewed and arranged on two pallets in a small grain warehouse consisting of 27 bags each in a 3 x 3 x 3 stack. Sensors were placed in the air spaces between bags to record conditions within the stack. One sensor was placed at the eave of the warehouse to record the condition of the ambient air before it enters the warehouse.
Additional sensors were placed to record the air condition at the headspace above the stacks and under the pallet. This arrangement ensured that the environmental condition of the warehouse and the conditions inside the bags were monitored over the storage period which lasted from May through August of 2019. The bag arrangement and position of the temperature and relative humidity sensors are shown in Figure 6.2.

![Figure 6.2. Bags arranged in two sets of small stacks in Ilorin, Nigeria](image)

6.2.1.2 Experimental set up in Lexington KY, USA

Woven polypropylene bags were procured from Central Ohio Bag & Burlap, Inc. Columbus, OH, USA. Corn harvested in October 2019 at the University of Kentucky research farm was dried on the farm and stored at 14% moisture content (wet basis). Two hundred bags were filled with 40 kg (about 88 lb) at the UK Feed Mill and transported to campus. Corn was mixed by pouring a portion of one bag into another bag and manually mixing to ensure a uniform initial condition in all the bags. 500 g samples were taken prior to final adjustment to 40 kg ± 50 g and the bags being sewed. The bags were randomly numbered from A1 to H24 with letters representing layers that contained 24 bags. The top
layer was “A” and the bottom layer was “H”. The temperature and relative humidity monitoring system was installed as the stack was formed. However, due to the limited number of temperature and relative humidity probes (32), T-Type thermocouples were also used. The thermocouples were connected to a data acquisition system CR3000 data logger (Campbell Scientific, Logan, UT, USA). All data was recorded hourly. The bags were then moved to a storage area and arranged on pallets with an alternating 4 x 6 or 6 x 4 pattern (24 bags per layer and 8 layers in height). All bags (192) were arranged on 4 pallets in a single stack. Data loggers and thermocouples were also placed in selected locations within the stack, underneath the pallets, and at about 1 meter above the stack to record the air conditions within the stack, at the floor and the headspace, respectively. The storage period was from December 2019 to September 2020. The experimental setup is shown in Figure 6.3. A detailed view of each of the layers with the corresponding position of sensors and thermocouples is presented in appendix C1.

The four monitoring units were positioned into four (4) regions, 1) core- bags at the center of the stack, 2) intermediate-bags that surrounded the bags at the center, 3) peripheral-bags at the top and sides of the stack that are exposed to the room conditions and, 4) bottom-bags that are on the pallets.
6.2.2 Insect count

Triplicate samples were taken from selected bags at the start of the experiment in Ilorin. Insects were separated from corn by using a US sieve (No. 10 2-mm openings) to remove adult insects. The insects were identified and counted Figure 6.4. Percent insect-damaged kernels numerical basis (IDKn) per 500 g due to insect exit holes on grain kernels was determined using the converted percentage damage method Equation [6.1] (Quitco & Quindoza, 1986). Percent weight loss due to insect damage was calculated using a count and weigh method (Tiongson, 1992). The insect population density was determined based on the number of insects per 1000g sample of corn (Equation [6.2]).

Equation [6.1]

\[
\%IDK(nb) = \frac{N_d}{\text{Total number grains}} \times 100
\]  

[6.1]

where,

\(nb\) = numeric basis
\( N_d = \text{number of damaged grains} \)

Equation [6.2]

\[
\% \text{ weight loss} = \frac{(U N_d) - (D N_u)}{U (N_d + N_u)} \times 100
\]  

[6.2]

where \( U = \text{weight of undamaged grains}, \)

\( N_d = \text{number of damaged grains}, \)

\( D = \text{weight of damaged grains}, \)

\( N_u = \text{number of undamaged grains}. \)

Figure 6.4 Insect count and identification at Ilorin, Nigeria
6.3 Determination of moisture content and grading factors of corn

Moisture content of corn stored in Ilorin was determined using the AOAC standard as described in chapter 5. In Lexington, at the start of storage four (4) random samples were collected from each layer (A to H). Moisture content of each corn sample was determined by drying 15 g sample in a convection oven at 103 °C for 72 hours (ASABE, 2007). Duplicate samples were analyzed from each bag. Monthly samples were taken from the selected bags in peripheral region of the stack and analyzed for moisture (January to June). The last sample was taken in August. The moisture content of the samples was determined on a wet basis using

Equation [6.3]

\[ MC_{wb} (\%) = \frac{G_W - G_D}{G_W} \times 100 \]  

[6.3]

where;

\( MC_{wb} \) is the wet basis moisture content, %

\( G_W \) is initial mass of corn, in g

\( G_D \) is the final mass of corn, in g

EMC of bagged corn at was determined from modified Henderson Equation [6.4] and modified Chung-Pfost Equation [6.5] using temperatures and relative humidity recorded by the data loggers at the four regions. The average of both values was reported as the EMC.

Equation [6.4]

\[ EMC = \left[ \frac{-\ln(1 - rh)}{A(T + C)} \right]^\frac{1}{B} \]  

[6.4]

where;

EMC = moisture content, dry basis decimal

rh= relative humidity of interstitial of air (decimal)
T = grain temperature (°C)

The estimated parameters of adsorption data for shelled corn A, B and C are 4.6715 E-5, 1.9704 and 82.205 respectively (Chen & Morey, 1989).

Equation [6.5]

\[ EMC = -\frac{1}{B} \ln \left[ -\frac{(T + C) \ln (rh)}{A} \right] \]

The estimated parameters of adsorption data for shelled corn A, B and C are 481.14, 0.16905 and 64.561 respectively (Chen & Morey, 1989).

The following quality parameters which are related to grading were determined as described by Meinders (1993).

i. Broken corn (BC)

ii. Foreign material (FM)

iii. Broken corn-foreign material (BCFM)

iv. Damage

About 200 g sample was taken from all the sample bags for quality analysis. The samples were placed in Ziplock bags and stored in a cooler (at 5 °C) before they were analyzed. The particle sizes in the samples were determined using round hole-screens 4.8mm (12/64 in) and 2.4 mm (6/64 in). Percent damage and percent BCFM were determined accordingly.

6.4 Data analysis

At the two experimental sites, temperature and relative humidity within the bags (representing the grain microclimate) and the environment surrounding the bags were recorded by data loggers (the system developed in chapter 5). Data collected were analyzed using SAS 9.4 (SAS Institute, 2013) with PROC GLM and LSMEANS for determining statistical significance with a 5% probability level. For the experiment in IlorinKW,
Nigeria, stack, position, and insect species were treated as dependent variables. The number of insects was the independent variable. Interactions among the dependent variables were tested where the main effect was found to be significant. For the experiment in Lexington KY, USA, the stack was divided into four groups (core- bags at the center of the stack, intermediate-bags that surrounds the bags at the center, peripheral-bag layer that are exposed, and bottom-bags that are on the pallet). The groups were treated as dependent variables. The average monthly temperature and EMC were analyzed using PROC GLM with repeated command to show statistical significance at 5% probability level.

6.5 Results and discussions

The focus of this chapter is on the storage conditions measured in Lexington, KY. These were the primary results used to validate the model. The results for Ilorin are summarized in Chapter 5 that was used in a publication to describe the design of the monitoring system.

6.5.1 Initial moisture content and grading properties of corn

The initial properties of corn stored in Lexington KY, USA are summarized in Table 6.1. Because corn in the individual bags were thoroughly mixed to obtain uniform moisture and temperature distribution in all bags, minimal differences were found in the measured moisture content. The average moisture content was 14.2 % and ranged from 14.0% to 14.4%. No heat damaged kernels were found, and the total percent damage was less than 3.0%. Also, BCFM percent was less than 1.5% in all the samples, thus the corn was categorized as US No. 1 grade.
Table 6.1 Initial moisture content of corn and grading properties

<table>
<thead>
<tr>
<th>Bag layer</th>
<th>MC (% wb)</th>
<th>Broken kernel (BC)</th>
<th>Foreign matter (FM)</th>
<th>BCFM</th>
<th>Damaged BCFM</th>
<th>Damaged %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>14.1±0.2</td>
<td>1.7</td>
<td>0.3</td>
<td>2.0</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>B</td>
<td>14.3±0.1</td>
<td>1.1</td>
<td>0.1</td>
<td>1.2</td>
<td>4.2</td>
<td>0.6</td>
</tr>
<tr>
<td>C</td>
<td>14.0±0.3</td>
<td>1.3</td>
<td>0.1</td>
<td>1.4</td>
<td>4.4</td>
<td>0.7</td>
</tr>
<tr>
<td>D</td>
<td>14.0±0.2</td>
<td>1.8</td>
<td>0.1</td>
<td>1.9</td>
<td>4.6</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>14.2±0.2</td>
<td>1.3</td>
<td>0.1</td>
<td>1.4</td>
<td>3.6</td>
<td>0.7</td>
</tr>
<tr>
<td>F</td>
<td>14.2±0.2</td>
<td>2.2</td>
<td>0.1</td>
<td>2.3</td>
<td>4.5</td>
<td>1.2</td>
</tr>
<tr>
<td>G</td>
<td>14.2±0.3</td>
<td>1.9</td>
<td>0.1</td>
<td>2.0</td>
<td>4.2</td>
<td>1.0</td>
</tr>
<tr>
<td>H</td>
<td>14.4±0.2</td>
<td>2.6</td>
<td>0.1</td>
<td>2.7</td>
<td>3.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>

6.5.2 Temperature and relative humidity distribution in bagged corn at Ilorin, Nigeria

The daily average temperatures recorded in the warehouse at Ilorin are shown in Figure 6.5 Daily average temperature of the warehouse (room), average corn temperature (bag), and air channel in the stack (space) in the warehouse at Ilorin, Nigeria. Figure 6.6 shows the average daily temperature measured in the bags by layer. The highest recorded temperatures were 31.0, 29.8, and 29.5 °C for the center, top and bottom bags respectively, occurring in May. The corresponding minimum daily average temperatures were 27.0, 27.5, and 27.8 °C, respectively. As expected, the average daily temperature variations followed a sinusoidal curve over the storage period with the temperature inside the bags lagging and with a lower amplitude than the environment. Temperatures inside the bags were initially higher than that of the warehouse environment or the air surrounding the bags for the initial 20 days. During this period, heat is removed from the bagged grain by convection with the air surrounding the bags. As the bagged grain cooled, the corn temperature dropped in June briefly below that of the air between the bags. However, after two months of storage, even though the room temperature continued to drop, the grain temperature was consistently slightly higher than the room and ambient temperature. This suggests that, arranging bags in small stacks after bagging may be a good
way of cooling before they are placed into a large stack for storage. The small volume of bags led to quicker changes in temperature than would be expected in a large stack. The warehouse was well ventilated which aided in the cooling of the stack.

![Figure 6.6 Average daily temperature of bagged corn by layer in the warehouse at Ilorin, Nigeria](image)

The average daily temperature of the room reached a maximum of about 33 °C in May and minimum of 23.5 °C in June. In contrast the temperature in the bags and surrounding air space were about 2.5 °C less than the room temperature at maximum and 4 °C lower at the minimum. The warehouse is designed to be naturally ventilated and to minimize the air temperature within the space. Based on the recorded temperatures, the air space within the warehouse was much cooler than the ambient temperature.
Figure 6.5 Daily average temperature of the warehouse (room), average corn temperature (bag), and air channel in the stack (space) in the warehouse at Ilorin, Nigeria.

Figure 6.6 shows the average daily temperature measured in the bags by layer. The highest recorded temperatures were 31.0, 29.8, and 29.5 °C for the center, top and bottom bags respectively, occurring in May. The corresponding minimum daily average temperatures were 27.0, 27.5, and 27.8 °C, respectively. As expected, the average daily temperature variations followed a sinusoidal curve over the storage period with the temperature inside the bags lagging and with a lower amplitude than the environment. Temperatures inside the bags were initially higher than that of the warehouse environment or the air surrounding the bags for the initial 20 days. During this period, heat is removed from the bagged grain by convection with the air surrounding the bags. As the bagged grain cooled, the corn temperature dropped in June briefly below that of the air between the bags. However, after two months of storage, even though the room temperature continued to drop, the grain temperature was consistently slightly higher than the room and ambient temperature. This suggests that, arranging bags in small stacks after bagging may be a good
way of cooling before they are placed into a large stack for storage. The small volume of bags led to quicker changes in temperature then would be expected in a large stack. The warehouse was well ventilated which aided in the cooling of the stack.

![Average daily temperature of bagged corn by layer in the warehouse at Ilorin, Nigeria](image)

Figure 6.6 Average daily temperature of bagged corn by layer in the warehouse at Ilorin, Nigeria

The average daily relative humidity recorded in the warehouse at Ilorin is shown in Figure 6.7. The highest daily average relative humidity in the warehouse (room) was 81%, 67% in the bags, and 64 % in the space around the bags. The relative humidity of the air surrounding the bags increased steadily by 10%. Similarly, the relative humidity in the bags, having reached a minimum (60 %) after about twenty days increased steadily for the remainder of the storage period reaching 67% lagging that of the space by about 3%. The observed trend was expected because the ambient condition generally gets cooler as rain peaks in September. A comparison of the differences in relative humidity in the bags at the top, center and bottom of the stack is shown in Figure 6.8. The relative humidity of the air
in the bagged grain at the center is only different by about 2.5% from bags at the top and bottom. The temperature combined with relative humidity recorded during the storage period resulted in a warm condition inside the bags making the stored grain susceptible to insect infestation.

Figure 6.7 Average daily relative humidity in the warehouse at Ilorin, Nigeria
6.5.3 Temperature and relative humidity distribution in bagged corn at Lexington, KY

In Lexington, bagged corn cooled from its initial temperature of approximately 10°C to slightly below 0 ° between December 2019 and February 2020 as shown in Figure 6.9. Subsequently, as the ambient temperature increased due to the change in seasons (moving from winter to spring), bagged grain temperature also increased. The average temperature of bagged grain at the top of the stack was consistently higher than those at the center and bottom of the stack, varying almost at the same rate as the room temperature. On the other hand, bags on the bottom tracked the floor temperature with minimal variation. A comparison of temperature profiles in the bags at the peripheral (bags that are exposed to room air or the air under the pallet) of the stack is shown in Figure 6.10. Natural convection currents on the top and side would likely be greater than the small air gap below the pallets. The temperature at the left and right side of the stack (with a space of about 1 m from the wall) were comparable to the top. This suggest that convective heat transfer at the top and sides of the stack was the same magnitude. However, the rate at which heat
was transferred at the bottom of the stack was a little slower. Variations in the convective heat transfer coefficient is an important consideration in modelling temperature distribution in a stack of bagged grain.

