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DESIGN AND TESTING OF A WIND ENERGY HARNESSING SYSTEM FOR FORCED CONVECTIVE DRYING OF GRAIN IN LOW WIND SPEED, WARM AND HUMID CLIMATES

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DESIGN AND TESTING OF A WIND ENERGY HARNESSING SYSTEM FOR FORCED CONVECTIVE DRYING OF GRAIN IN LOW WIND SPEED, WARM AND HUMID CLIMATES

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Biosystems and Agricultural Engineering in the College of Engineering at the University of Kentucky.

By

Francis Akumabi Agbali
Lexington, Kentucky
2019

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ABSTRACT

DESIGN AND TESTING OF A WIND ENERGY HARNESSING SYSTEM
FOR FORCED CONVECTIVE DRYING OF GRAIN IN LOW WIND SPEED,
WARM AND HUMID CLIMATES

Forced convective drying using a wind turbine mechanically connected to a ventilation fan was hypothesized for low cost and rapid grain drying in developing countries. The idea was tested using an expandable wind turbine blade system with variable pitch, at low wind speeds in a wind tunnel. The design was based on empirical and theoretical models embedded in a graphical user interface (GUI) created to estimate airflow-power requirements for drying ear corn. Output airflow (0.0016 - 0.0052 m$^{3}$kg$^{-1}$s$^{-1}$) increased within the study wind speed range (2.0 - 5.5 m/s). System efficiency peak (8.6%) was observed at 3.5 m/s wind speed. Flow resistance was overcome up to 1m fill depth in 0.5 m x 0.5 m wide drying bin. Drying study at different airflow rates (no forced convection, 0.002 m$^{3}$kg$^{-1}$s$^{-1}$ and 0.008 m$^{3}$kg$^{-1}$s$^{-1}$) were conducted in a controlled environment at 35°C and 45% relative humidity with mean drying time; 40.3, 37.9 and 22.9 h respectively, that reduced with increasing airflow while drying the ear corn from 22% to 15% moisture content. The overall result supports the hypothesis that the wind convection system increased grain drying rates and should be further developed.

KEYWORDS: ear corn, post-harvest losses, forced convection, grain drying, wind turbine, lift, aerodynamic efficiency,

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March 2019
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DEDICATION

To all who seek knowledge especially in the developing countries of Africa!
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1.1 INTRODUCTION

The absence of appropriate and sustainable grain drying technologies is a major challenge to farmers who live in hot and humid developing countries of sub-Saharan Africa. The cost of sophisticated grain drying machinery and absence of sustainable, clean thermal or electrical energy for rapid grain drying has been cited as a major factor supporting post-harvest quantity and quality losses recorded in most developing countries. Contamination of staple grains with toxigenic molds and other pathogens, also occur as a result of long holding after harvest in warm and humid climates. This condition has been associated with the increase in liver cancers cases due to the carcinogenic effect of mycotoxins (Abdoulaye et al., 2016; IBRD, 2017; Bradford et al., 2018; Kamala et al., 2016; Olayemi, Adegbola, Bamishaiye, & Awagu, 2012). According to these findings, eighty percent (80%) of all cases of liver cancers globally occur in developing countries of SSA, South East Asia and parts of Latin America.

It is estimated that one-third of the world’s food is lost from farm-to-fork, with postharvest handling and management being a critical risk and control point for losses. In sub-Saharan Africa (SSA) for instance, between 14 to 25% of grains produced are lost and annual grains postharvest losses (PHLs) in direct monetary terms are estimated at about $4bn. (IBRD, 2017; Mada, Hussaini, & Adamu, 2014). In addition to massive losses, which impoverishes low-income farmers, poorly dried grains with high moisture contents are great medium for the growth and proliferation of molds and other pathogens under the conducive warm and humid climates. Quantification of the impact of consuming
contaminated grains on individuals is difficult because of concurrent predisposing factors, especially in developing countries where poor record keeping and ineffective food policy implementation makes it difficult to clearly underpin chronic disease like liver cancers with long term, low dose consumption of intoxicated grains. Thus, grain contamination has become a silent killer. However, acute levels disorders leading to death have been reported in countries where high doses of Aflatoxin, a mold toxin have been consumed in grains (Yard et al., 2013). Official documents of the Agency for Cancer Research firmly implicate consumption of a number of mycotoxins in grains as indicators for carcinogenesis, teratogenesis, and mutagenesis. This close association of incidence of diseases causing food contaminants and locations with common climatic conditions and the large dependence on cereal grains as staples calls for closer ecological focus.

Grain postharvest losses in hot and humid climates, often classified as tropical countries, is a consequence of the tropical ecology in which environmental biotic factors optimize the luxurious combination of growth conditions at mesophilic ambient for maximum proliferation. In an extensive review in 2018 (Bradford et al., 2018), it was shown that addressing grain postharvest loss and mycotoxin contamination in humid climates require an approach which the focus on high ambient humidity reduction. This approach is referred to as the “dry chain” and moisture is identified as the problem while rapid drying after grain harvest with subsequent storage in moisture resistant containers was proffered as the solution. The phrase “dry it and keep it dry” therefore summarizes the main theme of combating postharvest losses in tropical developing countries where low-temperature storage is expensive and energy demanding.
In other to achieve the rapid removal of moisture from grain in high humid climates, some engineering and biotic interventions are required. These interventions targets modifying the conditions which favor rapid spoilage of biological products, by enhancing the rate of moisture transfer. In achieving the moisture removal objective, the cost of reducing the moisture content is a major concern and the intervention has to be environmentally and socio-economically sustainable. In other words, the technology is required to take the environment and agricultural practice of the region into consideration. Corn cultivation in temperate regions, for instance, occurs in a single season annually with harvest occurring at the onset of fall when ambient temperatures are low and therefore, help to inhibit germination and reduce mesophilic biotic growth. The low ambient temperature also assists in long grains-holding without significant biochemical changes. Most planting and harvesting activities in these regions are automated with machinery aimed at reducing human effort and increasing throughput. Such farming equipment also performs other postharvest tasks such as shelling and cleaning hence the term “combined harvester”. Harvested grains (shelled by the combined harvesters) are then dried high throughput electric dryers which is possible because of good access to electric power. In most technologically advanced countries within temperate regions, use of continuous flow rapid dryers is, therefore, the standard practice, and grains are dried at temperatures between above 40°C depending on the type of drying system (Bakker-Arkema, Montross, Liu, & Maier, 1996).

In tropical SSA on the other hand, there are generally two major raining seasons. There is no intense frost which could be deleterious to cultivation and corn cultivation is practiced twice a year. In areas having close proximity to water bodies which allow for
irrigation, corn may be cultivated throughout the year harvesting and farming back-to-back. The major harvest season occurs at a period of high ambient humidity and warm mesophilic temperature. Owing to low-income power and the absence of widespread mechanization, planting and harvesting are generally done manually. Harvested ear corn is often first dried to suitable kernel moisture content for easy manual shelling; after which drying down, to a long storage moisture content below 15% (dry basis, db), is embarked upon the shelled grain. In SSA, sun drying with natural ventilation remains the most common method of ear corn drying at ambient or greenhouse enhanced temperatures between 25°C and 50°C. These agricultural, environmental and technological differences result in the need for grain handling systems that are technologically different and for which specific engineering characteristics must be understood as “a sound understanding of the process that is to be controlled is essential for the design of a control system” (Srzednicki, 1996).