Generally, the air beneath the pallets had a lower temperature than the grain at the center. In a large stack (as represented by the set up in Lexington, KY), grain temperature at the center responded slower to changes in the surrounding air. Unlike in the small stack in Ilorin, where there was no clear stratification by layer, as the height of the stack increased, temperature gradients formed. Temperature changes in the stack are due to convective heat transfer. Conduction from bags exposed to convection into the interior is a slower process. This has been well documented in bulk grain storage. However, conduction into the interior is a slower process. The top layer of bags appeared to be at equilibrium with the room conditions. Although temperatures at the core and the intermediate region of the stack tended to be lower that at the top. The is in contrast to the observation made by Lane and Woloshuk (2017b) who reported that though the fluctuation in environmental condition caused cyclic cooling and heating of grain stored in woven polypropylene and PICS bags, the center of the grain never reached an equilibrium with the environmental temperature.
Figure 6.9 Average daily temperature profile in the corn stack in Lexington, KY USA

Figure 6.10 Temperature profile of the bags in the peripheral of the large stack at Lexington, KY
This indicates that there is a tendency for temperatures to remain unchanged in the center of the stack. If the grain was bagged in hot weather, as is usually the case in many African countries, the center of the stack would remain hot. On the other hand, when the grain is sufficiently cooled before bagging and stored in sufficiently large stacks, bags that are not exposed are insulated from the environmental condition thus limiting spoilage.

A comparison of the temperature profiles of selected bags (located in the intermediate and core of the stack) in layers B to G is presented in Figure 6.11. The uniformity observed in the trend is an indication of how compact the stack was. When the stack is tight, convection due to air channels surrounding bags is reduced and fluctuation in the microclimate of bagged grain is reduced which is good for maintaining the quality of stored grain.

Figure 6.11 Temperature profile of selected bags that are completely covered in the stack

The maximum average daily relative humidity recorded in the room during the storage period was 95% occurring in March and the lowest was 38% occurring in April.
Average daily relative humidity at the floor of the stack ranged from 87% to 40%. In the bags the average daily relative humidity ranged from 71% to 63%, 74% to 62% and, 78% to 62% at the top, center and bottom of the stack, respectively (Figure 6.12).

The relative humidity in the bags at Lexington was generally stable throughout the storage period compared to the fluctuations observed in the room and at the floor. Between December and May, the relative humidity of the air was higher than the floor relative humidity. In summer, the relative humidity under the stack was greater than the humidity in the room. Again, this is because of ventilation in the room and presumably the cooler floor, increasing the relative humidity beneath the stack. As the ambient condition cools (moving from summer to onset of fall), the room relative humidity trends higher than underneath the bags. The relative humidity within the stack was similar until May. By May, the relative humidity in the top had larger fluctuations than the bottom and core. By late summer, the relative humidity in the bottom was greater than the core and the top.

Figure 6.12 Average daily relative humidity in the room and bagged corn at Lexington KY, USA
Figure 6.13 shows the comparison of the relative humidity in selected bags at different layers. During the first five (5) months of storage (December to May), there were three distinct trends in the relative humidity. The observed differences may be due to natural convection but may also be due to minor differences in the initial moisture content. Generally, the relative humidity in bagged corn increased by about 10%. This was similar to the increase of 8% that was recorded in the small stack. However, the size of the stack and the prevailing ambient condition in Lexington during the storage period, did not cause a prolonged warm condition within the stack.

![Figure 6.13 Average daily equilibrium relative humidity for selected bags in Lexington KY, USA](image)

6.5.4 Moisture migration in bagged corn stored

The predicted EMC of grains in the top, center and bottom of the stack in Ilorin, Nigeria is shown in Figure 6.14. Generally, the moisture content increased linearly irrespective of the position of the bags. This was expected because the initial moisture
content of the corn was quite low (10%), the RH increased during the storage period, and the stack was relatively small.

Figure 6.14 EMC of bagged corn stored in the warehouse at Ilorin, Nigeria

The air conditions within the bag would result in the grain absorbing moisture from the surrounding air. The predicted moisture content increase at the end of storage based on the EMC data was 1.2, 1.2, and 1.4 points for the top, center, and bottom. The increase in the actual moisture content for bags at the three positions after four months of storage was 1.2, 1.2, and 1.5 points for the top, center, and bottom, respectively. This shows that the relative humidity sensors can be used to predict changes in moisture content during storage.

Despite the humid environment within the warehouse, corn increased in moisture content, but remained at a level that likely would not lead to spoilage. However, if the initial moisture was 14% and a similar gain in moisture was observed, storage problems would likely occur at the observed temperatures (>27 °C). As demonstrated in chapter 4, woven polypropylene bags are permeable to air and water vapor to a degree that can cause
moisture redistribution within the stack. However, because the stack was small, the moisture content gradient was negligible, and moisture migration was not observed.

The scenario is different in the larger stack at Lexington. As shown in Figure 6.15, the EMC of bagged corn at the top reduced over the storage period. EMC of bagged corn at the bottom of the stack increased while the change in the EMC of the bags at the center was negligible. The top, center, and bottom behaved similarly until April, the divergence that was observed in the last half of the storage season was due to the warm condition caused by high temperature and relative humidity over the summer period. The big fluctuation observed at the top layer in the last half of the storage season was in response to the changing ambient condition.

The average monthly EMC (wb) of bagged corn in the large stack is presented in Table 6.2. Changes in corn moisture in the four regions were very marginal compared to the observed trend at Ilorin. This was due in part to the stable relative humidity recorded in the bags at Lexington, the size of the stack, and the initial moisture content (14%) of grain used. Generally, EMC of bagged corn at the peripheral reduced by about 0.8%, EMC of the bags at the core and intermediate region was stable throughout the storage period while the EMC of bottom bags increased by about 0.6%.
Figure 6.15 EMC of corn stored in Lexington, KY USA

Monthly, average measured moisture content of bagged corn at the peripheral of the stack is presented in Table 6.3. Moisture content decreased in all the bags (excluding layer H). The magnitude of moisture loss tends to decrease from layer A (1.5%) to G (0.3%). The moisture content in the bottom bags (layer H) was stable due to the damp condition of the floor as illustrated by the temperature and relative humidity profile.
Table 6.2 Average monthly calculated EMC (wb) of bagged corn at four regions in the stack at Lexington

<table>
<thead>
<tr>
<th>Months</th>
<th>Stack Region</th>
<th>Peripheral</th>
<th>Bottom</th>
<th>Intermediate</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec-19</td>
<td></td>
<td>14.5±0.2ʰ</td>
<td>14.2±0.1</td>
<td>14.3±0.2</td>
<td>14.2±0.1</td>
</tr>
<tr>
<td>Jan-20</td>
<td></td>
<td>14.2±0.2</td>
<td>13.9±0.0</td>
<td>14.1±0.1</td>
<td>13.9±0.2</td>
</tr>
<tr>
<td>Feb-20</td>
<td></td>
<td>14.3±0.2</td>
<td>13.9±0.0</td>
<td>14.1±0.1</td>
<td>13.9±0.1</td>
</tr>
<tr>
<td>Mar-20</td>
<td></td>
<td>14.3±0.1</td>
<td>13.8±0.1</td>
<td>14.0±0.1</td>
<td>13.8±0.1</td>
</tr>
<tr>
<td>Apr-20</td>
<td></td>
<td>14.2±0.3</td>
<td>13.9±0.1</td>
<td>14.0±0.0</td>
<td>13.8±0.1</td>
</tr>
<tr>
<td>May-20</td>
<td></td>
<td>14.3±0.2</td>
<td>14.0±0.1</td>
<td>14.1±0.0</td>
<td>13.9±0.0</td>
</tr>
<tr>
<td>Jun-20</td>
<td></td>
<td>14.1±0.4</td>
<td>14.3±0.1</td>
<td>14.1±0.0</td>
<td>14.0±0.0</td>
</tr>
<tr>
<td>Jul-20</td>
<td></td>
<td>13.8±0.2</td>
<td>14.6±0.2</td>
<td>14.2±0.1</td>
<td>14.0±0.0</td>
</tr>
<tr>
<td>Aug-20</td>
<td></td>
<td>13.8±0.2</td>
<td>14.7±0.2</td>
<td>14.2±0.1</td>
<td>14.1±0.0</td>
</tr>
<tr>
<td>Sep-20</td>
<td></td>
<td>13.8±0.2</td>
<td>14.8±0.2</td>
<td>14.2±0.1</td>
<td>14.1±0.0</td>
</tr>
</tbody>
</table>

ʰ values are the mean ± standard error, n=18.

Table 6.3 Average monthly measured moisture content of bagged corn at the peripheral region of the stack in Lexington

<table>
<thead>
<tr>
<th>Months</th>
<th>Bag layers</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-20</td>
<td></td>
<td>14.3 *</td>
<td>14.0</td>
<td>14.1</td>
<td>13.8</td>
<td>14.0</td>
<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
</tr>
<tr>
<td>Feb-20</td>
<td></td>
<td>13.8</td>
<td>13.8</td>
<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
<td>13.6</td>
<td>13.4</td>
<td>13.5</td>
</tr>
<tr>
<td>Mar-20</td>
<td></td>
<td>13.6</td>
<td>13.8</td>
<td>13.7</td>
<td>13.7</td>
<td>13.7</td>
<td>13.5</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Apr-20</td>
<td></td>
<td>13.6</td>
<td>13.6</td>
<td>13.7</td>
<td>13.6</td>
<td>13.6</td>
<td>13.7</td>
<td>13.8</td>
<td>13.6</td>
</tr>
<tr>
<td>May-20</td>
<td></td>
<td>13.3</td>
<td>13.5</td>
<td>13.5</td>
<td>13.3</td>
<td>13.4</td>
<td>13.6</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Jun-20</td>
<td></td>
<td>12.8</td>
<td>13.3</td>
<td>13.4</td>
<td>13.3</td>
<td>13.3</td>
<td>13.6</td>
<td>13.6</td>
<td>13.7</td>
</tr>
<tr>
<td>Aug-20</td>
<td></td>
<td>12.8</td>
<td>13.2</td>
<td>13.0</td>
<td>13.3</td>
<td>13.3</td>
<td>13.4</td>
<td>13.4</td>
<td>13.7</td>
</tr>
</tbody>
</table>

*values are the mean, n=36.

6.5.5 Insect infestation

Live insects were found in the bagged grain four months after fumigation in Ilorin. From the triplicate samples of 500 g collected, 2 live adults of *Tibolium castenuem* and 1 larva were found (Table 6.4). This shows that fumigation using polypropylene bags is not effective for total control of insects which further supports some previous work on the fumigation of bagged grains (Ala et al., 2020).
Table 6.4 Insects found in corn after fumigation in Ilorin

<table>
<thead>
<tr>
<th>Insects</th>
<th>Stack A</th>
<th></th>
<th>Stack B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Live</td>
<td>Dead</td>
<td>Live</td>
<td>Dead</td>
</tr>
<tr>
<td>Sitophilus zeamais</td>
<td>-</td>
<td>7</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Tribolium castaneum</td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Rhizopata dominca</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>2</td>
<td>15</td>
<td>-</td>
<td>14</td>
</tr>
</tbody>
</table>

After four months of storage the percent insect-damaged kernels (IDKn%) in the bags ranged between 7–24% while percent weight loss (%WL) ranged between 0.1 – 18%. Similar values were reported by (Anankware et al., 2013) who compared insect infestation in corn stored in woven polypropylene bags and triple bags. The total number of insects observed at the three layers (top, middle, and bottom) in the two stacks are presented in Table 6.5. Insect populations at the bottom of the stack A and B and in the middle of stack B were significantly (p<0.01) higher than the numbers counted at the other positions. Insect species that were identified and counted are presented in Table 6.6. Maize weevil (Sitophilus zeamais) was the predominant specie found in the bags accounting for about 50% of the entire population of insects found. This was expected because of the prevailing temperature and relative humidity in the bags match the optimum condition for maize weevil development (Throne, 1994). This result agrees with the findings of (Ala et al., 2020) who reported S. zeamais as the most predominant internal feeder with significant damage to bagged corn stored in some markets in Nigeria. About 56% of insects in stack A were found at the bottom layer with 26% found at the top layer. Similarly, in stack B, 37% were found at the bottom and 28% were in the bags at the top layer. The distribution is, however, not significantly affected by the position of the bags in the stacks. The concentration of insects in the bottom layer may be due to the seemingly damp condition.
which was conducive for their development. The increase in insect population was due to the warm temperatures in the warehouse.
Table 6.5. Percent IDK and percent weight loss values, range (average and standard error) in bagged corn after four months of storage in Ilorin

<table>
<thead>
<tr>
<th>Variable</th>
<th>Stack A</th>
<th>Stack B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Middle</td>
</tr>
<tr>
<td>% IDKnb</td>
<td>12.7 – 13.3 (13.0 ± 0.5)</td>
<td>17.7 – 23.8 (18.9 ± 2.9)</td>
</tr>
<tr>
<td>%WL</td>
<td>0.1 – 5.3 (2.8 ± 0.9)</td>
<td>0.9 – 5.7 (2.7 ± 0.7)</td>
</tr>
</tbody>
</table>

Table 6.6 Number of insects in polypropylene bags after four months of storage in Ilorin a

<table>
<thead>
<tr>
<th>Insect</th>
<th>Stack A</th>
<th>Stack B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Middle</td>
</tr>
<tr>
<td>Sitophilus zeamais</td>
<td>5.7 ± 1.5 A  b</td>
<td>2.6 ± 0.8 B</td>
</tr>
<tr>
<td>Tribolium castaneum</td>
<td>0.3 ± 0.1 B</td>
<td>0.9 ± 0.1 B</td>
</tr>
<tr>
<td>Rhizopata dominca</td>
<td>0.3 ± 0.1 B</td>
<td>0.4 ± 0.1 B</td>
</tr>
<tr>
<td>Others</td>
<td>4.8 ± 0.6 A</td>
<td>4.1 ± 0.6 A</td>
</tr>
<tr>
<td>Total</td>
<td>11.1 ± 1.1 B</td>
<td>7.8 ± 1.4 B</td>
</tr>
</tbody>
</table>

a Values are the mean number of insects per 500 g of maize ± SE.

b Letters represent significance (P < 0.01) across each row.
This result is in line with the findings of Lane and Woloshuk (2017) who reported that warm environments encourage insect infestation in bagged grains. Papanikolaou et al. (2018), also reported that the combination of environmental conditions, moisture content of the grain, as well as the interaction among the insect pest species, also affects the development of pests in stored commodities. Furthermore, it has been demonstrated that some stored product insects can penetrate polypropylene packaging materials either at the larvae or adult stage (Scheff et al., 2018), thus suggesting that some of the insects might have gained access into the bagged grain from outside. There was no indication of insect infestation in corn samples collected at Lexington at the start and up until July 2020 when some Angoumois grain moth (Sitotroga cerealella) were sighted flying around the stack. Maize weevils (Sitophilus zeamais) were found in bag H13 located at the bottom right side of the stack in August. Two factors responsible for the presence of insects are the warm weather and problems with rodents. As shown earlier, the weather in Lexington warms up during the summer months. This prolonged warm period was conducive for insects. There were a couple of times when squirrels were sighted running out of the stacks, they cut open some of the bags ate the germs of the corn and spilled grain onto the floor. which provided easy access for maize weevils that were found. The absence of insects from December 2019 to June 2020 was expected due to the low temperatures recorded during the period which is not conducive for stored product insects. Corn in Lexington was likely not infested in the field due to lack of insect development during the summer months. Based on the fumigation results in Ilorin, corn was infested from filed to storage. The difference is likely due to the warm and humid conditions present during harvest in Ilorin relative to Lexington.
6.6 Conclusions

Placement of data loggers in a warehouse provides new information on the magnitude of changes occurring in bagged corn in response to changing environmental conditions during storage. This study demonstrated that the microclimate of bagged corn stored in warehouses is greatly affected by the condition of the air surrounding the bags due to the low protection offered by polypropylene bags. This study showed that for a small stack with most of the bags (~60%) exposed to air, the temperature and relative humidity in the bags change rapidly with the environment. The moisture increase observed in the small stack was approximately 1.0 to 1.5 percentage points. When combined with the warmer temperatures encouraged the development of insects. Therefore, pest control measures targeting multiple species may be required.

In a larger stack, the temperature and relative humidity of bagged corn is expected to respond slowly to changes in environmental conditions due to insulating properties of corn. Although small stacks show the potential of eliminating localized hotspots, persistent hot and humid air surrounding the bags can cause deterioration in the condition of stored grains and enhance insect growth. Thus, large stacks are preferred especially where grains can be sufficiently cooled (below 10 °C) before they are bagged and stored in the warehouse. The use of monitoring temperature and relative humidity is key in managing bagged grain due to the difficulties with taking samples especially at the center of the stack.
CHAPTER 7. MODELING OF HEAT AND MASS TRANSFER IN BAGGED CORN STORED IN A NATURALLY VENTILATED WAREHOUSE

Part I-Mathematical modelling of the temperature distribution in corn stored in woven bags

Abstract

Temperature and moisture content are two important factors that affects storage stability of crops. A two-dimensional finite difference model that predicts the temperature distribution of corn stored in woven polypropylene bags in a naturally ventilated warehouse is described. Thermal diffusivity used for bagged corn was determined through inverse heat transfer using measured temperatures. The model was validated by comparing predicted with experimentally measured temperature in bags located in different locations within a small stack and a large stack. Generally, the predicted temperatures were consistent with the measured temperatures with a mean standard error of 1.1 °C and 0.5 °C in the large and small stack, respectively. Average standard error was 1.6 °C for the bags at the top, 0.8 °C for the middle bags and 1.2 °C the bottom bags. In the small stack, mean standard error was 0.6 °C, 0.5 °C and 0.4 °C for top, middle and bottom bags, respectively. The model can be used to predict temperature distribution in a stack of bagged grain and to determine the required number sensors and appropriate placement for effective monitoring of bagged grain quality during storage.

Keywords: bagged grain, storage, temperature, monitoring, loss management

7.1 Introduction

Temperature and moisture content are the two most important factors that affect the quality of stored grain. Temperature affects insect population and mold development. Moisture content affects mold activities as well as insect distribution in stored grain. Monitoring these two factors are critical components of grain storage management. Grain
quality can deteriorate quickly when these factors are not properly managed especially in bagged storage system where the woven polypropylene bags are permeable to water vapor.

Temperature and moisture content monitoring in a bagged grain system is faced with two challenges. One, temperature data loggers and moisture meters are expensive for most farmers in developing countries where bagged storage systems are popular. The second challenge is that sampling is very difficult in bagged storage systems unlike in storage bins where samples can be taken without necessarily compromising the integrity of the storage structure or losing the crop. Sampling is seldom done in bags, or at best, samples are obtained from bags at the periphery of the stack leaving the condition of the interior bags unknown.

This complication has left farmers to manage their stored grain at their discretion without any scientific means of checking the quality. Consequently, they either store for a very short time and sell at low prices or for longer periods and risk insect and/or mold infestation. Storage losses in grain stored in polypropylene bags have been widely reported to range between 20 and 30% in Sub-Saharan Africa.

Predictive models have been successfully used as an alternative management technique which allow deterioration potential in stored grain to be identified (Iguaz et al., 2004). Mathematical models that describe grain storage process abound in the literature especially for bulk storage of grain in bins and flat storages. Modelling of heat and mass transfer in stored grains with or without aeration have been published, which has improved grain storage management in developed countries.

Most of the models originated from laws on the conservation of heat and mass within a given volume and the equations are solved using numerical methods due to the complex nature of the boundary conditions making analytical solutions nearly impossible in most cases. The development of computers with great speed and capabilities have made numerical solutions less cumbersome and more realistic boundary conditions can now be incorporated into equations describing heat and moisture distribution in stored grain. Finite
difference, finite element, and discrete elements are the numerical methods that have been used to solve heat and mass transfer problems in grain storage (Panigrahi et al., 2019). Finite difference methods have been used to model temperature and moisture distribution in stored grains in storage bins (Abe & Basunia, 1996; Khankari et al. (1995). Others have used finite element methods in developing models that predict temperature distribution in storage bins (Alagusundaram et al., 1990; Jia et al., 2000; Jian et al., 2005). Montross et al. (2002), also developed a finite element model for predicting the ecosystem of stored grain using realistic boundary conditions. A neural-deterministic method has also been used to predict temperature and moisture distribution in wheat stored in a steel bin (Markowski et al., 2007).

Recently, silo bags have been used for grain storage especially in South America where it was developed and since been adopted in several other countries around the world including US, Sudan, Russia and Canada (Arias Barreto et al., 2013; Bartosik, 2012). The bags serve as a hermetic storage container by limiting oxygen and increasing the carbon dioxide content a condition that slows down or eliminates insect activities. Hermetic storage systems are of huge benefit in tropical climates where conventional silos have had limited success due to the problem of moisture migration and condensation (Navarro et al., 1994). Silo bags have been tested under different field and grain conditions to establish their suitability for long term storage. The successes with silo bags have encouraged researchers to develop or adapt mathematical models used for storage bins to silo bags. Many of these modelling activities used numerical methods to predict moisture and temperature distribution as well as oxygen and carbon dioxide concentrations in silo bags for wheat storage (Abalone et al., 2011; Arias Barreto et al., 2013; Gastón et al., 2009) and soybean (Arias Barreto et al., 2017; Ochandio et al., 2017). The models predicted the temperature and moisture distributions well and established the effectiveness of silo bags as a hermetic storage system in controlling insect pests due to the levels of oxygen and carbon dioxide concentration and the average temperature predicted in the bags.
The situation within grain stored in woven polypropylene bags, however, is very
different compared to silo bags. Woven polypropylene bags are not gas tight compared to
silo bags. Also, samples are rarely taken from them, because the way they are arranged as
shown in Figure 7.1., it is practically impossible to take samples from the bags inside the
stack without compromising the integrity of the stacked bags unlike in silo bags which easy
to sample (Gastón et al., 2009). Modeling is currently the only alternative that can provide
a basis for adequate distribution of sensors for temperature measurement in bagged grain
and information on grain quality since most of the bags cannot be accessed.

Limited research has been conducted on the mathematical modeling of temperature
distribution in grain stored in woven polypropylene bags. One study evaluated the storage
of “gari” (granulated cassava flakes) stored in woven polypropylene bags (Igbeka, 1987).
The research simulated moisture change in hessian and jute bags using the finite difference
method. They reported a lower moisture transfer in hessian bags compared to jute bags and
that the moisture content of the product would remain at a safe level for a period of six (6)
months. However, the model is extremely limited in the sense that only single bags were
considered which is rarely the case in real life. Secondly, the model was oversimplified
with the assumptions used. For instance, the model assumed that moisture transfer occurred
by diffusion in the vertical direction and that convection in the bag was negligible. This is
far from reality as the bags are exposed to air within the room and moisture redistribution
cannot be established by neglecting diffusion. Secondly, the assumption that temperature
and relative humidity surrounding the bags are constant during the storage period is
unrealistic.

Deployment of temperature and relative humidity sensors in bag storage systems is
currently not being practiced. This is because farmers generally cannot afford many of the
devices available in the market. According to World Bank (2011), the low use of grain
quality monitoring devises such as moisture meters and temperature sensors is a major
challenge in providing effective monitoring. However, a major drawback is knowing the
required number of sensors that can be used in a stack that will provide the temperature
distribution for effective monitoring. Considering the required capital outlay for such a
task, warehouse managers often resolve to guess work based on their experience.
Modelling can, however, provide a cheap means of arriving at the required design. A good
model can give the temperature distribution and as such temperature gradient within the
stack will be known, with which the expected location of sensors can be determined
without putting the quality of the stored grain at risk.

Therefore, the objective of this study was to (1) adapt the heat transfer model
presented by (Khankari et al., 1994) with some modification for predicting the temperature
distribution in corn stored in woven polypropylene bags arranged in stacks under naturally
ventilated conditions due to the inherent variability in environmental condition within the
warehouse; (2) to validate the model with experimental data from a small stack and a large
stack; and (3) to determine the adequate number of sensors needed to monitor temperature
distribution in a stack of a particular size from the predicted model.

7.2 Materials and methods

7.2.1 Model development

To describe the model development, the grain stack used for the validation in
Lexington will be described. The schematic diagram of the front view of a stack of bagged
grain with 192 bags of 40 kg (88 lbs) of corn is presented in figure 7.2. The setup is treated
as an axisymmetric homogeneous solid (with uniform temperature and moisture in all the
bags at the start of storage). Heat is transferred from the center of the bags by conduction
and in and out of the stack externally from the surroundings (perimeter represented by the
room and floor conditions) by convection.
The following assumptions were considered in developing the model. Assumptions are listed here for the heat transfer model described below.

1. Initial temperature and moisture gradients within individual bags are negligible.
2. The bag material provides no resistance to heat or mass transfer. The bag material is assumed to have negligible thermal resistance compared to the grain.
3. Temperature and moisture gradients within the kernels are negligible.
4. Inter-kernel heat transfer within individual bags as well as the direct diffusion of grain moisture is negligible.
5. Grain and air within the bags are in equilibrium.
6. The air in the intergranular spaces of the grain mass and in spaces around the bags is stagnant, thus heat transfer is mainly governed by temperature gradient laws.

7. Heat and moisture generation due to grain respiration and other biological activities are not considered.

8. The air channels surrounding the bags are discontinuous and as such heat and mass transfer due to convection within the stack is negligible except on the exposed surfaces.

9. Heat transfer along the length of the stack compared to heat transfer along the width and the height of the stack is negligible. Therefore, a two-dimensional model is adopted.

10. The convective heat and mass transfer coefficient is by surface type (side, bottom, or top).

The energy balance is given by Equation [7.1] (Singh et al., 1993)

Equation [7.1]

\[
\left( \rho_g c_g \frac{\partial T}{\partial t} \right) = \left( k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} \right)
\]  

[7.1]

where \( \rho_g \) is bulk density of bagged grain (kg m\(^{-3}\)), \( c_g \) is specific heat of grain (J kg\(^{-1}\) K\(^{-1}\)), \( k \) is thermal conductivity (W m\(^{-1}\) K\(^{-1}\)), \( T \) is temperature (K), \( t \) is the time interval (s) and \( x \) and \( y \) are the cartesian coordinates (m).

Rearranging

Equation [7.2]

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]  

[7.2]
Let $\alpha = \frac{k}{\rho g c_p}$

where $\alpha$ is the thermal diffusivity in $m^2 s^{-1}$

The initial and boundary condition associated with Equation [7.2] is

Equation [7.3]

$T(x, y, 0) = T_0(x, y)$ for $t = 0$ \[7.3\]

And the boundary conditions at the right and left sides are

Equation [7.4]

$$-k_1 \frac{\partial T}{\partial x} = h_v (T - T_r) \quad [7.4]$$

At the top of the stack

Equation [7.5]

$$-k_2 \frac{\partial T}{\partial y} = h_H (T - T_r) \quad [7.5]$$

At the bottom of the stack

Equation [7.6]

$$-k_2 \frac{\partial T}{\partial y} = h_H (T - T_f) \quad [7.6]$$

where;

$T$ is grain temperature, $T_r$ is the room temperature, $T_f$ is the floor temperature (all in °C), $h_v$ and $h_H$ are the convective heat transfer coefficients of still, indoor air in the vertical and horizontal directions respectively, in Wm$^{-2}$°C$^{-1}$ (McQuiston et al., 2005).

$k_1 = \frac{a dt}{dx^2}$ and $k_2 = \frac{a dt}{dy^2}$

The stability criteria is given as (Holman, 1990).
At the interior nodes the solution is stable if

Equation [7.7]

\[
\frac{(\Delta x)^2 + (\Delta y)^2}{2\alpha \Delta t} \geq 4
\]  

[7.7]

At the convective boundaries, the solution is stable if;

Equation [7.8]

\[
\frac{(\Delta x)^2 + (\Delta y)^2}{\alpha \Delta t} \geq \left( 2 \left( \frac{h_v \Delta x}{k} \right) + 2 \left( \frac{h_h \Delta y}{k} \right) + 8 \right)
\]  

[7.8]

7.2.2 Input material parameters

The thermal properties of bagged corn are different than bulk corn stored in bins and silos or corn stored in silo bags. Published values for the thermal diffusivity were tested in the model but predicted values did not describe the heat transfer accurately. Specific heat as a function of moisture content was taken from ASABE (2008). The bulk density was determined by taking the weight of corn in the bags divided by the volume of the stack. Thermal diffusivity was calculated from experimentally measured temperature in the bags using an inverse heat transfer method. The relationship between transient heat transfer over a given dimension and the thermal diffusivity is given by

Equation [7.9]

\[
\alpha = \frac{d^2T}{dt^2} \frac{d^2T}{dx^2} + \frac{d^2T}{dy^2}
\]  

[7.9]

Multiple segments of experimental data over an extended period where the corn temperature continuously changed (increased or decreased) were fitted to the previous equation. Data for a period of at least 60 hours was used in the equation. Thermal diffusivity was calculated using the Goal Seek Add-In (Microsoft Excel, Microsoft Corp., Redmond,
Subsequently, thermal conductivity was calculated from thermal diffusivity and specific heat with final values shown in Table 7.1. The specific heat was unchanged from literature values.