Apart from technical feasibility, the cost is a major factor involved in the adoption of farming technologies among low-income smallholder farmers and low-cost, less sophisticated technologies are more like to be more adopted in developing countries. Delayed harvest is one of the methods that farmers use in some developing countries as a means of drying grains like corn. This practice has however been shown to contribute to grain losses due to damage by birds, wild animals, and contamination with mold toxins (Kaaya, Warren, Kyamanywa, & Kyamuhangire, 2005). Moreover, although moisture content reduced over a 4 weeks period of postmaturity harvest, the moisture content in most cases never attained the safe level below or equal to 15%. Open sun drying remains the other major method of grain drying in several developing countries. For this reason, renewable energy applications have been recommended by development agencies and
researchers (Bhudeva, 2013; IRENA, 2016; USDOS, 2013). Application of wind energy systems for performing various agricultural tasks such as water pumping and milling of grains were very common before the modern generation of electricity. Between 1850 and 1970, over 6 million small wind machines were used for pumping water in the United States. A decline in the application of wind-powered devices for direct agricultural purposes tends to be associated with the development of electricity and increasing application of wind turbines for the purpose of electricity generation from which most other applications derive their power.

Renewable energy sources are mostly free and abundantly available in forms that can be harnessed and renewables like wind and solar provide a means for low-cost energy application. Wind energy systems are clean sources of power much like solar but can function at all times of the day so long as the wind blows. The potential of wind applications for small scale mechanical systems among smallholder farmers is reflected by the United States Department of Energy’s assertion that wind power could drive $60 billion investment in rural America and provide over 80,000 new jobs with $1.2 billion in new income for farmers and landowners by 2020 (GAO, 2004). It has also been noted that a concept of wind power cooperatives is on the rise (UCS, 2003), creating an opportunity for smallholder farmers to take advantage of wind energy solutions. In developing countries where electricity from the grid is unreliable and the cost of personal generation of electricity for heating and drying purposes is relatively high, a close look at the potentials of free and renewable energy like solar and wind becomes necessary.

The application of new technologies which improve or enhance drying are being reported but not yet widely adopted. Some of the common types of innovations include the
use of solar dryers with or without forced convection. When forced convection is involved, photovoltaic modules are widely used to power the fans adding to the cost of the technology. When no forced convection is involved, the rate of moisture removal from within the drying chamber is reduced and condensation of moisture-laden air unto the already dried grain often occurs resulting in poor and longer drying times (Irtwange & Adebayo, 2009). The long drying time of high moisture grain at mesophilic conditions results in an increased risk of mold growth and contamination of grains with toxigenic mold metabolites.

This paper examines the potentials for simulating rapid grain drying in developing countries through easy to build, wind energy harnessing system that is effective for rapid grain drying. Harnessing wind energy for improved grain drying in developing countries is an attempt to address the peculiar combination of factors associated with inherent postharvest losses. These factors include the environmental challenges of drying in hot and humid conditions (Kaminski and Christiaensen, 2014; Bradford, 2018) which affect the rate of drying and encourages the growth of spoilage microorganisms in food materials like grains. A small, low-cost wind energy harnessing device that can be locally built or adopted would provide smallholder farmers, who cannot afford sophisticated and expensive drying technology, a means to rapidly dry their produce. Wind energy utilization will in addition to reducing running cost lower farmers dependence on combustive energy with associated carbon emission. It is thus both economically and environmental a more sustainable means for reducing postharvest losses.
1.1.1 Statement of the research problem

The motivation for a study on the design and testing of a wind energy harnessing system for forced convective drying of grain in low wind speed, warm and humid climates stems from the following:

a. There is an ongoing challenge in smallholder farmers’ ability to rapidly dry matured, harvested ear corn in developing countries of SSA leading to about 25% physical and quality losses annually. There is, therefore, a need for a means by which ear corn can be rapidly dried from the moisture content between 23% and 30% at harvest to below 13% within two days in order to forestall mold growth.

b. The drying challenges in the study area stems mainly from high environmental relative humidity (70% to 85%) at mesophilic temperatures (25°C to 35°C) during the harvest months of July and August, necessitating improvement in the rate of moisture removal through forced convective drying platforms or bins.

c. Smallholder farmers in developing countries lack the ability to adopt or afford sophisticated drying equipment for high temperature (>40°C), high throughput continuous drying. The closest alternative is a recourse to the combustion of biomass with its attendant impacts. In order to increase the ability of smallholder farmers to achieve rapid drying of grains, the development of new, small and sustainable wind and solar energy applications is required.

d. Wind energy profile within the region falls within the “low wind speed” region between 2.5 m/s to 6.5 m/s. Thus requiring some trial to validate the potentials of wind systems for such application as mechanical drying. Other considerations include the need to determine the viability of a fully mechanical wind turbine for
forced convection application in regions with high relative humidity air used in drying.

Potential pitfalls or obstacles to the viability of small wind systems for mechanical drying were identified. The possibilities of low availability – a term used to describe the amount of potential downtime was noted. Although wind turbines have been used in water pumping, the technical difference between air and water pumping were also noted and form the basis for a prototype trial as well as recommendations that the study will provide.

1.2 OBJECTIVES AND RESEARCH APPROACH

The broad objective of this study is to investigate the potentials of a wind energy harnessing system for mechanical drying of ear corn in warm and humid developing countries with low wind speed profile.

The specific objectives for achieving the broad objective are;

(i) To review, design and test a wind energy harnessing device suited for the forced convective grain drying needs of smallholder farmers in low wind speed regions.

(ii) To determine by simulated drying tests under controlled environment systems, the effect of typical wind-energy-powered forced convection on the rate of ear corn drying in warm and humid climates.

1.3 HYPOTHESIS

Based on the fundamental knowledge of the role forced convection play in moisture removal, the null hypotheses for this project in keeping with the two major objectives of the study are:
1. There is no significant difference in mean airflow for natural and wind powered forced convection using a mechanical wind energy harnessing system.

2. There is no significant difference in net drying rate or grain moisture content at target drying time for natural and wind powered forced convective drying in warm and humid climates.
CHAPTER TWO: LITERATURE REVIEW

2.1 POSTHARVEST LOSSES IN DEVELOPING COUNTRIES

The lack of access to good grain drying systems in developing countries has been cited (Bradford et al., 2018; Kumar & Kalita, 2017) as a major factor impacting the recurring loss of grain and grain value in warm and humid climates. Increased biochemical reaction rates at mesophilic temperatures result in concomitant growth and contamination of grains by carcinogenic, teratogenic and mutagenic mold metabolites like aflatoxin (IARC, 2003) in tropical climates. Poor grain drying results in quality losses and destroys trade potentials. In some cases, the contamination of such grains with toxic metabolites results in epidemics which could lead to death. Researchers who examined impact of aflatoxin contamination in parts of SSA (McMillan et al., 2018) stated that consumption of 20 – 120 micrograms of aflatoxin, a common mycotoxin found in the area, per kilogram human body weight, over a period of 1 to 3 weeks is associated with acute aflatoxicosis which resulted in reported death in the region. In some countries like Kenya, these epidemics have become fairly common leading to increased concern about the quality of postharvest grain management in the region. Epidemiological data from a 2017 report (Wong et al., 2017) also show that globally, 83% of reported cases of liver cancers, occur in developing countries with recognized risk factors including exposure to dietary aflatoxin (Magnussen & Parsi, 2013; Wong et al., 2017).