<table>
<thead>
<tr>
<th>Description</th>
<th>Bulk density kg /m³</th>
<th>Specific heat J/kg K</th>
<th>Thermal conductivity W/m K</th>
<th>Thermal diffusivity m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bagged Corn</td>
<td>570</td>
<td>2040</td>
<td>0.68</td>
<td>5.85x10⁻⁷</td>
</tr>
</tbody>
</table>

7.2.3 Finite difference and solution scheme

Transient heat conduction in two-dimensions using the finite difference is outlined here. The advantage of the explicit method is that the temperature at the current time can be estimated from the previous temperature at the previous time step. However, the limitation with this approach is that once the material properties are specified the choice of grid size and time step will be restricted by stability criterion. However, due to the slow nature of changes in grain stored in bags, a relatively large grid size and time step would give an adequate solution. A two-dimensional rectangular section in a stack of bagged grain is represented by Figure 7.2.

![Figure 7.2](image)

Figure 7.2. Cross section of an ideal bag arrangement in a stack (front view)
Equation [7.2] is transformed into finite difference form using forward difference in space and central differences in time.

Equation [7.10]

$$T_{(i,j)}^{n+1} - T_{(i,j)}^n = k_1 \left( \frac{T_{(i-1,j)}^n - 2T_{(i,j)}^n + T_{(i+1,j)}^n}{dx^2} \right) + k_2 \left( \frac{T_{(i,j-1)}^n - 2T_{(i,j)}^n + T_{(i,j+1)}^n}{dy^2} \right)$$ [7.10]

Let $k_1 \frac{a dt}{dx^2}$ and $k_2 \frac{a dt}{dy^2}$

where;

$i=dx, j=dy, n =$ present time, $n+1$ is the future time.

Considering a section of the stack of height H and width W, in m, the following equations are applied at the various nodes. Equation [7.11] and Equation [7.12] are solved for the future temperature at the interior and bottom nodes, respectively.

Equation [7.11]

$$T_{(i,j)}^{n+1} = T_{(i,j)}^n + F_1 \left( T_{(i-1,j)}^n - 2T_{(i,j)}^n + T_{(i+1,j)}^n \right) + F_2 \left( T_{(i,j-1)}^n - 2T_{(i,j)}^n + T_{(i,j+1)}^n \right)$$ [7.11]

Equation [7.12]

$$T_{(i,j)}^{n+1} = T_{(i,j)}^n + F_1 \left( T_{(i,j+1)}^n + T_{(i,j+1)}^n - 2T_{(i,j)}^n \right) + 2F_2 \left( T_{(i,j+1)}^n - T_{(i,j)}^n \right) + \frac{\alpha \Delta t}{k \Delta y} h_{H(i,j)} \left( T_R^n - T_{(i,j)}^n \right)$$ [7.12]

Similar expression for the grain temperature at the corners and edges are shown in the appendix C1. The stack was divided into a grid in the x- and y-directions. The model was developed and validated using data from Ilorin and Lexington. This would result in maximum matrix size of 14 by 14 finite difference equations that was solved in MATLAB (R2019a, The MathWorks, Natick, MA). The solution was unstable at higher grid sizes,
however, the solution showed that a 7 by 7 grid size would give an accurate prediction of temperatures at the various nodes for the stack in Lexington.

7.2.4 Experimental data for model validation

Two corn storage experiments were setup in two different location to provide experimental data for the purpose of validating the model. The first was a setup for a small size stack stored at Ilorin Kwara state, Nigeria. Corn was procured, cleaned and placed in woven polypropylene bags of 40 kg (about 88 lbs) each. Bags were labeled and arranged in two different stacks (3x3x3 bags) comprising of 54 bags in total, as shown in Figure 7.3. Sensor probes capable of acquiring temperature and relative humidity data were inserted into the approximate center of selected bags before closure. Bags with sensors were then placed at the top, middle and bottom layer in each of the stacks such that the temperature at these locations could be monitored during the storage period. Three other sensors were also placed in the eave of the building, in between the stacks and beneath the pallet to measure the temperature of the air outside (ambient), room and floor, respectively. The experiment lasted from May 3 to September 3, 2019 and data was recorded hourly. The second setup was a large stack of 192 bags of 40 kg capacity arranged in a single stack (6x4x8 bags). The bags were labeled A to H (from top to bottom) with each layer containing 24 bags. Sensors were also distributed in a similar way to the small stack. The schematic view of the arrangements of sensors in bags layer A(top), D (middle) and H (bottom) of the stack is shown in Figure 7.4.. Temperatures were recorded hourly from December 9, 2019 to July 15, 2020 and data was observed each week. Bags, A10, D5, and H23 were in the periphery of the stack while bags D10, D11, and H11 were in the center of the stack. Schematic representation of each of the layers on the stacks and locations of sensors is presented in appendix B.
Figure 7.3. Bagged corn arranged in two small stacks in Ilorin, Nigeria
Figure 7.4. Schematic view of sensor placement in the top, middle and bottom layers of the stack (plan view) in Lexington, KY.
7.3 Results and discussions

7.3.1 Predicted temperatures in bagged corn

Predicted temperatures in the small stack (3 x 3 x 3 bags) for the four month storage period in Ilorin, Nigeria is shown in Figure 7.5. The initial temperatures in all the bags was about 28.5 °C. After one month of storage (June 3rd, 2019), the average ambient temperature was 30.1 °C and the temperature within the stack was about 28.7 °C with a tiny layer (representing about 0.1 m thickness of grain at the top of the stack) at about 28.0 °C. The warmest part of the stack was at the center, about 0.3 °C higher than the surrounding bags. However, as the storage period progressed the warm front moved outward, with the temperature at the center reducing to about 27 °C after two months of storage even though the temperature of the room had increased by about 1 °C. At this point, the temperature is mostly uniform in about 95% of the stack. After three months (August 3rd, 2019), lower temperatures moved into the center of the stack, and the top and the bottom of the stack were marginally warmer. Although the contour lines show an increase, the differences were negligible. At the end of the storage period about 70% of the stack was near 27 °C with the remaining portion representing a tiny layer of about 0.2 m (located at the top and bottom) being at about 1 °C higher.

Generally, there was no stratification in temperatures predicted at the bottom, middle and top of the stack. This is due principally to the size of the stack with the surrounding air penetrating the stack thus maintaining thermal equilibrium between the air in the warehouse (room temperature) and the bagged corn.
Figure 7.5. Contour plots of the predicted temperature in bagged corn in a small stack in Ilorin, Nigeria
In comparison, the temperature distribution within the large stack in Lexington during December 2019 to March 2020 is shown in Figure 7.6. The initial temperatures within the bags in all locations were 10.6 °C (this was in December 2019 when the ambient temperature was 14 °C and the room temperature was 12 °C) with a cold front (9 °C) moving upward from the bottom of the stack. After the first 24 hours of storage, a tiny layer surrounding the bags was already responding to room condition with the temperature decreasing by about 0.5 °C as was expected due to conduction.

In January 2020, as the ambient temperature continued to drop, the center was warmer than the remainder of the stack due to convective current moving upward through the center of the stack. At this point, there was a gradient of about 1.5 °C from the approximate center of the bags at the topmost layer and a further 1.0 °C from the upper surface. This process continued throughout the remainder of the winter months with the grain at the center of the stack cooling by about 1.5 °C after two months and warming up marginally by 0.5 °C as the room temperature increased by 5 °C after three months in storage as weather transitioned from winter to spring. Consequently, the temperature gradient between the center and the peripheral region of the stack dropped to 1.0 °C as a uniform temperature slowly developed across the stack.

The predicted temperatures in the large stack showed a stratification within the bags at the top, middle and bottom after two months of storage with the temperature at the middle > bottom > top by 1 °C. At this stage, more than 60 percent of the grain mass was at 6.5 °C represented at the core of the stack. This contrasts with the observation in the small stack where uniform temperatures existed in all the bags after two months of storage.
Figure 7.6 Contour plots showing predicted temperatures from Dec 2019 to March 2020 in a 4 x 6 x 8 stack of bagged corn in Lexington, KY.
As the ambient condition warmed up (weather changed from spring to summer), the warm air in the room moves up along the warm top and sides of the stack and downward through the center thus causing the cold front to move into the center of the stack. A similar process is observed in grains stored in silos. During winter, the grain at the center of the bin is usually warmer than those at the other parts while at summer, the process is reversed (Abe & Basunia, 1996). This process caused temperature gradient between the center and the peripheral of the bag to increase by five folds reaching 5 °C in April 2020 (Figure 7.7). It should be noted that the grain in the stack at this stage of storage was divided into five (5) isotherm lines with the thickness of each region increasing from the sides to the center. The temperature in about 60% of the grain representing the core of the stack are below 15 °C (layer C down to H) with the temperature in the bags at the periphery at about 2 °C higher. However, as the warm weather persisted, the temperature distribution in the stack approached a uniform condition (about 23 °C) with a portion of the stack representing layers F down to H at the center being 1 °C cooler than the grains in other regions. The differences between the temperature at the top and the sides is due primarily, to the fact that the volume of air in the space between the walls and the stack is very small compared to the air volume above the stack. After seven (7) months of storage, the temperature gradient reduced to about 2 °C across the stack with almost flattened contours. This observation correlated to the response of the bagged grain to the changes in the room temperature as the ambient condition changes.
Figure 7.7 Contour plots showing predicted temperatures from April to July 2020 in a 4 x 6 x 8 stack of bagged corn in Lexington, KY.
7.3.2 Temperature variations in the small stack

Measured daily average temperature at the top, center and bottom of the small stack (represented by the set up in Ilorin) is compared with the corresponding predicted daily average temperature in Figure 7.8. to Figure 7.10., respectively. The measured temperatures presented are the temperatures recorded using the temperature and relative humidity sensor installed during the storage study (Chapter 5). The predicted temperatures are for $\Delta x = 0.2 \text{ m}$, $\Delta y=0.09 \text{ m}$ and $\Delta t=1 \text{ h}$. The result of the explicit finite difference method used is found to be only stable with the grid size of 7 by 7 and one-hour time step. The stability of the solution at higher time steps was not investigated. The dimension of the small stack is 1.65 m by 0.6 m (width by height). Data shown in Figure 7.8. is for the sensor in the top bag positioned at $\sim 0.3$ m from the side of the stack and 0.5 m from the floor. Data from the sensor positioned in the bag at the center ($\sim 0.8$ m from the side and 0.3 m from the floor) is shown in Figure 7.9., while data from sensor positioned in the bottom bag ($\sim 1.3$ m from the side and 0.1 m from the floor) is shown in Figure 7.10.. Grain temperatures (top and center bags) were consistently higher than the room temperature. Temperature in the bottom bag was lower than the room temperature in the first two months of storage. The predicted temperatures closely followed the measured temperatures at all three locations. However, after about 70 days of storage, the predicted temperatures were closer to the room temperature, diverging from the measured temperature. The higher temperature observed during this period is likely due to insect activity within in the bags (the grain was infested as reported in chapter 6).

Generally, the bagged grain was in thermal equilibrium with the surrounding air (room temperature) throughout the storage period. This was due to the relatively large volume of air surrounding the bags.
Figure 7.8. Measured and predicted temperatures at the top layer of a small stack of bagged corn (3 x 3 x 3) and room temperatures in Ilorin from 3 May to 3 September, 2019.

Figure 7.9. Measured and predicted temperatures in the bag at the middle layer of a small stack of bagged corn (3 x 3 x 3) and room temperatures in Ilorin from 3 May to 3 September, 2019.
Temperature variations in the large stack

Predicted temperatures at three locations in the large stack (in Lexington KY) are compared with the measured temperatures (Figure 7.11. to Figure 7.13). Figure 7.11. shows the data for the sensor in the bag at the topmost layer (A10) positioned at ~ 1.0 m from the side of the stack and 1.6 m from the floor. Data from the sensor at D11 (~ 1.5 m from the side and 1.0 m from the floor) is shown in Figure 7.12, while data from the sensor positioned in H23 (~1.5 m from the side and 0.3 m from the floor) is shown in Figure 7.13. The predicted temperatures are for $\Delta x = 0.21$ m, $\Delta y=0.13$ m and $\Delta t=1$ h representing a grid size of 14 by 14. The solution of the explicit finite difference method for the large stack
was found to be stable for the grid sizes 7 by 7 to 21 by 21 with an hour time step. The stability of the solution at higher time steps was not investigated.

The temperature in bag A10 (Figure 7.11.) is similar to a point near the bin wall and was very close to the air in the room with a smaller amplitude in daily temperature variation observed between day 1 and day 130. The grain temperature at the top surface of the stack lagged the room temperature by about a day during this period but was, in thermal equilibrium with the ambient for the remainder of the storage period. The grain reached 1.0 °C in January (23), and 28.0 °C in July (2) which coincided with the maximum room temperature, the minimum room temperature was -1.4 °C on January 21.

![Figure 7.11. Measured and predicted daily average temperatures of bag A10 at the topmost layer (1.6 m from the floor) of 4 x 6 x 8 stack of corn in Lexington, KY with room temperature from Dec 9, 2019 to July 15, 2020.](image)

In the middle layer (bag D11 Figure 7.12) the amplitude of daily temperature variation was much smaller than that of the surrounding air. Also, the predicted and
measured temperatures changed slowly with the change in room temperature. The maximum temperature in the bag was 26 °C recorded on day 215 with the minimum (2.4 °C) recorded on day 47. The temperature in the bag lagged the room temperature by about 3 days for the most part of the storage period.

Figure 7.12 Measured and predicted temperatures in bag D11 in the middle layer (1.0 m from the floor) of 4 x 6 x 8 stack of corn in Lexington, KY with room temperature from Dec 9, 2019 to July 15, 2020.

A similar trend was observed in the bottom layer (bag H11 Figure 7.13). The maximum temperature in the bags was 28.4 °C which is marginally higher than the room temperature and the lowest temperature was 3 °C. However, the temperature at the bottom layer was generally lower than at the other parts of the stack. This was due to the cold convective current moving along the floor as observed in the small stack (comparisons between predicted and measured temperatures at other locations within the stack where sensors were installed are presented in Appendix C2).
The predicted temperatures closely followed the measured temperatures at the three locations in the stack with the temperature increasing from December to July as expected. A similar trend was reported by (Abbouda, 1992) where the temperature of milo stored in a metal bin increased between December and August in Manhattan, KS. However, unlike what was observed in a metal bin, bagged grain temperatures were never higher than the room temperature either during the brief period of cooling (December to February) or during the extended heating period (March to July). The average daily grain temperature at the top surface of the stack was only 2 °C higher than the center. Other researchers have also reported that grain temperatures near the wall are generally higher than other locations in the bin (Jia et al., 2000; Markowski et al., 2007). Gastón et al. (2009) also reported that, grain at the peripheral of silo bags (thickness layer of about 0.2 m from the surface of the
bag are) are in thermal equilibrium with the ambient condition, a situation which predisposes about 25% of grain in the bag to spoilage.

In metal bins and silo bags, grain temperature can be higher than that of the ambient which can cause moisture condensation. This is not a problem in grain stored in woven polypropylene bags because there are no radiation effects. In the event of warm air moving from a warm region at the center, the moisture condensation that could result from that is evaporated at the surface which is why the moisture content of the grain in the bags at the top surface reduced over time (as demonstrated in chapter 6). Furthermore, moisture redistribution within the stack is not likely to occur as a result of temperature gradients but as a result of convection.

Temperature differences were affected by the size of the stack. The small stack generally behaved like a single bag exposed to differences in air temperature. In the large stack, bags at the periphery closely followed the hourly variation in room temperature. The comparison between the predicted and measured values of temperatures at the top, middle and bottom in the small stack using the weekly mean with a regression line is shown in Figure 7.14. Predicted temperatures generally followed the measured temperatures at the three locations with the values spreading above and below the regression line. This shows that the model generally matches the measured values in all cases and cannot be said to under predict or over predict temperatures at these locations. The same observation holds for the large stack. Variations between predicted and measured temperatures in the center bag of a small stack were generally higher. This was likely because of air channels from the surrounding bags.
Figure 7.14 Regression of measured weekly average temperatures versus predicted temperatures in the top, middle and bottom layers of the small stack in Ilorin KW, Nigeria.

The accuracy of the model was quantified using average absolute difference (AAD) and standard error (SE) values. These were calculated for selected positions representing the top, the middle and bottom layer in the stack and are shown in Table 7.2. for the small and large stacks. The accuracy of the model for the three locations in the small stack was within 0.5 °C. In the large stack, the accuracy was between 1.0 °C and 1.7 °C. The observed variations between the measured and predicted values were higher at the top and the bottom of the stack. Iguaz et al. (2004) also reported errors in predicted temperatures were higher at the top and bottom of bins in which rough rice was stored without aeration. The authors stated that a possible cause of deviations between measured and predicted temperatures could be the convection at the boundaries. However, the errors of estimate are similar to those reported by (Abe & Basunia, 1996) and can be considered acceptable for the purposes
of stored grain management as long as temperature increases do not exceed 2 °C between weekly observations. Standard errors for other positions where sensors were installed are presented in appendix C3.

Equation [7.13]

\[ ADD = \frac{|Measured\ T - Predicted\ T|}{sample\ size} \]  \[7.13\]

Equation [7.14]

\[ SE = \sqrt{\frac{(Measured\ T - Predicted\ T)^2}{sample\ size}} \]  \[7.14\]

Table 7.2. Average absolute difference and standard error between measured and predicted temperatures in selected bags in the small and large stacks in Ilorin and Lexington, respectively.

<table>
<thead>
<tr>
<th>Measurement point (x, y)</th>
<th>Small stack</th>
<th>Large stack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AAD (°C)</td>
<td>SE (°C)</td>
</tr>
<tr>
<td>Top</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Middle</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Overall average</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

7.4 Conclusions

A two-dimensional finite difference conduction model was developed to predict the temperature distribution in two stacks of bagged grain stored in naturally ventilated warehouses. The model for a small stack of 1.7 m wide and 0.7 m high and corresponding node spacing of 0.2 m and 0.09 m, respectively, predicted corn temperatures within ± 0.5
°C which is acceptable for managing bagged grain. The average standard error and average absolute difference for the top, middle and bottom bags were 0.5 °C and 0.5 °C, respectively. For a large stack of 3 m wide and 1.7m, high, the standard error was between 1.0 °C and 1.7 °C using a width and height node of 0.2 m and 0.1 m, respectively. The output of the model showed that one sensor inserted at the center of the stack is enough to monitor the temperature distribution in a small stack during storage. Similarly, two sensors with one inserted at the top layer and the other at the center of the stack is enough to monitor temperature distribution in a large stack containing about 100 bags of the usual 100 kg size of grain.

The conduction model developed generally agreed well with the measured temperatures and can be used to predict temperature distribution in large stacks of bagged grain. The model can also be used to determine the required number of sensors needed for monitoring the temperature distribution in a stack of a given dimension.
Part II: Mathematical modeling of heat and mass transfer in corn stored in woven polypropylene bags in a naturally ventilated warehouse

7.5 Introduction

Moisture content and temperature are considered as the most important factors for maintaining grain storage stability. This is because a large portion of grain spoilage is due to moisture migration (moisture uptake and redistribution) usually from the interior of grain bulk induced by temperature gradients (Chang & Weng, 2002). The principal aim of storage is maintaining grain quality. To achieve this, grain should be stored in a safe place with a uniformly low temperature and moisture maintained. This will limit the impact of biotic (insects, molds, grain respiration) and abiotic factors (temperature, relative humidity, and solar radiation) (Brooker et al., 1997). In grain storage, heat and mass transfer (moisture migration) usually occurs simultaneously due to transfer of latent heat in the grain bulk resulting in temperature and moisture gradients. The process causes convective currents which drives moisture migration (Rocha et al., 2013). Although the temperature profile predicted from the thermal model can be used for monitoring grain condition, it can only be realistically applied when the moisture content of stored grain is expected to only change marginally. However, this is not usually the case. Moisture content of stored grain changes in response to varying ambient conditions. During storage, grain temperature and moisture change over time. The magnitude of the change is influenced by initial moisture contentment, and other factors such as the condition of air surrounding the storage structure (in this case the conditions inside a warehouse). Other sources of moisture include water from leaks in the roof, insect activities and respiration. Mass transfer is considered to affect the heat transfer within the grain bulk. It is not just enough to know grain temperature during storage, the moisture content must also be known with a certain level of accuracy for adequate monitoring. Therefore, in this section a coupled heat and mass transfer model is developed to predict temperature and moisture distribution in bagged corn stored under
naturally ventilated warehouse based on previous models by (Gastón et al., 2009; Khankari et al., 1995b).

7.6 Materials and methods

A rectangular stack was considered with the total volume sliced into a finite number of spatial elements in the vertical and horizontal direction. The following additional assumptions were made in developing the mass transfer model:

1. The interstitial air within the bagged grain and the grain are in thermal and sorption equilibrium throughout the stack,
2. Internal heat generation (due to respiration and insect heating) is negligible,
3. A two-dimensional model is assumed. Therefore, only heat and mass transfer in the vertical and horizontal directions are considered.
4. Heat and moisture resistance of the woven polypropylene bag is negligible compared to the bulk grain heat transfer. And
5. Heat transfer is influenced by moisture within the grain.

7.6.1 Energy and mass balance

Equations governing coupled heat and mass transfer within stored grain is given by Equation [7.15] and Equation [7.16] (Gastón et al., 2009).

Equation [7.15]

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} \right) + \alpha \left( \frac{\partial^2 T}{\partial y^2} \right) + \left( \frac{h_{fg}}{c_g} \frac{\partial W_g}{\partial t} \right) \tag{7.15}
\]

Equation [7.16]

\[
\rho_g \frac{\partial W_g}{\partial t} = D_{eff} \left[ \left( \frac{\partial^2 W_g}{\partial x^2} + \frac{\partial^2 W_g}{\partial y^2} \right) + \left( \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial y^2} \right) \right] \tag{7.16}
\]

where \( \alpha = \frac{k}{\rho_g c_g} \)
T is temperature in °C, t is time, in s, \( \alpha \) is thermal diffusivity, in m\(^2\) s\(^{-1}\), \( h_{fg} \) is latent heat of vaporization and considered constant at 2476.55 k J kg\(^{-1}\) (Khankari et al., 1995a), \( W_g \) is the grain moisture content (percent dry basis), \( \rho_g \) is bulk density of grain (kg m\(^{-3}\)), \( C_g \) is specific heat capacity of grain (J kg\(^{-1}\) K\(^{-1}\)), \( x \) and \( y \) are the direction of heat transfer (m), \( k \) is thermal conductivity of grain (W m\(^{-1}\) K\(^{-1}\)), and, \( D_{eff} \) effective diffusivity of water vapor in interstitial air in the grain (m\(^2\) s\(^{-1}\)).

Effective diffusivity is expressed as (Khankari et al., 1995a)

Equation [ 7.17 ]

\[
D_{eff} = \frac{D_v \varepsilon}{\tau R_v} \quad [7.17]
\]

where \( D_v \) is the diffusivity of water vapor in air, in m\(^2\) s\(^{-1}\), \( \varepsilon \) (porosity of grain bed, decimal) and \( \tau \) (tortuosity, dimensionless) are assumed to be 0.53 and 1 respectively. \( R_v \) is the water vapor gas constant 461.52 J kg\(^{-1}\) K\(^{-1}\).

Diffusivity of water \( (D_v) \) is given by (Thorpe et al., 1991)

Equation [ 7.18 ]

\[
D_v = \frac{9.1 \times 10^{-9}(T_k)^{2.5}}{T_k + 245.18} \quad [7.18]
\]

where \( T_k \) is the absolute temperature, in K. If air-vapor behaves like an ideal gas, the partial pressure can be expressed in terms of the change in moisture and temperature assuming the partial pressure of water vapor in grain and that surrounding air is in equilibrium (Khankari et al., 1995a).

Equation [ 7.19 ]

\[
\frac{\partial p_v}{\partial x_j} = \left( \frac{\partial p_v}{\partial W_g} \right)_T \frac{\partial W_g}{\partial x_j} + \left( \frac{\partial p_v}{\partial T} \right)_{w_g} \frac{\partial T}{\partial x_j} \quad [7.19]
\]
Let \( \sigma = \frac{\partial p_v}{\partial W_g} \bigg|_T \) and \( \omega = \frac{\partial p_v}{\partial T} \bigg|_{W_g} \),

where \( \sigma \) is the change in the partial pressure due to change in the moisture content at constant temperature (Pa), and \( \omega \) is the change in partial pressure due to change in the temperature at constant moisture content (Pa K\(^{-1}\)).

Substituting \( \sigma \) and \( \omega \) into (3) we have

Equation [7.20]

\[
\frac{\partial W_g}{\partial t} = \left[ \left( \frac{D_M}{\rho_g} \frac{\partial^2 W_g}{\partial x^2} + \frac{D_T}{\rho_g} \frac{\partial^2 T}{\partial x^2} \right) + \left( \frac{D_M}{\rho_g} \frac{\partial^2 W_g}{\partial y^2} + \frac{D_T}{\rho_g} \frac{\partial^2 T}{\partial y^2} \right) \right]
\]

[7.20]

where;

\( D_M = \sigma D_{eff} \) and \( D_T = \omega D_{eff} \)

Parameters \( \sigma \) and \( \omega \) can be determined from the modified Henderson equilibrium relative humidity equation as in (ASABE, 2007)

Equation [7.21]

\[
ERH = 1 - \exp\left[-A(T+C)(100W_g)^B\right]
\]

[7.21]

where ERH is the equilibrium relative humidity in decimal, \( W_g \) is the decimal dry basis moisture content of grain, and \( T \) is temperature, in °C.

Constants \( A, B \) and \( C \) for shelled corn are reported as: 4.6715 x 10\(^{-5}\), 1.9704, and 82.205 respectively (ASABE, 2007).

The ERH is related to the vapor pressure and saturated vapor pressure as

Equation [7.22]

\[
ERH = \frac{P_v}{P_s}
\]

[7.22]

The saturated vapor pressure is expressed as (Gastón et al., 2009)

Equation [7.23]
\[ P_s = \exp \left[ 54.12 - \left( \frac{6547.1}{T} \right)^{-4.23} \ln T \right] \]  

[7.23]

Vapor pressure based on modified Henderson equation is given as (Gastón et al., 2009)

Equation [ 7.24 ]

\[ P_v = P_s \left\{ 1 - \exp \left[ -A(T+C)(100W_g)^B \right] \right\} \]  

[7.24]

\( \sigma \) and \( \omega \) are determined by differentiating the sorption isotherm relationship with respect to moisture and temperature respectively.

Equation [ 7.25 ]

\[ \sigma = P_s \left\{ 100BA(T + C)^{B-1} \exp \left[ -A(T + C)(100W_g)^B \right] \right\} \]  

[7.25]

and

Equation [ 7.26 ]

\[ \omega = \frac{P_v}{P_s} \frac{dP_s}{dT} + P_s \left( A(100W_g)^N \right) \left( 1 - \frac{P_v}{P_s} \right) \]  

[7.26]

The term \( \frac{dP_s}{dT} \) derived by differentiating Equation [ 7.23 ] with respect to temperature

Equation [ 7.27 ]

\[ \frac{dP_s}{dT} = \left[ \frac{6547.1 \cdot 2}{T^2} - \frac{4.23}{T} \right] \exp \left[ 54.12 - \left( \frac{6547.1}{T} \right) - 4.23 \ln T \right] \]  

[7.27]

Substituting into Equation [ 7.26], \( \omega \) is given as

Equation [ 7.28 ]
\[ \omega = \frac{P_v}{P_s} \left[ \frac{6547.1}{T^2} - \frac{4.23}{T} \right] \exp \left[ 54.12 - \left( \frac{6547.1}{T} \right) - 4.23 \ln T \right] + \right] + \]
\[ P_s \left( A (100W_g)^B \right) \left( 1 - \frac{P_v}{P_s} \right) \]  

[7.28]

Moisture movement into and out of the external bags are governed by convection. So, a convective term is added to the mass balance equation at the edges of the stack. In situations where heat and mass transfer occur simultaneously, the heat and mass transfer coefficients are related by the Lewis number (Le) which is the ratio of thermal diffusivity to mass diffusivity (Holman, 1990).

Equation [7.29]

\[ \frac{h}{h_m} = \rho c_p \left( \frac{\alpha}{D} \right)^{2/3} = \rho c_p Le^{2/3} = \left( \frac{k}{D} \right)^{2/3} \]  

[7.29]

where;

h is the convective heat transfer coefficient \((\text{W} \cdot \text{m}^{-2} \cdot \text{°C}^{-1})\), \(h_m\) is the convective mass transfer coefficient \((\text{m}^2 \cdot \text{s}^{-1})\), and \(D\) is mass diffusivity \((\text{m}^2 \cdot \text{s}^{-1})\).

Rearranging in terms of \(h_m\),

Equation [7.30]

\[ h_m = \frac{h}{\left( \frac{k}{D} \right)^{2/3}} \]  

[7.30]

The temperature and moisture at any given time within the bag grain is obtained by simultaneously solving Equation [7.15] and Equation [7.16].

7.6.2 Finite difference scheme

Equation [7.15] expressed in finite difference form is
\[
\frac{T_{n+1}^{(i,j)} - T_n^{(i,j)}}{dt} = \alpha \left( \frac{T_{n-1}^{(i,j)} - 2T_n^{(i,j)} + T_{n+1}^{(i,j)}}{dx^2} \right) + \alpha \left( \frac{T_{n-1}^{(i,j-1)} - 2T_n^{(i,j)} + T_{n+1}^{(i,j+1)}}{dy^2} \right) + \frac{h_{fg}}{c_p} \left( W_{g(i,j+1)}^{n+1} - W_{g(i,j)}^{n} \right) \quad [7.31]
\]

Let \( k_1 = \frac{\alpha dx^2}{dt} \) and \( k_2 = \frac{\alpha dy^2}{dt} \) and \( k_3 = \frac{h_{fg}}{c_p} \)

Considering a rectangular coordinate with width \( H \) and height \( W \), temperature at the various nodes at any increment time \( dt \) for the interior nodes is

Equation [ 7.32 ]

\[
T_{n+1}^{(i,t+1)} = T_n^{(i,t)} + k_1(T_{n-1}^{(i,t)} + T_{n+1}^{(i,t)} - 2T_n^{(i,t)}) + k_2(T_{n-1}^{(i,t)} + T_{n+1}^{(i,t)} - 2T_n^{(i,t)}) + k_3(W_{g(i,t+1)}^{n+1} - W_{g(i,t)}^{n}) \quad [7.32]
\]

Similar expressions are derived for the various nodes at the top, bottom, sides, and corners with the convective term added. The details are in appendix C1.