Generally, grain quality deterioration results from poor handling practices, such as bare floor drying, and long exposure of mechanically damaged grain kernels to spoilage microflora as well as pests and contaminants. Grain value loss in warm and humid,
developing countries is also strongly associated with ecological predisposition when harvest occurs in a season of high rainfall and warm temperatures. These conditions require radical and non-passive approach for rapid drying of grains harvested with high (>17%) moisture content. During a period of high ambient temperature (25°C and 35°C) and relative humidity (75 – 90%), failure to dry rapidly is the culprit of tropical postharvest losses.

A practice involving the rapid reduction of grain moisture content to below 15% within 48 hours (Bogart, 2015; Bradford et al., 2018) is required in tropical climatic conditions as a means of forestalling grain spoilage which is optimum at mesophilic temperatures. Aspergillus flavus, which is notorious for aflatoxin production, for instance, grows within a temperature range of 20°C to 38°C with an optimum toxin production at 27°C (Price, 2005; Prandini, 2009). During the major corn harvest months between July and August, the ambient temperature in the guinea savannah belt of sub-Saharan Africa, as a case study, is in the range of 25 - 28°C, while relative humidity is almost constantly above 80-85%. This shows that the average tropical climate is rich for mycoflora proliferation and therefore, spoilage and contamination of high moisture food produce is the natural pathway within such climates.

Researchers and stakeholders have suggested that a potential solution for addressing drying needs specific to developing countries require economic sustainability. Interventions with potentials for reducing postharvest losses need to be within the economic reach of low-income farmers. Costly and sophisticated solutions are likely to escape the economic and technological wherewithal of smallholder farmers. The involvement of locals at an extension level in the development of the technology has also
been recommended as a major ingredient for technology adoption (Howes et al., 2017; Greeley, 1986; Lee, 2005). In a paper titled “Why promising technologies fail: the neglected role of user innovation during adoption”, the authors recommended that promising technologies should have a component in which the users would contribute to the development process. In other words, technologies that will be sustainable in developing countries must not only be adoptable economically but also include user innovation and input (Douthwaite, Keatinge, & Park, 2001).

2.2 SOME AGRICULTURAL PRACTICES IN SUB-SAHARAN AFRICA (SSA)

Agricultural practices in developing countries of SSA are mostly manual. Most farmers grow their crops at a subsistence scale on small owned or leased land (often 1 to 3 hectares in size). Corn is the most cultivated cereal in SSA with Nigeria and South Africa being the leading producers with an annual yield of between 11 to 13 megatons respectively (OECD, 2016). Smallholder corn farmers in SSA generally have an average yield of a metric ton per season per hectare (Fintrac, 2016). Corn is generally stored for less than 35 weeks for consumption while between 35% and 60% are sold within 3-8 weeks of harvest (Abdoulaye et al., 2016; Mada et al., 2014). Farmers in Uganda who stored their produce up to about 8 weeks for sale and not more than 17 weeks for consumption experienced less losses and required lower use of storage protectants than those in in Ethiopia and Tanzania who stored for over 35 weeks for consumption and 23 weeks to sell (Abdoulaye et al., 2016).

Holding grains for a long time is an economic decision that farmers make in order to take advantage of the better selling price after the glut which follows harvest is over. The closer from harvest time products is sold, the lower the profit owing to glut and the
awareness of losses the will occur as a result of the inability to properly dry grains. Rapid moisture removal systems would, therefore, help reduce the burden of spoilage during storage and enable the farmers to hold their grain until more profitable pricing seasons. Apart from being affordable, in other to achieve the desired profitability, a technology for reduction of grain moisture must be economical to run.

Another common feature of farming and grain postharvest drying practice in a developing country is small scale operation. Surveys reported in Kolade and Harpham (2014) show that 44% of male and 72% of female farmers in Nigeria, for instance, cultivate less than 1 hectare per household providing 90% of the food consumed, using about 40.96% of the agricultural land in the country (Kolade, 2014). Farming is generally conducted on a household basis and in small cooperative parks where five to ten members and sometimes a little larger numbers join in farming for each other in turn while the beneficiary member provides food drink and snacks. This cooperative system is sometimes referred to as the traditional farming group systems (Ukaga, 1992; Adeyemo, 2005; Afolami, 2012). The lack of automation and mechanization tend to encourage the continuation of small scale farming with its associated challenges. As an example, corn drying practices in developing countries is generally dictated by the fact that harvest is conducted by hand picking and most times at moisture content higher than 20%. Small batches of manually harvested corn, therefore, have to be first dried on the cob to enable manual shelling before storing grains in sacks as shelled kernels (Davies, 2013). Corn stored in cribs generally remains on cob throughout most of the storage life until they are ready to be used making drying on the cob a common feature of developing country grain drying systems.
In view of the existing practices in developing countries, a critical control point for spoilage control in produce like corn is the immediate postharvest stage where corn is held on cobs and require rapid moisture removal both for spoilage control and for post-processing. Until the farming practices change immensely, and large scale farming equipment become common among farmers, small to medium scale postharvest technologies will continue to serve farming household better. More farmers would also be able to afford new technologies if the cost is low. Group or cooperative farming has been identified as a means by which smallholding farmers can jointly afford the cost of new and medium scale technologies like wind or solar dryer as such implements or equipment using natural, near-zero cost and renewable energy can be used in turn by members of such groups or even leased to non-members.

2.3 COMBATING GRAIN SPOILAGE IN DEVELOPING COUNTRIES

Some attempt at mitigating the effect of the factors (high humidity, a manual process dominated agriculture and cost) associated with grain quality losses have been embarked upon by researchers in SSA and from around the world. The development of biological methods for controlling mycotoxin contamination of grains by researchers at the International Institute for Tropical Agriculture (IITA) is perhaps the most coordinated effort at combating grain quality losses in Africa. These researchers employ the use of biological control agents in which toxigenic Aspergillus species are targeted by non-pathogenic and atoxigenic molds which had been engineered in the laboratory to out-compete the deleterious organisms for growth resources (Atehkneng et al., 2008). The biological approach like Aflasafe® results in a reduction of contamination at harvest and have been reported to greatly impact the grain safety standards in sub – Saharan Africa.
with aflatoxin contamination by 80 to 99 percent but represents only one side of the coin. Some researcher has argued that adoption rates are within 67 – 70% and that actual reduction of contamination on farmers sites are difficult to quantify (Pitt, 2019). The use of physical methods and barriers to microbiological growth during storage have on the other hand been reported with verifiable proves. Use of hermetic storage after drying with renewable energy as a way of reducing the cost to farmers have been shown to reduce grain postharvest losses from 25% to 1% during 1-year storage in tropical hot and humid climates (Villers, 2015).