Equation [ 7.16] is expressed in finite difference form as

Equation [ 7.33 ]

\[
\frac{W_{g(i,j)}^{n+1} - W_{g(i,j)}^{n}}{dt} = \frac{D_M}{\rho_g} \left( \frac{W_{g(i-1,j)}^{n} - 2W_{g(i,j)}^{n} + W_{g(i+1,j)}^{n}}{dx^2} \right) + \frac{D_T}{\rho_g} \left( \frac{T_{n-1}^{(i,j)} - 2T_n^{(i,j)} + T_{n+1}^{(i,j)}}{dx^2} \right) + \frac{D_M}{\rho_g} \left( \frac{W_{g(i,j-1)}^{n} - 2W_{g(i,j)}^{n} + W_{g(i,j+1)}^{n}}{dy^2} \right) + \frac{D_T}{\rho_g} \left( \frac{T_{n-1}^{(i,j)} - 2T_n^{(i,j)} + T_{n+1}^{(i,j)}}{dy^2} \right) \quad [7.33]
\]

Let \( F_{M1} = \frac{D_M}{\rho_g dx^2}; F_{M2} = \frac{D_M}{\rho_g dy^2}; F_{T1} = \frac{D_T}{\rho_g dx^2}; F_{T2} = \frac{D_T}{\rho_g dy^2} \)

The moisture content at any increment time \( dt \) is

Equation [ 7.34 ]
\[ W_{g}^{n+1}(i,j,t+1) = W_{g}^{n}(i,j,t) + F_{M1}\left(W_{g}^{n}(i-1,j,t) + W_{g}^{n}(i+1,j,t) - 2W_{g}^{n}(i,j,t)\right) + 
F_{M2}\left(W_{g}^{n}(i,j-1,t) + W_{g}^{n}(i,j+1,t) - 2W_{g}^{n}(i,j,t)\right) + 
F_{T1}\left(T_{(i-1,j,t)}^{n} + T_{(i+1,j,t)}^{n} - 2T_{(i,j,t)}^{n}\right) + 
F_{T2}\left(T_{(i-1,j,t)}^{n} + T_{(i,j+1,t)}^{n} - 2T_{(i,j,t)}^{n}\right) \]  

[7.34]

Similarly, finite difference expressions were written for nodes at the edges, and corners (see appendix C1).

7.6.3 Solution scheme

The solution scheme for the temperature and moisture for each time step involved dividing the domain into a grid of 14 by 14 (196 nodes) and solving equations [7.34] and [7.32] in MATLAB (R2019a, The MathWorks, Natick, MA) for moisture and temperature respectively. Temperature and moisture content values for initial and boundary conditions at time zero (t=1 in Matlab) was set to the average values in the bags. The transport properties (\(D_{eff}, D_v, ERH, P_s, \sigma, \) and \(\omega\)) were estimated from the initial moisture content and temperature. After which the parameters, \(D_M, D_T, FM_1, FM_2, FT_1\) and \(FT_2\) were updated at each time step. Temperature and moisture values at the subsequent times were then solved using the updated values of the transport properties. The procedure is repeated until the end of storage (5855 hours in Lexington).

The procedures for experimental data and placement of sensors in the bags was described in part I. Nineteen (19) temperature and relative humidity sensors were placed in the bags (the specific locations of each of the sensors are shown Figure B.1 to Figure B.8 in appendix B). EMC was calculated from temperature and relative humidity recorded by the sensors using the modified Henderson equation. Samples were taken monthly in bags located at the periphery of the stack (top, sides and front) for moisture analysis using the oven method described in Chapter 6. Predicted temperatures and EMC were compared with the measured temperatures and calculated EMC for all the 19 locations. The measured
moisture content (MC) in percent wet basis, calculated EMC and predicted EMC were compared at three locations at the peripheral of the stack (A10, B16, D5). The predicted and calculated EMC of Bag H18 was compared with the measured MC of bags in layer H at the bottom.

7.7 Results and discussions

7.7.1 Simulated temperature in a large stack- Lexington KY, US.

The temperature distribution in bagged corn stored in a large stack (4 x 6 x 8) for eight (8) months predicted by the two dimensional coupled heat and mass transfer model is shown in Figure 7.15. The contours are similar to those predicted by the thermal model described in Chapter 7 part I (Figure 7.6 and Figure 7.7). However, temperature changed slower due to the interdependency of moisture and temperature. After two months of storage, the contour plots are identical with the grain at the center of the stack at 6.5 °C, the top of the stack at 4 °C and the sides are 5 °C. The gradient across the stack was 2 °C and 1 °C from top to the center and bottom to the center, respectively. As the weather condition warmed up, the grain temperature increased around the periphery and heat flowed towards the center as expected. That created a gradient of 3° between the peripheral bags on the side and top to the center (after 4 months). The floor remained cold and that was evident in the temperatures near the bottom of the stack. Unlike in the pure thermal model where about 60% of the stack was at 15 °C, about 50 percent bags (from the center) are at 14 °C and the contour gradient reduced to 0.5 °C and the center is 0.5 °C cooler. As the storage period progressed, the gradient further reduced to 1.8 °C and 0.8 °C across the stack (from top to bottom) after six (6) and eight (8) months respectively. The warmest part of the stack was at the top layer after six months. The period from the sixth month to the eighth month represent the time when the grain warmed due to the prolonged high temperature (>22 °C) and relative humidity (>65 %). After 8 months, only the bottom bags (representing just 13% of the stack) were less than 24 °, all other bags were than > 24 °C.
This is expected as the weather transitioned from winter to summer. The numerical solution did not consider the vertical line of symmetry about the center. Future iterations might employ different boundary conditions around the stack.
Figure 7.15 Contour plots showing temperature distribution from Dec 9, 2019 to August 8, 2020 in a 4 x 6 x 8 stack of bagged corn in Lexington, KY
7.7.2 Simulated EMC in a large stack- Lexington KY, US.

Figure 7.16 shows the EMC distribution in a large stack of corn (4 x 6 x 8 bags) predicted by the two-dimensional coupled heat and mass transfer model with an initial moisture content of 14.4 % wet basis (or 16.8% dry basis) during eight months of storage. All output utilized dry basis moisture content. The average EMC in all the bags was 17 % (dry basis) after 2 months with a small portion of the bags on the pallet (bottom bags) appearing to lose moisture as indicated by the lower EMC (about 16 %). However, after 4 months, the EMC showed a marginal reduction from the sides. As the storage period increased, this phenomenon become more pronounced (six months and eight months) with a dry region surrounding the stack and a higher moisture region moving from the bottom of the stack due to the higher humidity conditions underneath the stack due to cooler floor temperature. However, this is restricted to the bottom layer of the stack. The EMC in the intermediate and core bags remained unchanged. After eight months, a moisture gradient of 0.5 % (dry basis) was observed between the bottom bags and bags at the top and intermediate layers. Moisture gradients were very marginal across the stack and one plausible reason for this is the effect of convection and air properties surrounding the bags.

This was expected because as ambient condition changed, grains in the peripheral layer (which are warmer) lose moisture while the bottom bags (which are cooler) gain moisture in order to maintain equilibrium with the surrounding air. Similar trends have been reported to occur in flat storages (Rocha et al., 2013) however, because the bags are permeable to water vapor, moisture is lost to the surrounding air by evaporation and as such moisture is not expected to accumulate at the top of the stack.
Figure 7.16 Contour plots showing EMC distribution from December 9, 2019 to August, 2020 in a 4 x 6 x 8 stack of bagged corn in Lexington, KY
7.7.3 Comparisons of predicted and measured temperatures in a large stack- Lexington KY, US.

Predicted temperature at four different locations in corn stored in a large stack in Lexington KY using the coupled heat and mass transfer conduction model are compared with the measured temperatures as shown in Figure 7.17 to Figure 7.20. These locations were chosen because of their closeness to the edges of the stack (top surface, right surface, left surface and bottom) where samples were taken for monthly moisture analysis as described in Chapter 6. Data from sensor in bag A10 located at ~ 1.0 m from the left side of the stack and 1.6 m from the floor is shown in (Figure 7.17) while Figure 7.18 shows the data from sensor in bag B16 (~0.3 m from the right side and ~ 1.4 m from the floor). Figure 7.19 shows the data from sensor in bag D5 (~ 0.3 m from the left side of the stack and 1.0 m from the floor), and the data from sensor in Bag H18 (~ 0.6 m from the left side and 0.3 m from the floor) is shown in Figure 7.20. Results for other locations are presented in appendix C4.

The predicted temperature of bag A10 is very similar to the output of the thermal model (Figure 7.11.). However, the temperature predicted by the coupled heat and mass transfer model performed better than the thermal model except at the bottom of the stack. Also, the measured and predicted temperatures only lagged the room temperature for about 150 days. Beyond that time the grain and the surrounding air appeared to be in thermal equilibrium. The implication is that bags at the surface are likely to deteriorate rapidly when warm condition persisted for long time.
The predicted temperatures also agreed well with the measured temperature in bag B16 (Figure 7.18) and bag D5 (Figure 7.19). There was a lag between the predicted temperature of the two bags and the room temperature. In bag D5, as the storage period progressed, the variation between the measured and predicted temperature increased. This variation increased as one moves closer to the bottom of the stack.

The predicted temperature of bag H18 is shown in Figure 7.20. The there was a close match between the predicted and the measured temperature for about 150 days. However, as the storage period progressed, the variation between the predicted and measured temperature increased. A plausible explanation for this is the damp condition in at the bottom layer and the low convection at the bottom of the stack.
Figure 7.18 Measured and predicted daily average temperatures of bag B16 at the topmost layer (1.4 m from the floor) of 4 x 6 x 8 stack of corn in Lexington, KY with room temperature from Dec 9, 2019 to July 15, 2020

Figure 7.19 Measured and predicted daily average temperatures of bag D5 at the topmost layer (1.0 m from the floor) of 4 x 6 x 8 stack of corn in Lexington, KY with room temperature from Dec 9, 2019 to August 8, 2020
Figure 7.20 Measured and predicted daily average temperatures of bag H18 at the topmost layer (0.3 m from the floor) of 4 x 6 x 8 stack of corn in Lexington, KY with room temperature from Dec 9, 2019 to August 8, 2020

The average weekly values of the predicted and measured temperatures were compared for the top, right side, left side and, the bottom of the stack with a regression line as shown in Figure 7.21. Generally, the predicted temperatures agreed very well with measured temperatures at the top, right side and the left side of the stack with the values spreading above and below the regression line. This shows that the model generally matches the measured values in all cases and cannot be said to under predict or over predict temperatures at these locations. Little variations can be observed at the bottom layer where the points are not as close to the regression line.
Figure 7.21 Regression of measured temperatures versus predicted temperatures in the peripheral layers of the large stack in Lexington KY.

The error of prediction for the temperature and EMC estimated as average absolute (AAD) difference and standard error in the bags at the peripheral, intermediate, the core and the bottom of the stack is presented in Table 3.1. Adding mass transfer to the equation increased the prediction accuracy of the heat transfer model by 20%, 15% and 8% at the peripheral, the core, and the intermediate layer respectively while the prediction accuracy at the bottom of the stack reduced by 7%. However, the observed variation at the bottom of the stack is acceptable for grain management because there are other factors that could contribute to temperature and moisture changes during grain storage that were not accounted for in the model. Absolute difference and standard errors for the individual bags is presented in appendix C6.
Although the model predicted the EMC to the nearest 1% the variations between the calculated and predicted EMC was such that cannot be represented by linear regression showing that, the model did not fit the data well.

Table 7.3 Average absolute difference and standard error between measured and predicted temperatures in a large stack in Lexington KY.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature (°C) AAD</th>
<th>SE</th>
<th>EMC (% db) AAD</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral</td>
<td>1.4</td>
<td>1.0</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1.3</td>
<td>1.1</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Core</td>
<td>1.3</td>
<td>1.1</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Bottom</td>
<td>2.7</td>
<td>1.5</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Overall average</td>
<td>1.6</td>
<td>1.2</td>
<td>0.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>

7.7.3.1 Comparison of measured and predicted moisture

A comparison between the predicted and calculated EMC is shown in Figure 7.22 to Figure 7.25. The average values of monthly MC measured by the oven method is overlaid on the plots. At the top of the stack, bag A10 (Figure 7.22) the measured MC of the grain changed by about 1.2% this is also reflected in the predicted EMC. The same can be said of the calculated EMC even though the condition appeared to change rapidly during the storage period. Even though the condition in the bags at the top layer was warmer than at other locations, the bag at the top still lost moisture. This shows that in the absence of a wide temperature gradient, moisture migration in bagged grain was driven primarily by natural convection at the top layer.
Figure 7.22 Comparison between Calculated and predicted EMC of bagged corn (bag A10) in Lexington KY

In the bag located at the right side of the stack, B16 (Figure 7.23) the moisture content was almost the same except for the initial change after about four weeks of storage. A similar result was obtained for the bag located at the left side of the stack, D5 (Figure 7.24). the plot was almost linear throughout the storage period. As reported in Chapter 6, moisture content of grain located at the intermediate and core of the stack was stable.
In bag H18 (Figure 7.25) located the bottom layer, measured MC changed by about 1 % point just after one month after which it remained stable. The calculated EMC was
not as transient as observed in the other three locations. This is because bag H18 was not in the peripheral of the stack (see Figure B.1 in appendix B) and was only compared to probable moisture content bags which are at the peripheral of the stack. The contrast between the calculated EMC and the predicted EMC is likely due to effect of solar radiation at the floor which was not counted for in the model.

The absolute difference and standard error between the measured temperature and the predicted EMC and, between the calculated EMC and predicted EMC is presented in Table 7.4. The average standard error between the measured MC and predicted EMC was 1 %, and the average standard error between the calculated EMC and predicted EMC was 0.5 %. The model thus predicted moisture distribution in bagged corn with an acceptable accuracy for managing grain stored in polypropylene bags.

Table 7.4 Average absolute difference and standard error between calculated and predicted EMC and between measured MC and predicted EMC in a large stack in Lexington KY a.