Alongside grain contamination with molds which is a major concern in grain postharvest losses (GPHLs), biological spoilage is only a continuation of the deleterious process, which starts at a physico-chemical level. Mechanical damage and biochemical activities fueled by high temperature are at the base of all grain spoilage activities. This explains the role of refrigeration and temperate climate ecology play in reduced grain spoilage in non-tropical locations. Therefore, an effective measure for combating GPHLs in tropical locations must be a combination of engineering or physical approaches which addresses the fundamental conditions which support the leading cause of physical and biochemical damages.

In describing the problem of grain spoilage in a warm and humid climate, Bradford et al (2018) opined that “high humidity is the enemy and the ‘dry chain’ is the solution”(Bradford, 2018). The ‘dry chain’ is a technique which utilizes high temperature for lowering relative humidity as an effective way to rapidly remove moisture in high humidity regions. In humid climates, air humidity is often close to saturation; remoistening of dried grain by stagnant air at saturation is, therefore, an expected feature when drying in
a tropical climate. This phenomenon is amplified by poor aeration which leads to hot spots and soft rot within grain storage systems. The dry chain did not highlight the role airflow rate plays in rapid drying by reducing re-condensation and by creating a virtual increase in surface area as more air is allowed to interphase with the surface of the grain removing the assumption that moisture gradient equilibrium is rapidly achieved between the grain and the desiccating air in humid climates. The use of control environment systems which redistribute temperature, relative humidity using adequate or appropriate airflow conditions, is therefore expected to offer complementary and more sustainable grain quality control at a small scale farmer/grain handler level. Technologies which reduce drying time through rapid removal of air laden moisture by application of forced convection tend to promise better control of mold growths when the ambient temperature is above refrigeration range (Irtwange & Adebayo, 2009).

Some current practices promoting a sustainable reduction in grain spoilage and contamination within tropical developing countries include a shift from traditional methods of sun drying on bare ground. Researchers (IBRD, 2017; Bradford et al., 2018; Kumar & Kalita, 2017) have recommended different systems including the use of dark colored tarpaulin as drying surfaces. Use of tarpaulin reduce the contact of grains with the soil which is the habitat for spoilage molds, enhances easy grain removal during drizzles and dark colored surfaces act as non-ideal “black bodies” which enhance the conversion of radiant to thermal energy. The increased surface temperature of the drying surface thus helps reduce the relative humidity of the drying air and results in better and faster drying. A researcher noted that 85% of farmers in Kenya who dry their corn on cob immediately after harvest on tarpaulin, stack them ankle deep and expose them to sunlight 8 hours every
day for about 4 days (Davies, 2013). This reduction of drying days from between 5 to 7 days to 4 days is evidence that solutions that simple, low cost and sustainable physical technologies have good chances for adoption among smallholder farmers in developing countries and produce desired results in reducing drying time. Other improvement techniques include the use of solar tent dryers. Some researchers, (Irtwange & Adebayo, 2009; Mumba, 1996) documented studies of active solar dryers which use photovoltaic modules for force convective drying. Results from these studies showed a reduction in moisture content from 33% wet basis (wb) to under 20%, (wb) in 90 kg of corn sample dried within 3 days.

Use of motorized biomass dryers has also been reported with a model referred to as the easyDry 500 performing outstandingly in terms of farmer adoption by adopting a ‘pack and go’ model in which the system is moved from farm site to farm site on motorcycles (VOCA, 2017). The use of diatomaceous earth, as well as other desiccating and pest control chemicals in grain storage systems, are also meant by which grains are being preserved in developing countries. Although the use of hermetic storage is not a drying method, grains that have been dried to a safe storage level of moisture content (below 13% in the case of corn) have also been reported for combating postharvest losses in sub-Saharan Africa. In a field study conducted in Zimbabwe between 2013 and 2014, hermetic storage was shown to preserve grains stored for up to 12 months without germination, dusting, damage or insect infestation (Chigoverah and Mvumi, 2016).

Tent dryers are about the most common and cheapest technologies that have been adopted in different developing countries owing to their ease of assembly and low cost. Although tent dryers use cheap transparent materials for enhancing greenhouse effect -
elevating air temperature and reducing relative humidity, removal of moisture from within the tent remain a challenge. The use of electric fans powered by photovoltaic panels constitutes a cost burden with the price of the photovoltaic module being a major part. Biomass dryer, on the other hand, uses heat from combustion of farm waste in addition to the use of diesel-powered machinery for forced convection with the major demerits of cost and impact on carbon emission.

With the highlighted efforts at combating grain spoilage in warm and humid, tropical and developing countries, widespread adoption of technologies being tried are still way behind being common and there is a need for the development of more low-cost technologies or solutions that can be locally fabricated, like a simple wind turbine for mechanical drying. Although the current study is a fully mechanical system, there is potential that its success could motivate addition benefits to the farmer through the addition of electric generators which can power small farm devices such as phones and low wattage lamps.

2.4 WIND ENERGY CONVERSION FOR MECHANICAL APPLICATION

Wind energy has been harnessed for aerodynamic operations of sailboats along the Nile as far back as 5000 BC and for various mechanical operations like water pumping, grain milling and crushing of sugar cane in Persia at about 200 BC long before the industrial revolution and the application of wind energy for electricity generation began only in the late 1800s (Pasqualetti, 2004; EIA, 2019). With the exception of the sailboats that used the slightly different mechanical (aerodynamic) mechanism of lift, most early generations wind turbines or windmills were high torque and drag powered mechanical machines. Extensive development has, however, occurred in wind energy harnessing systems over
the several thousand years of wind energy utilization by man and the knowledge base for wind power extraction is robust. The mechanism of wind energy dissipation is well established and the theories and principles for the operation of wind energy harnessing devices have been documented in what is now mostly referred to as the Blade Element Momentum Theory (BEMT).

The BEMT is the combination of the momentum theory and the interaction of lift and drag forces acting on any material in the path of wind flow. The BEMT attempts to solve a common problem that wind energy designers are always faced with:

How to estimate the actual power that any particular wind energy harnessing system can extract from the wind at the design stage; determining how to estimate at each wind speed, how much energy can be extracted from a flux of wind by any chosen turbine blade size, shape, and orientation,

This question often requires to be answered at the design stage when the popular indicators commonly used for evaluating turbine power output namely, downstream wind speed and or turbine efficiency are yet to be empirically determined. Deriving a means by which designers can estimate these desired design property is the focus of the Blade Element Momentum Theory.

The following determinations lay the foundation upon which BEMT is built.

(i) **Determination of the power in the Wind:**

The power in a stream of wind is easily defined in terms of the kinetic energy in the drifting wind particles and wind power much like the power exerted by the kinetic
energy in any other fluid flowing within a space could be defined in terms of the area and speed of the flow, as well as the density of the fluid.

Kinetic Energy ($E$) is defined as the energy of a mass of a body in motion and Power ($P$) is the rate of dissipation of energy. So that:

$$E \text{ (Joules)} = \frac{1}{2} m u^2 \quad \ldots (2.1)$$

*Dimensionally: $M^1 L^2 T^{-2} = M^1 L^2 T^{-2}$*

And power (Watt) being the time rate of change of energy is expressed as:

$$P \text{ (Watt)} = \frac{E \text{ (Joules)}}{t \text{ (secs)}} \quad \ldots (2.2)$$

*Dimensionally: $M^1 L^2 T^{-2} \cdot T^{-1} = M^1 L^2 T^{-3}$*

Where $m$ (kg) is the mass of the material and $u$ (m/s) is the velocity or speed of the body.

Dimensional equations are a way of validating appropriate relationships and shows the validity of the relationship between physical phenomenon when the dimensional equation for the two sides of the equation agree. For instance, we know that energy spent over time is equal to power just as the force applied to a system multiplied by the velocity initiated in the system is also the measure of power applied because there is dimensional consistency in both relationships and the relationship agree with the dimensional form of Power. In the dimensional form, energy is denoted by $M^1 L^2 T^{-2}$ (Joules).
Power may alternatively be expressed in terms of force applied multiplied by the velocity initiated. But Force is denoted by mass multiplied by acceleration according to Newton’s second law.

\[ P \text{ (watt)} = F \text{ (N)} \times u \text{ (m/s)} = m \text{ (kg)} \times a \text{ (ms}^{-2}\text{)} \times u \text{ (ms}^{-1}\text{)} \quad \ldots(2.3) \]

Dimensionally:
\[ M^1 \cdot L^1 T^{-2} \cdot L^1 T^{-1} = M^1 L^2 T^{-3} \]

The definition above as denoted by the equation is accepted since dimensional consistency is established with those of power. A form of the above equation for power is useful in the measurement of power extracted by a wind turbine where the rotational velocity of the wind turbine shaft and torque (a force moment) is used in dynamometry for estimating the power in a wind energy harnessing system.

Since \[ E = \frac{1}{2} m u^2 \quad \ldots(2.1) \]

Determining the mass of air in a wind stream is achieved by estimating the mass as a function of the density and the volumetric flow rate of the air.

\[ \rho = m v^{-1} \quad \ldots(2.4) \]

\[ m = \rho v \quad \ldots(2.5) \]

where \( \rho \) is the Density (kg/m\(^3\)) and \( v \) is the volume (m\(^3\)) and \( m \) is the mass of air (kg) and where \( t \) is the time (seconds) of energy extraction equation 2.1 becomes:

\[ E = \frac{1}{2} \rho v u^2 \quad \ldots(2.6) \]
From equation (2.6), equation (2.2) becomes:

\[ P = \frac{1}{2} \rho v u^2 t^{-1} \quad \text{(2.7)} \]

**Figure 2.1: A Virtual Cylinder Describing A Wind Tube**

For a cylindrical tube of wind stream (air flowing through a circular cross section of radius \( r \) (m) and a speed \( u = x(m)/t(s) \), the control volume which defines the wind stream will be a virtual cylinder with volume; \( v \) (m³) whose length is \( x(m) \) and whose cross-sectional area \( A(m^2) = \pi r^2 \).

\[ v \ (m^3) = x \pi r^2 \quad \text{(2.8)} \]

\[ P_w = \frac{1}{2} \rho x \pi r^2 u^2 t^{-1} \quad \text{(2.9)} \]

But \( x(m) \cdot t^{-1} (s) = u \ (m/s) \) \quad \text{(2.10)}

And \( \pi r^2 = A \ (m^2) \) \quad \text{(2.11)}

\[ P_w = \frac{1}{2} \rho u^2 u^1 A = \frac{1}{2} \rho A u^3 \quad \text{(2.12)} \]

Dimensionally:

\[ M^1L^3 \ L^2 \ (L^1T^1)^3 = M^1L^2T^3 \ (Consistent) \]
Thus power in cylindrical wind stream of radius $r$ (m), moving at a velocity $u$ (m/s) with an air of density $\rho$ (kg/m$^3$) is expressed by equation (2.12). Equation (2.12) which describes the power in the wind of known wind velocity, area, and air density shows that the wind velocity having a cubic power have the most impact on the amount of power that is in the wind. This equation, however, does not tell how much power that a wind turbine or a material in the path of wind flow would be able to extract from the wind stream.

(ii) Determination of Actual Power in the Shaft of a Wind Turbine

The second phase of evaluation commonly embarked upon in wind turbine application is the determination of actual power a particular device extract from the wind. Assuming all materials (irrespective of shape, weight, size, and orientation) placed in the path of wind have the same capacity to extract energy from the wind, the determination of potential power output of any wind turbine would have been easy. But a challenge arise from the fact that, depending on the shape and orientation of a turbine blade or any material in the path of wind, only some fraction of the total energy in the wind can be harnessed and two wind turbines having the same number of blades and the same radius but having different blade shape and blade orientation towards the wind, would often perform differently in the same wind stream. In other words, wind turbine efficiency is material (including weight and surface properties), shape and orientation specific. The easiest way to evaluate the power output of a wind turbine, therefore, tend to be to test them empirically. In practice, the power of a wind energy harnessing device (i.e. the rate at which the device extract kinetic energy from the wind and converts it into shaft rotational energy) may be monitored or estimated using force and rotational speed sensors.
Recall that: \[ \text{Power} = \text{Force} \times \text{Distance} / \text{Time} \quad \ldots (2.13) \]

\[ \text{Torque} = \text{Force} \times \text{Distance} \quad \ldots (2.14) \]

\[ P_t (Hp) = \frac{\text{Torque (ft-lbf)} \times \text{RPM}}{5252} \quad \ldots (2.15) \]

\[ P_t (kW) = \frac{\text{Torque (Nm)} \times \text{RPM}}{9549} \quad \ldots (2.15a) \]

Where \( \frac{1}{5252} \) comes from \( \frac{2\pi}{33,000} \) with \( 2\pi \) denoting a complete rotation or revolution and 33,000 work in foot-pounds per minute in a horsepower. 9549 on the other hand, comes from \( \frac{60 \times 1000}{2\pi} \) which is required to convert the RPM to revolutions per second (the SI unit of angular velocity) as well as the conversion from Watts to kW.