<table>
<thead>
<tr>
<th>Bag</th>
<th>Calculated EMC – Predicted EMC (% db)</th>
<th>Measured MC – Predicted EMC (% db)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADD 0.6</td>
<td>SE 0.6</td>
</tr>
<tr>
<td>A10</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>B16</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>D5</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>H18</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*a values were estimated from the monthly averages measured MC and EMC.*
Although, the predicted EMC appeared to follow calculated EMC and the measured MC at the four locations in the stack to certain degree with low error of prediction, the predicted data did not match the calculated EMC as expected. The calculated EMC had greater variation than the predicted EMC. This is because instantaneous values of measured temperature and relative humidity were used to estimate EMC. However, moisture content will not change as fast as the temperature and relative humidity of the interstitial air. Another reason for the observed variation could be differences in the hybrid and its impact on the EMC equation. The coefficients used in the modified Henderson equation may not necessarily match that of the actual corn used in the storage experiment. Also, a significant difference between the desorption and adsorption EMC values of corn at certain relative humidities and temperatures may also account for the observed variations.

Moisture loss was only recorded at the top layer of the stack. The EMC of the bags in the core of the stack and at the bottom was almost unchanged. This could not be compared with measured MC because samples were not grabbed from the bags in the
intermediate and core of the stack in order to maintain the equilibrium condition of the stack. However, samples will be taken when the storage study is terminated and the final moisture content of corn in the enclosed bags can be compared to those at the peripheral and bottom layer.

7.7.4 Conclusions

A two-dimensional finite difference model for simulating transient temperature and moisture distribution in a stack of bagged grain was described. The model was based on heat conduction and moisture diffusion in bagged grain. The model was applied for predicting temperature and EMC distribution in stack containing 192 bags of corn that was 1.7 m high and 3.0 m wide. The predicted temperature generally agreed well with the measured temperatures with the absolute difference ranging from 0.7 °C and 4.5 °C and standard error from 0.8 °C and 2.1 °C. The two-dimensional coupled heat and mass transfer model improved the prediction accuracy of the heat transfer model.

The predicted EMC generally agreed with the calculated EMC and tracked the measured monthly moisture content of the bagged corn. The average absolute difference and standard error between calculated and predicted EMC in bagged corn was 0.7 % and 0.8 % respectively. This level of accuracy is reasonable in grain storage management because there are other factors that influence moisture migration that were not accounted for in the model. However, even the prediction error was low, and the predicted EMC followed the observed trend in the calculated EMC and measured MC for most parts of the storage period, the model did not match the calculated and measured data well.

This first attempt at predicting temperature and moisture distribution in bagged grain gave us a better understanding of the roles of other transport parameter such as porosity and tortuosity factors which played role in heat and mass transfer in porous media but have not been reported in the literature for bagged grain. A good understanding of permeability of air in bagged grain, porosity and tortuosity factors and the effects of the air
channel on the magnitude and direction of these factors will improve the performance of the model. Sorption isotherm of the variety of grain to be stored is also an important factor because mathematical relationships used in the heat and mass transfer model were derived from the sorption isotherm equations.
CHAPTER 8. CONCLUSIONS

The goal of this research was to provide a comprehensive analysis of the ecosystem of the bagged grain storage system with the aim of improving temperature, moisture and insect management in order to reduce storage losses associated with the system. This was achieved by determining the water vapor permeability of the bag materials used for grain storage (section 1); the development of a monitoring system (section 2); analysis of temperature, moisture and insect population in bagged grain during storage (section 3); and the analysis of heat and mass transfer within a small and large stack of bagged grain (section 4). These four sections give a detailed account of the impact of the storage environment on the microclimate of bagged grain during storage. Specifically, the amount of water vapor exchanged between stored grain and the atmosphere in the warehouse.

8.1 Water vapor transmission and permeability

The water vapor transmission rate and water vapor permeability of polypropylene bags and jute bags were determined using the ASTM E96 Standard Test Methods. The bag materials were tested under environmental conditions similar to those experienced in some regions in Nigeria (25°C / 65% r.h., 28°C / 75% r.h. and 30°C / 80% r.h.). The temperature and relative humidity combinations resulted into a vapor pressure deficit of 1.11, 0.95 0.85 kPa respectively. Water vapor transmission rate in the bags decreased with the vapor pressure deficit decreases with values ranging from 478 g m⁻² day⁻¹ for jute (under 25°C / 65% r.h.) to 216 g m⁻² day⁻¹ for opaque polypropylene. Water vapor permeability ranged from 6.4 x 10⁻⁴ g (m day Pa)⁻¹ for jute under (25°C / 65% r.h) to 4.7 x 10⁻⁵ g (m day Pa)⁻¹ for opaque polypropylene. Clear and opaque polypropylene bag materials show identical performance in terms of water vapor transfer under the tested conditions. However, jute bags show a significantly different performance with higher values compared to the polypropylene bags. The higher water vapor transfer rate recorded for jute shows why it is
a better material when grain is fumigated in bags. The water vapor transmission rate of bag materials were linearly related to the vapor pressure deficit of the air surrounding air.

Corn with initial moisture content at 10% and 12% (wet basis) was stored in mini bags made from the same materials to evaluate the change in moisture content under the tested conditions. Water vapor permeability of the bag materials was weakly correlated with the moisture change in stored corn. The vapor pressure deficit and initial moisture content of the corn were the driving potential for moisture change in the bags. This shows that moisture exchange between bagged grain and the surrounding air within the warehouse can be significant. This implies that, the temperature and relative humidity within the warehouse where grains are stored should be known for proper management of the stored grains to prevent deterioration due to warm humid weather.

This is the first time that water vapor permeability values of bag materials used to store grain has been reported. The values are useful in analyzing moisture migration and redistribution in stacks of bagged grain.

8.2 Monitoring system

A temperature and relative humidity monitoring system for bagged grain was developed in this study. The goal was to accurately monitor the trend in temperature and relative humidity in bagged grain and the warehouse during grain storage. The main components of the systems are eight temperature and relative humidity sensors (Sensirion, model SHT35) integrated on a PCB and connected to Custom Arduino based data acquisition system. Four (4) units of the monitoring system were developed. The system is capable of recording temperature, relative humidity and a time stamp at user defined interval. It can easily be adapted for use in different stacks with the probes providing flexibility for placing the sensors in desired bags in specific locations. With the probes properly secured in position during bag closing, one can be sure that measurement taken
will be the representative values of the temperature and relative humidity of air in the interstitial space within the bags as they can be located at the approximate center of the bag.

Monitoring is of more importance in bagged grain storage system considering the constraints of sampling. While it is easy to draw samples from the peripheral of the stack, it is almost impossible to draw samples from bags enclosed in the center of the stack. The great thing about this development is that the condition of grain can be monitored in real time and appropriate decisions can be made based on the measurements made over time without necessarily deploying more labor or compromising the integrity of the bags. The onset of spoilage due to combination weather, insect and mold activities can be inferred from the temperature, relative humidity and calculated EMC. Thus, farmers and or warehouse managers can decide when to rearrange the bags (for the purpose of aerating the stack), take the stored grain out for drying (to prevent the development of mold), carry out additional fumigation to arrest insect activity or sell the grain.

8.2.1 Calibration

The manufacturer reported an accuracy of ±1.5% at 0-80% for relative humidity and ±0.1 °C, at 20-60 °C for temperature. However, accuracy of the developed monitoring system was ascertained by testing the system under constant temperature and relative humidity in an environmental control chamber with the relative humidity compared to fixed pointset by selected saturated salt solutions. The accuracy of sensors was determined 0.3°C and 3.7% for temperature and relative humidity respectively. The accuracy of the sensor was improved by adjusting the relative humidity values using a calibration equation.

8.2.2 Temperature and relative humidity measurement and calculated EMC

The system was deployed in separate stacks of corn and paddy rice for four months (May 2019 to September 2019) in Nigeria. The system measured the temperature and
relative humidity of bagged grain and the environment within the warehouse adequately. The calculated EMC values agreed with measured moisture values to the nearest 1%. At the end of the storage study in Nigeria, the system was re-calibrated, and the results showed no drift in the values recorded under the range of tested conditions.

The system was further deployed in a stack of bagged corn for 11 months (December 2019 to October 2020) in Lexington, USA. The system performed to expectation in acquiring data that described the conditions within the warehouse and the microclimate of bagged grain during storage.

8.3 Bagged grain ecosystem

8.3.1 Temperature and relative humidity

Temperature and relative humidity in bagged corn generally tracked the room condition. Small stack behaves like a single bag with all exposed surfaces with the internal environment of the bag responding spontaneously to the changing room condition with little or no lag. This suggests that condition of bagged corn will deteriorates faster when a condition that is conducive for insect and mold (> 25 °C and > 65% RH) persisted for a long time as observed in the experiment in Ilorin KW, Nigeria.

In a large stack, the microenvironment of bags that are completely covered by other bags (intermediate and core) responded slowly to the changing room environment. Even though the microclimate in these bags also track that of the room, there was a noticeable lag (about 4 days). Stratification in temperature and relative humidity was observed along the vertical direction. This implies that in a sufficiently large stack, the bags in the intermediate and the core layers are protected from the direct impact of the varying room condition.
8.3.2 Moisture

Moisture migration in bagged grain is largely due to diffusion and convective air current surrounding the bags. In small bags, the process is driven by convection and moisture redistribution does not occur except for transfer of moisture from the surrounding air due to vapor pressure deficit. However, moisture content of sufficiently dry corn (<10% wet basis) will not rise beyond the safe level (13% wet basis) over a period of four months under the environmental condition recorded in Ilorin. In a large stack, convection driven moisture redistribution can occur causing marginal moisture gradient of about 1.0% point between the upper surface layer and the core of the stack. However, the presence of air channels within the stack (depending on how tight the bags are arranged) tends to maintain the thermal and sorption isotherm between the bags and the surrounding air. As a result, changes in moisture content are only noticed at the peripheral and bottom layer of the stack in which case the upper surface lost moisture while the bottom layer gained moisture.

8.3.3 Insects

The level of insect infestation observed in bagged grain stored in the warehouse is largely related to residual infestation and the prevailing environmental condition at the time of storage. Insect population increase rapidly when there is residual infestation as shown in the set up in Ilorin. Field to store infestation is a problem that requires some treatment before storing grains in the hot humid climates. Corn stored in Ilorin KW, Nigeria was heavily infested because of field to store transfer of insects, ineffective fumigation and the warm weather. The low infestation recorded in Lexington KY, USA supports the argument that transfer of insect pest from field to store is not probable under the temperate condition. Also, insects emerged in corn stored in Lexington KY during the duration of warm weather (June to August)
Moisture condensation is rarely going to occur in bagged grain system and in most cases, moisture may not rise above the safe level as demonstrated in the two cases, however, insect infestation is a big threat to grain storage using woven polypropylene bags. Even though the global trend is to eliminate chemical treatment in grains that will be consumed by humans, proper fumigation of grains before storage (especially in bagged storage systems) is very important in addressing the problem of transfer of insect pests from field to store. Farmers are encouraged to arrange their bags of grains in sufficiently large stacks such that the exposed surface area is small compared to the overall volume of the stack.

8.4 Heat and Mass Transfer in bagged grain

The two-dimensional heat conduction model predicted the temperature distribution in bagged grain well (accurate to the nearest 1 °C) and described temperature distribution in the two stacks. This information is useful for determining adequate number of sensors needed to effectively monitor the temperature of bagged grain in a warehouse. If the temperature in the warehouse is known, the model can be used to predict the temperature distribution in stack of any dimension. Accuracy of temperature prediction was increased by coupling heat and mass transfer.

8.4.1 Air channels

Air channels around the bags played a crucial role in maintaining both thermal and sorption equilibrium between bagged grain and the surrounding air. This is an advantage on the one hand because it prevents moisture build up in the stack that can lead to condensation or aid mold growth. On the other hand, it can also be a disadvantage because it can aid grain deterioration under prolonged adverse weather condition.
8.5 Future works

In order to provide relevant information and solutions to the aspects that this research work was unable to address, research efforts should target the following areas.

1. Bulk density, thermal conductivity and thermal diffusivity of bagged grain is different than those stored in bins or silo bags. Moisture and temperature distribution in grain stacks cannot be accurately predicted if these parameters are not well defined. Currently, these values have not been published in the literature. Thus, there is a need to experimentally determine these properties for grains commonly stored in bags (such as corn, grain sorghum, millet, paddy, rice cowpea, etc.). Interestingly, the density of bagged grain is directly related to the tightness of the bags and their arrangement in stacks. This will provide relevant data for arriving at the correct.

2. The convective heat and mass transfer coefficients had a major impact on the heat and mass transfer especially at the peripheral bags. These two parameters need to be described more accurately in order to be able to accurately predict heat and mass transfer in the peripheral bags where the convective terms are added to the heat and mass balance equations.

3. Volume occupied by air channels in stacks of bagged grain do influence temperature and moisture distribution within the stack. There is need to devise a methodology to quantify the volume of air channels in stacks. The interaction of these air channels with heat and mass transfer needs to be accounted for. This can be determined experimentally or perhaps with computational fluid dynamics. It is also impacted by the bag size and stacking arrangement employed at individual warehouses.
4. A limitation of the model developed is that hourly temperature and relative humidity in the warehouse must be known to set a realistic boundary condition. However, this is not practicable under certain circumstances. A model coupling the warehouse environment to the outdoor conditions is needed.

5. For proper management of insects in bagged grain, the correlation between insect population distribution and the temperature and relative humidity needs to be established. More well define/controlled storage studies are needed to achieve this. This information would also be useful in modelling the population dynamics of insects in bagged grain. Efforts should be made to attempt this using data collected from previous storage studies in Nigeria.
APPENDICES

APPENDIX A1. Components of the monitoring system

Table A. 1 Components of the Prototype unit

<table>
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<tr>
<th>Description</th>
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<th>Quantity</th>
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<td>SHT35 Sensor Housing</td>
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APPENDIX A2. CAD work for the Printed Circuit Boards

Figure A. 1 Bottom Copper of the PCB
Figure A. 2 Bottom Silkscreen
Figure A. 3 Bottom solder mask
Figure A. 4 Top Copper
Figure A. 5 Top silk screen
Figure A. 6 Top solder mask
Figure A. 7 Top paste mask
APPENDIX A3. Sensor calibration

The process of calibrating the sensor involved preparation of saturated salt solutions by adding water to measured quantities of sodium chloride (NaCl), Magnesium Nitrate (Mg(NO₃)₂) and Magnesium chloride (MgCl₂) as described in ASTM (2012). The solutions were prepared in glass jars and placed in a controlled environmental chamber. Thereafter the sensors where placed in the glass jars through a rubber stopper with a space of about 2.5 cm separating the tip of the sensors and the solution. Relative humidity recorded by the sensor is compared with humidity fixed point of the saturated aqueous salt solutions used at three different temperatures in Table A. 5. The plot of the calibration line is shown in Figure A. 8.