If the torque in a wind turbine shaft is measured using a dynamometer and the rotational speed of the turbine is measured by a tachometer, then the power in the shaft can be calculated using equation (2.15) or (2.15a) depending on which system of measurement the readings were taken. Although this method of determination of turbine power is useful for the evaluation of actual power output during testing and running of a wind turbine, this method does is not helpful at the design stage, since the design process cannot be a blind or hopeful process based on trial and error. There has to be a way of setting out to build a turbine with clear expectations of some anticipated output – that is the essence of design. Engineers and wind systems designers therefore, desire a predictive means by which the power output of a particular type of chosen wind turbine blade can be estimated based on input at the design stage.
(iii) Estimating wind turbine power using the efficiency term

Apart from estimating turbine power output through actual testing for torque and rotational speed at different wind speed, a common equation which has been widely used for estimating wind turbine power is similar to the equation for the power in a wind stream (equation (2.12)) multiplied by an additional term called the turbine efficiency.

\[ P_t = \frac{1}{2} \rho A u^3 \eta \]  

...(2.16)

Where \( \eta \) is the efficiency of the wind turbine. Although this equation appears simplistic and is often referenced, it can be intuitively deduced as being similar to equations (2.15) and (2.15a) in its dependence on some empirical data for the determination of the efficiency and therefore has little value at the design stage. Equation (2.16) however provides a means by which turbine dimension in terms of radius or diameter might be estimated for a given or anticipated power and efficiency. In other words, if a particular amount of power (for instance, 1kW) is required from a design, the minimum diameter of a turbine blade that will deliver the desired power can be approximated based on the assumption that the turbine attains some hypothetical value of efficiency.

In practice, equation (2.16) is only as good as the efficiency deployed into it because, the efficiency sums the effect of the shape, weight, orientation and aerodynamic capabilities of the wind turbine. These properties are all lumped in one term failing to solve a design problem. Secondly, in non-steady state operations, wind turbine efficiency is not a number but a curve since turbine efficiency generally changes with wind speed. Therefore, using a hypothetical number as the efficiency will grossly misrepresent the actual power output at different wind speed in non-steady state operations. Thus, the limitation of equation (2.16) at the pre-field-testing stage partially extends also to its
empirical application unless steady state data have been obtained for the turbine efficiency at the different wind speeds across which range the turbine performance is to be evaluated.

2.4.1 Momentum Theory and Betz Limits

The need for estimating the potential power output of different geometric configurations for extracting wind energy has been long identified. A number of scientists by the early 1900s observed that there is a limit to which energy can be harnessed from the wind by different shapes. In particular, wind energy transfer phenomenon around different materials limiting power output was comprehensively analytically determined by a German Physicist – Albert Betz. In his conclusion, he showed using mathematical equations that only 59.3% of the energy in the wind can be extracted by the best (ideal) harnessing device or turbine. Betz work provided a great guide for defining the limits of the ideal wind turbine but provided no direct clue to how to design geometric properties that resulted in the ideal wind turbine.

The momentum theory is mathematical derivations based on the law of conservation of mass and momentum which shows that the momentum change of a system is equal to the sum of forces acting on it. When applied to a control volume in which a wind turbine is placed, the momentum theory is able to provide insight into some of the unknown to be elucidated at the stage of design for accurate estimation of wind turbine power. The most part of these mathematical derivations was documented in the Lanchester-Betz-Joukowsky limit and is most commonly cited as a baseline for understanding wind energy harnessing problems (Van Kuik, 2007; Manwell, 2010).
In order to establish how much energy the best turbine can extract from the wind per time (power), Betz made some assumptions which are reflected in the control volume below.

![Control volume for the conservation of momentum considerations](image)

**Figure 2.2: Control volume for the conservation of momentum considerations**

In the one-dimensional control volume shown in figure 2.2, wind moves from the region designated 1 at a speed $U_1$, impacts the turbine located between 2 and 3 and then moves at a reduced speed which is denoted $U_4$ far downstream of the turbine. $p_1$, $p_2$, $p_3$, and $p_4$ are the value of pressure in the respective zones 1, 2, 3 and 4 within the control volume. Similarly, $U_1$, $U_2$, $U_3$, and $U_4$ are the wind speed at the respective locations or zones. A disc or a hypothetical wind turbine (which in practice could be anything from the worst to the ideal wind energy harnessing device) is placed in the control volume. In this procedure, analytical considerations are made and as is shown later, for different values of upstream to downstream ratio. A practical way of looking at this analysis therefore will be to imagine that different types of wind turbine blade design or settings are placed in the control volume for each iteration so that the lowest ratio represents a blade type which allows no wind to pass through and the highest ratio is a wind turbine blade type in which all the wind that
moved from zone 1 passed through the blade type undiminished to zone 4. Therefore, each iteration which gives a set of efficiency represents the ability of a wind turbine type to harness wind energy. This procedure could also in practice represent simply changing blade orientation or other parameters which impact on the ability of wind turbines to aerodynamically extract energy from the wind. The basic assumptions made in Betz analysis are stated below:

(a) The control volume represents a virtual space in the natural ambient environment (i.e. non-pressurized systems) cut out around (from far upstream to far downstream) of a wind turbine and therefore, the static pressure far upstream and far downstream of the rotor will be the same as the ambient static pressure. (i.e. \( p_1 = p_4 = p_{atm} \))

(b) There is non-rotating wake (i.e. flow plane is maintained up and downstream of the rotor and therefore one-dimensional analysis is sufficient to describe the phenomenon)

(c) There is an infinite number of blades and the thrust across the blade swept area is uniform and there is no frictional drag resulting from the interaction of the elements within the control volume.

(d) The consideration is valid for air – an incompressible fluid of uniform density or homogeneity under steady-state flow conditions.

As are intuitively obvious, these assumptions are simplifications made to create a classical case or scenario from which, the property of wind flow and turbine interaction (a rather complex phenomenon) resulting in energy extraction can be closely examined and understood. For instance, steady state and one-dimensional flow assumption enormously simplify the evaluation which can then be later remodeled for multi-dimensional flow with
rotational wakes. With the above assumptions, and considering conservation of momentum, Betz deduced the maximum energy that can be extracted by an ideal wind turbine.

Basically, with the conservation of momentum, it is expected that the total momentum entering the control volume minus the momentum leaving is equal to the power extracted by the turbine rotor. Therefore, assuming that inlet and outlet regions are at atmospheric pressure, it will be expected that downstream wind velocity; $U_4$ will be a reduced version of far upstream wind velocity; $U_1$, with the difference in upstream and downstream momentum being equal to the net power extracted by the wind turbine.

The wind velocity; $U_2$ near upstream and $U_3$ near downstream around the rotor, being induced by the presence of the blade is assumed to be the same and through a series of calculations shown below and summarized in Appendix A, these near upstream and near downstream velocities are shown to be the mean (average) of the far upstream and far downstream velocity.

$$U_2 = \frac{(U_1 + U_4)}{2} = U_3 \quad \ldots(2.17)$$

### 2.4.1.1 Derivation of equation 2.17

From figure 2.1, steady state condition is assumed and the mass flow rate into the control volume would be equal to the mass flow rate through every section of the control volume.

Thus,

$$\dot{m} = \rho A_1 U_1 = \rho A_2 U_2 = \rho A_3 U_3 = \rho A_4 U_4 \quad \ldots(2.18)$$
The Thrust Forces, $T_1$ and $T_4$ at the inlet (upstream) and exit (downstream) can be defined in terms of the mass flow rate and the wind velocity and the Thrust on the Turbine Rotor within zone 2 and 3 can be defined in terms of the difference the upstream and downstream values.

\[ T_1 = \dot{m}U_1 \quad \text{...(2.19)} \]
\[ T_4 = \dot{m}U_4 \quad \text{...(2.19a)} \]
\[ T_2 = \dot{m}(U_1 - U_4) \quad \text{...(2.19b)} \]

If we recall that according to Bernoulli’s equation, $p_1 - p_2 = \frac{1}{2} \rho (U_2^2 - U_1^2)$ thus;

\[ p_1 + \frac{1}{2} \rho U_1^2 = p_2 + \frac{1}{2} \rho U_2^2 \quad \text{...(2.20)} \]

and
\[ p_3 + \frac{1}{2} \rho U_3^2 = p_4 + \frac{1}{2} \rho U_4^2 \quad \text{...(2.20a)} \]

By rearranging equations 2.20 and 2.20a, with the aim of isolating the blade zone (2 – 3) pressure and velocity terms, we get:

\[ p_2 = p_1 + \frac{1}{2} \rho U_1^2 - \frac{1}{2} \rho U_2^2 \quad \text{...(2.21)} \]
\[ p_3 = p_4 + \frac{1}{2} \rho U_4^2 - \frac{1}{2} \rho U_3^2 \quad \text{...(2.21a)} \]

and
\[ p_2 - p_3 = p_1 + \frac{1}{2} \rho U_1^2 - \frac{1}{2} \rho U_2^2 - p_4 - \frac{1}{2} \rho U_4^2 + \frac{1}{2} \rho U_3^2 \quad \text{...(2.22)} \]

Recall that $p_1 = p_4$ (atmospheric pressure) and that velocities at the blade $U_2$ and $U_3$ are approximately the same, thus by eliminating like terms, equation 2.22 becomes:

\[ p_2 - p_3 = \frac{1}{2} \rho (U_1^2 - U_4^2) \quad \text{...(2.23)} \]

Since pressure equals force per area, thrust force in the blade zone will be equal to the pressure in the zone multiplied by the area.
\[ T_{(2-3)} = \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) \quad \text{...(2.24)} \]

But recall that the term \( \frac{1}{2} \rho A_2 U_2 \) is equal to the mass flow rate. (equation 2.18) and the thrust of the blade zone was shown by equation 2.19

\[ T_{(2-3)} = \dot{m}_2(U_1 - U_4) \quad \text{...(2.19)} \]

By equating the right-hand side of (2.24) and (2.19), and writing the mass flow rate in the long form, we get:

\[ \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) = \rho A_2 U_2(U_1 - U_4) \quad \text{...(2.25)} \]

Finally, the blade zone velocity can be made the subject and equation 2.25 becomes:

\[ U_2 = \frac{1/2 \rho A_2 (U_1^2 - U_4^2)}{\rho A_2(U_1 - U_4)} \quad \text{...(2.25a)} \]

Equation 2.25 can be simplified over a two-step process by factorizing the squared component and eliminating like terms to becomes:

\[ U_2 = \frac{1/2 \rho A_2 ((U_1 + U_4) \cdot (U_1 - U_4))}{\rho A_2(U_1 - U_4)} = \frac{(U_1 + U_4)}{2} \quad \text{...(2.26)} \]

Equation 2.26 shows that the near upstream and near downstream velocities around the turbine rotor can be taken as the average of the up and downstream velocities. (End of Derivation) (Manwell, 2010)

**2.4.1.2 Derivation of the Betz limit**

Based on equation 2.26 above, the mass of air which flows through the rotor per unit time can be expressed in terms of the mean velocity of the air, the swept area of the rotor and the density of the air since the mean velocity is the average distance traveled per
unit time and distance traveled multiplied by the area of flow will give volume. Since density is the mass per volume, the volumetric flow rate multiplied by the density will give mass per unit time.

\[ m = \rho A \frac{(u_1 + u_4)}{2} \]  \hspace{1cm} \text{...}(2.27)

Where \( A \) is the swept area of the turbine rotor and can be assumed to be the same as \( A_2 \) the swept cross-sectional area of the blade zone in the control volume (Figure 2.1).

From Newton’s second law of motion, the power extracted by the wind turbine can be estimated in terms of the amount of wind flowing through the turbine rotor per minute and the drop in the wind speed or velocity.

\[ P_t = \frac{1}{2} m (u_1^2 - u_4^2) \]  \hspace{1cm} \text{...}(2.28)

Incorporating equation (2.27) into equation (2.28), the power extracted by the turbine becomes:

\[ P_t = \frac{\rho}{4} A (u_1^2 - u_4^2)(u_1 + u_4) \]  \hspace{1cm} \text{...}(2.29)

The efficiency of a wind turbine much like every other device is estimated by a ratio of the actual power extracted by the turbine versus the total power available in the wind stream.

Recalling from equation (2.12) the power in the upstream wind can be expressed as:

\[ P_w = \frac{1}{2} \rho A u_1^3 \]  \hspace{1cm} \text{...}(2.12a)

The efficiency of the wind turbine at extracting power from the upstream wind can, therefore, be determined by dividing equation (2.29) by equation (2.12a):
\[
\frac{P_t}{P_w} = \frac{\frac{1}{2} \varrho A (U_1^2 - U_4^2)(U_1 + U_4)}{\frac{1}{2} \varrho A U_1^3} \quad \text{(2.30)}
\]

\[
\frac{P_t}{P_w} = \frac{\frac{1}{2} (U_1^2 - U_4^2)(U_1 + U_4)}{U_1^3} \quad \text{(2.30a)}
\]

\[
\frac{P_t}{P_w} = \frac{\frac{1}{2} U_1^2 \left( 1 - \frac{U_4^2}{U_1^2} \right) U_1 \left( 1 + \frac{U_4}{U_1} \right)}{U_1^3} \quad \text{(2.30b)}
\]

\[
\frac{P_t}{P_w} = \frac{1}{2} \left( 1 - \left( \frac{U_4}{U_1} \right)^2 \right) \left( 1 + \left( \frac{U_4}{U_1} \right) \right) \quad \text{(2.30c)}
\]

Equation 2.30c shows that the efficiency of turbines which follow the considerations for Betz limit analysis can be evaluated based on the far upstream and far downstream velocities. Recall that \( \frac{U_4}{U_1} \) is the ratio of the far downstream to the far upstream velocity. Also, the energy extracted by the turbine rotor is expected to result in a reduction in the magnitude of the far upstream velocity. Therefore, it is possible to estimate the potential efficiency for any turbine rotor in terms of the amount of reduction in the velocity. A very efficient turbine rotor will be one in which the energy extracted results in a far downstream which is a fraction of the far upstream velocity in a way that equation (2.30c) produces the highest value.