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<thead>
<tr>
<th>Temp °C</th>
<th>Measured MgCl₂</th>
<th>Expected MgCl₂</th>
<th>Measured Mg(NO₃)₂</th>
<th>Expected Mg(NO₃)₂</th>
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b Source: (Green, 1977)
Figure A. 8  Calibration line showing the plot of humidity fixed point of three saturated salt solution at three different temperatures and the relative humidity measured by the sensors.
APPENDIX B. Arrangements of bags and locations of sensors and thermocouples

The positions of the bags and the specific locations of temperature and relative humidity sensors and thermocouples are shown in Figure B.1 to Figure B.8 (from bottom layer H to the topmost layer A). Note the alternation of the arrangements. As shown in the four views, layers H, F, D and B are arranged (4 x 6 x 8) while layers G, E, C and A are arranged (6 x 4 x 8)
Figure B.1 Bag arrangements and sensor and thermocouple distribution in layer H
Figure B.2 Bag arrangement and distribution of sensors and thermocouple at layer G
Figure B.3 Bag arrangement and distribution of sensors and thermocouple at layer F
Figure B.4 Bag arrangement and distribution of sensors and thermocouples at layer E
Figure B.5 Bag arrangement and distribution of sensors and thermocouples at layer D
Figure B.6 Bag arrangement and distribution of sensors and thermocouples at layer C
Figure B.7 Bag arrangement and distribution of sensors and thermocouples at layer B
Figure B.8 Bag arrangement and distribution of sensors and thermocouples at layer A
APPENDIX C1. Finite difference expressions for external nodes.

1. The following expressions were derived for calculating the instantaneous temperatures at the external nodes for the thermal model in Chapter 7-part I.

i. At the Top edge \((x = 0; y \neq 0; y \neq H)\)

\[
T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i,j+1,t)}^{n} + T_{(i,j-1,t)}^{n} - 2T_{(i,j,t)}^{n}) + k_2(T_{(i+1,j,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\Delta t}{k\Delta y} h_{H(i,j)}(T_{R}^{n} - T_{(i,j,t)}^{n}) + k_3(M_{(i,j,t+1)}^{n+1} - M_{(i,j,t)}^{n})
\]

ii. At the Bottom edge \((x = W; y \neq 0; y \neq H)\)

\[
T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i,j+1,t)}^{n} + T_{(i,j-1,t)}^{n} - 2T_{(i,j,t)}^{n}) + 2k_2(T_{(i-1,j,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\Delta t}{k\Delta y} h_{H(i,j)}(T_{R}^{n} - T_{(i,j,t)}^{n})
\]

iii. At the right edge \((x \neq 0; x \neq W; y = H)\)

a. \(T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i+1,j,t)}^{n} + T_{(i-1,j,t)}^{n} - 2T_{(i,j,t)}^{n}) + 2k_2(T_{(i,j-1,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\Delta t}{k\Delta x} h_{V(i,j)}(T_{R}^{n} - T_{(i,j,t)}^{n})\)

iv. At the left edge, external \((x \neq 0; x \neq W; y = 0)\)

a. \(T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i+1,j,t)}^{n} + T_{(i-1,j,t)}^{n} - 2T_{(i,j,t)}^{n}) + 2k_2(T_{(i,j+1,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\Delta t}{k\Delta x} h_{V(i,j)}(T_{R}^{n} - T_{(i,j,t)}^{n})\)

v. At the top left corner \((x = 0; y = 0)\)

\[
T_{(i,j,t)} = \frac{T_{(i,j+1,t)} + T_{(i+1,j,t)}}{2}
\]

[1]

vi. At top right corner \((x = 0; y = H)\)

\[
T_{(i,j,t)} = \frac{T_{(i+1,j,t)} + T_{(i,j-1,t)}}{2}
\]
vii. At bottom right left corner \((x = W; y = 0)\)

\[
T_{(i,j,t)} = \left[ T_{(i-1,j,t)} + T_{(i,j+1,t)} \right] / 2
\]

viii. At bottom right corner \((x = W; y = H)\)

\[
T_{(i,j,t)} = \left[ T_{(i-1,j,t)} + T_{(i,j-1,t)} \right] / 2
\]

2. The following expressions were derived for calculating the instantaneous temperatures at the external nodes for the coupled heat and transfer model in Chapter 7 part II.

i. At the Top edge \((x = 0; y \neq 0; y \neq H)\)

\[
T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i,j+1,t)}^{n} + T_{(i,j-1,t)}^{n} - 2T_{(i,j,t)}^{n}) + k_2(T_{(i+1,j,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\alpha \Delta t}{k \Delta y} h_H(i,j)(T_{R}^{n} - T_{(i,j,t)}^{n}) + k_3(M_{(i,j,t+1)}^{n+1} - M_{(i,j,t)}^{n})
\]

ii. At the Bottom edge \((x = W; y \neq 0; y \neq H)\)

\[
T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i,j+1,t)}^{n} + T_{(i,j-1,t)}^{n} - 2T_{(i,j,t)}^{n}) + 2k_2(T_{(i-1,j,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\alpha \Delta t}{k \Delta y} h_H(i,j)(T_{R}^{n} - T_{(i,j,t)}^{n}) + k_3(M_{(i,j,t+1)}^{n+1} - M_{(i,j,t)}^{n})
\]

iii. At the right edge \((x \neq 0; x \neq W; y = H)\)

\[
T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i+1,j,t)}^{n} + T_{(i-1,j,t)}^{n} - 2T_{(i,j,t)}^{n}) + 2k_2(T_{(i,j-1,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\alpha \Delta t}{k \Delta x} h_V(i,j)(T_{R}^{n} - T_{(i,j,t)}^{n}) + k_3(M_{(i,j,t+1)}^{n+1} - M_{(i,j,t)}^{n})
\]

iv. At the left edge, external \((x \neq 0; x \neq W; y = 0)\)

\[
T_{(i,j,t+1)}^{n+1} = T_{(i,j,t)}^{n} + k_1(T_{(i+1,j,t)}^{n} + T_{(i-1,j,t)}^{n} - 2T_{(i,j,t)}^{n}) + 2k_2(T_{(i,j+1,t)}^{n} - T_{(i,j,t)}^{n}) + \frac{\alpha \Delta t}{k \Delta x} h_V(i,j)(T_{R}^{n} - T_{(i,j,t)}^{n}) + k_3(M_{(i,j,t+1)}^{n+1} - M_{(i,j,t)}^{n})
\]

v. At the top left corner \((x = 0; y = 0)\)
\[ T_{(i,j,t)} = \frac{T_{(i,j+1,t)} + T_{(i+1,j,t)}}{2} \]

vi. At top right corner \((x = 0; y = H)\)

\[ T_{(i,j,t)} = \frac{T_{(i+1,j,t)} + T_{(i,j-1,t)}}{2} \]

vii. At bottom right left corner \((x = W; y = 0)\)

\[ T_{(i,j,t)} = \frac{T_{(i-1,j,t)} + T_{(i,j+1,t)}}{2} \]

viii. At bottom right corner \((x = W; y = H)\)

\[ T_{(i,j,t)} = \frac{T_{(i-1,j,t)} + T_{(i-1,j,t)}}{2} \]

3. The following expressions were derived for calculating the instantaneous EMC at the external nodes for the coupled heat and transfer model in Chapter 7 part II.

i. At the Top edge \((x = 0; y \neq 0; y \neq H)\)

\[
W_{g}^{n+1}_{(i,j,t+1)} = W_{g}^{n}_{(i,j,t)} + 2F_{M1}\left( W_{g}^{n}_{(i-1,j,t)} - W_{g}^{n}_{(i,j,t)} \right) + \\
2F_{M2}\left( W_{g}^{n}_{(i,j-1,t)} + W_{g}^{n}_{(i,j+1,t)} - 2W_{g}^{n}_{(i,j,t)} \right) + \\
2F_{T1}\left( T_{(i-1,j,t)}^{n} - T_{(i,j,t)}^{n} \right) + \\
F_{T2}\left( T_{(i,j-1,t)}^{n} + T_{(i,j+1,t)}^{n} - 2T_{(i,j,t)}^{n} \right) + \\
F_{M2}h_{m}\left( W_{gf(t)}^{n} - W_{g}^{n}_{(i,j,t)} \right)
\]

ii. At the Bottom edge \((x = W; y \neq 0; y \neq H)\)

\[
W_{g}^{n+1}_{(i,j,t+1)} = W_{g}^{n}_{(i,j,t)} + F_{M1}\left( W_{g}^{n}_{(i-1,j,t)} + W_{g}^{n}_{(i+1,j,t)} - 2W_{g}^{n}_{(i,j,t)} \right) + \\
2F_{M2}\left( W_{g}^{n}_{(i,j-1,t)} - W_{g}^{n}_{(i,j,t)} \right) + \\
F_{T1}\left( T_{(i-1,j,t)}^{n} + T_{(i+1,j,t)}^{n} - 2T_{(i,j,t)}^{n} \right) + \\
2F_{T2}\left( T_{(i,j-1,t)}^{n} - T_{(i,j,t)}^{n} \right) + \\
F_{M1}h_{m}\left( W_{gr(t)}^{n} - W_{g}^{n}_{(i,j,t)} \right)
\]
iv. At the left edge, external \( (x \neq 0; x \neq W; y = 0) \)

\[
W_{g(i,j,t+1)}^{n+1} = W_{g(i,j,t)}^n + F_{M1} \left( W_{g(i-1,j,t)}^n + W_{g(i+1,j,t)}^n - 2W_{g(i,j,t)}^n \right) + 2F_{M2} \left( W_{g(i,j+1,t)}^n - W_{g(i,j,t)}^n \right) + F_{T1} \left( T_{(i-1,j,t)}^n + T_{(i+1,j,t)}^n - 2T_{(i,j,t)}^n \right) + 2F_{T2} \left( T_{(i,j+1,t)}^n - T_{(i,j,t)}^n \right) + F_{M1} h_m \left( W_{g(t)} - W_{g(i,j,t)}^n \right)
\]

v. At the top left corner \( (x = 0; y = 0) \)

\[
W_{g(i,j,t)} = \left[ W_{g(i,j+1,t)} + W_{g(i+1,j,t)} \right] / 2
\]

vi. At top right corner \( (x = 0; y = H) \)

\[
W_{g(i,j,t)} = \left[ W_{g(i+1,j,t)} + W_{g(i,j-1,t)} \right] / 2
\]

vii. At bottom right left corner \( (x = W; y = 0) \)

\[
W_{g(i,j,t)} = \left[ W_{g(i-1,j,t)} + W_{g(i,j+1,t)} \right] / 2
\]

viii. At bottom right corner \( (x = W; y = H) \)

\[
W_{g(i,j,t)} = \left[ W_{g(i-1,j,t)} + W_{g(i,j-1,t)} \right] / 2
\]
APPENDIX C2. Measured and predicted temperatures in selected bags.

Temperature profiles of bagged corn in Layers B to H are presented in figures C1 to C7.

Figure C2.1 Temperature profile of layer B
Figure C2.2 Temperature profile of layer C
Figure C2.3 Temperature profile of layer D
Figure C2.4 Temperature profile of layer E
Figure C2.5 Temperature profile of layer F
Figure C2.6 Temperature profile of layer G
Figure C2.7 Temperature profile of layer H
APPENDIX C3. Standard error of the predicted temperatures in bags with either temperature and relative humidity sensor or thermocouple.

Table C.1 Average standard errors for the various combination of thermal and physical properties of bagged corn.

<table>
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<tr>
<th>Bags</th>
<th>$\alpha=1.54E-06$</th>
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<th>$\alpha=9.4E-07$</th>
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<tr>
<td></td>
<td>RMSE (°C)</td>
<td>RMSE (°C)</td>
<td>RMSE (°C)</td>
</tr>
<tr>
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<td>$h=7$, $hH=6$</td>
<td>$h=6$</td>
<td>$h=4$</td>
</tr>
<tr>
<td>A13</td>
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</tr>
<tr>
<td>B11</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>B14</td>
<td>1</td>
<td>1</td>
<td>1.3</td>
</tr>
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<td>B15</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>B19</td>
<td>0.9</td>
<td>0.9</td>
<td>1.2</td>
</tr>
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<td>1.3</td>
<td>1.5</td>
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<td>1.2</td>
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<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>D11</td>
<td>0.9</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
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<td>1.1</td>
<td>1.4</td>
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<td>0.7</td>
<td>0.9</td>
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<td>1.7</td>
</tr>
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<td>2.4</td>
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<td>0.7</td>
<td>0.9</td>
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<td>1.5</td>
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<td>0.9</td>
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<td>0.9</td>
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<td>0.7</td>
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<td>1.6</td>
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<td>1.3</td>
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APPENDIX C4. Comparisons of measured temperatures in selected bags and temperatures predicted by the coupled heat and transfer model

Figure C4. 1 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer B
Figure C4. 2 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer C
Figure C4. 3 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer D.
Figure C4 4 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer E

Figure C4 5 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer F
Figure C4  6 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer G

Figure C4  7 Comparison of predicted and measured temperatures in a large stack in Lexington KY, at layer H
APPENDIX C5. Comparisons of calculated EMC in selected bags and EMC predicted by the coupled heat and transfer model

Figure C5.1 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer A
Figure C5.2 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer B.
Figure C5. 3 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer C
Figure C5. 4 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer D
Figure C5. 5 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer E

Figure C5. 6 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer F
Figure C5. 7 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer G

Figure C5. 8 Comparison of calculated EMC and predicted EMC in a large stack in Lexington KY at layer H
APPENDIX C6. Prediction error of temperature and EMC using the coupled heat and mass transfer model

Table C. 2 Absolute difference and standard error for predicted EMC bagged corn

<table>
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<th>Bags</th>
<th>Temperature (°C)</th>
<th>EMC (% db)</th>
<th>ADD</th>
<th>RMSE</th>
<th>ADD</th>
<th>RMSE</th>
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<tr>
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<td>Temperature</td>
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<td></td>
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<td></td>
<td></td>
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</tr>
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</table>
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Throne, J. E. (1994). Life history of immature maize weevils (Coleoptera: Curculionidae) on corn stored at constant temperatures and relative humidities in the laboratory. *Environmental Entomology, 23*(6), 1459-1471. doi:https://doi.org/10.1093/ee/23.6.1459


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References (Chapter 7 Part II)


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VITA

Education


Professional positions held


Scholastic and professional honors

Poster Presentation Award- American Society of Agricultural and Biosystems Engineers, 2018 Annual Meeting.

Technical Presentations


Omodara Michael A, Montross Michael D, McNeill Samuel D, Agbali Francis A, Turner Aaron P. Permeability of grain storage bags. Poster presentation at the 2018 ASABE Annual International Meeting held at Cobo Center, 1 Washington Blvd., Detroit, Michigan. July 29 to August 1, 2018

Professional publications


Michael Ayodele Omodara