There are two common means of performing this procedure. The first method involves the graphical solution of the speed ratios. In this method, a value of far upstream velocity is chosen and a corresponding value of far downstream wind velocity is obtained by removing an infinitesimal fraction of the original speed from the far upstream velocity. Using the two values, a corresponding efficiency is calculated using equation (2.30c). Then the same small amount of wind speed reduction is applied to the last value of downstream velocity.
velocity while keeping the upstream velocity constant. The calculation is conducted over and over until the far downstream velocity is almost zero. For instance, if upstream wind speed is chosen to be 12 m/s, then an iteration of corresponding downstream velocities may be made from 12 m/s (in which case, the blades of the wind turbine did not reduce the upstream wind velocity and therefore no power was generated), and the next may be 11.5 m/s and 11 m/s and 10.5 m/s till the last one is 0 m/s (which implies that the turbine blade blocked all the wind). A graphical plot of the far downstream to the far upstream wind velocity and their corresponding efficiency is then made.

Figure 2.2 is a typical plot of speed or velocity ratio to efficiency. Irrespective of the value of upstream velocity, the plots will always be normalized since it is a ratio plot and should always look like Figure 2.2 provided steady-state condition is assumed and the chosen value of upstream wind speed remains constant.

![Figure 2.3: Betz limit Plot of Efficiency Versus Speed Ratio](image-url)
Figure 2.3 shows that the efficiency of the turbine changed as the ratio of upstream to downstream wind velocity increased. Maximum efficiency of 0.593 (59.3%) was reached at a wind speed ratio of 0.333 or $\frac{1}{3}$. In other words, a wind turbine will have a maximum efficiency if its blades are so designed that at the prevailing wind speed, the downstream wind speed becomes one-third of the upstream wind speed. On this basis, Betz concluded that the maximum efficiency any wind turbine could achieve was 59.3% and that only 59.3% of the total energy in the wind could be extracted by the best wind energy harnessing device possible.

The second method involves applying the derivative of the thrust equation. In this method, the process takes off from equation (2.24) and the mass flow rate is expressed in terms of $U_2$, the turbine zone wind velocity. To achieve this, the near upstream velocity is defined in terms of a factor; $a$ - called the induction factor. The induction factor is described as the ratio of the fractional decrease between the upstream wind speed and the wind speed at the rotor and the initial upstream wind speed.

$$a = \frac{(U_1 - U_2)}{U_1} \quad \ldots(2.31)$$

$$U_1 a = U_1 - U_2 \quad \ldots(2.31a)$$

$U_1 a$ is called the induced velocity while $a$ is the axial induction factor. The wind velocity at the turbine blade $U_2$ can, therefore, be defined as:

$$U_2 = U_1 (1 - a) \quad \ldots(2.32)$$

Recall also that from equation (2.17)

$$U_2 = \frac{(U_1 + U_4)}{2} \quad \ldots(2.17)$$
\[
\frac{u_1 + u_4}{2} = U_1 (1 - a) \quad \text{(2.33a)}
\]
\[
U_1 + U_4 = 2U_1 (1 - a) \quad \text{(2.33b)}
\]
\[
U_4 = 2U_1 - 2U_1 a - U_1 \quad \text{(2.33c)}
\]
\[
U_4 = U_1 - 2U_1 a \quad \text{(2.34d)}
\]
\[
U_4 = U_1 (1 - 2a) \quad \text{(2.33)}
\]

Thus from equation (2.24),
\[
T_{(2-3)} = \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) \quad \text{(2.34)}
\]

But Power = Force \times Speed
\[
P = T_{(2)} U_2 \quad \text{(2.35)}
\]
\[
P = \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) U_2 = \frac{1}{2} \rho A_2 U_2 (U_1 - U_4) (U_1 + U_4) \quad \text{(2.36)}
\]

From equation (2.36), (2.32) and (2.33), adding the values of \(U_2\) and \(U_4\) in terms of \(a\)
\[
P_t = \frac{1}{2} \rho A_2 U_2 (U_1 - U_4)(U_1 + U_4)
\]
\[
= \frac{1}{2} \rho A_2 (U_1 (1 - a))(U_1 - U_1 (1 - 2a))(U_1 + U_1 (1 - 2a)) \quad \text{(2.36)}
\]
\[
= \frac{1}{2} \rho A_2 (U_1 - U_1 a)(U_1 - U_1 + 2U_1 a)(U_1 + U_1 - 2U_1 a) \quad \text{(2.36a)}
\]
\[
= \frac{1}{2} \rho A_2 (2U_1^2 a - 2U_1^2 a^2)(U_1 + U_1 - 2U_1 a) \quad \text{(2.36b)}
\]
\[
= \frac{1}{2} \rho A_2 (4U_1^3 a - 4U_1^3 a^2 - 4U_1^3 a^2 + 4U_1^3 a^3) \quad \text{(2.36c)}
\]
\[
= \frac{1}{2} \rho A_2 (4U_1^3 (1 - a - a + a^2)) \quad \text{(2.36d)}
\]
\[
= \frac{1}{2} \rho A U^3 4a (1 - 2a + a^2) \quad \text{(2.36e)}
\]
\[
P_t = \frac{1}{2} \rho A U^3 4a(1 - a)^2 \quad \text{(2.36f)}
\]
The turbine efficiency is then estimated by dividing the turbine power by the total power in the wind shown in equation (2.12a)

\[ C_p = \frac{\frac{1}{2} \rho A u^3}{\frac{1}{2} \rho A u_1^3} = 4a(1 - a)^2 \]  

\( \ldots (2.37) \)

A derivative of equation (2.37) with respect to \( a \) is then taken. When the roots of the derivatives are obtained, the maximum coefficient of power is obtained at \( a = 1/3 \) and with a value of 0.593 similar to the observed value from the graphical method.

\[ f(a) = 4a(1 - a)^2 = 4a(1 - 2a + a^2) \]  
\[ \ldots (2.38) \]

\[ = (4a - 8a^2 + 4a^3) \ldots (2.38a) \]

Using the power law, the derivative of equation (2.38) is shown below:

\[ f'(a) = (4 - 16a + 12a^2) \]  
\( \ldots (2.39) \)

Evaluating the root of equation (2.39) at zero: (Replacing the induction factor \( a \) with the letter \( x \) to distinguish the induction factor; \( a \), from the quadratic equation terms)

\[ 12x^2 - 16x + 4 = 0 \]

Using the quadratic formular, where the equation terms \( a = 12 \), \( b = -16 \) and \( c = 4 \)

\[ x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{-(-16) \pm \sqrt{(-16)^2 - (4 \times 12 \times 4)}}{(2 \times 12)} \]

\[ x = \frac{16 \pm \sqrt{64}}{24} = 1 \text{ or } 0.3333 \]

If the root is 1, a trivial solution to the equation arises where \( C_p = 0 \) (since the term \((1 - a)^2 \) will become zero). Therefore, the only real value for \( a = 0.3333 \).

At \( a = 0.3333 \), \( C_p = 4(0.333)(1 - 0.333)^2 = 0.5926. \)
Thus the same end is achieved whether the graphical or the derivative method is used and Betz concluded that the best wind turbine rotor possible is one in which a value of \( a = 1/3 \) or 0.3333. In other terms, it is the turbine in which the ratio of far downstream velocity to far upstream velocity is equal to 1/3. He also concluded that this type of turbine could obtain a maximum efficiency or coefficient of power of 59.3% the total power in the wind flowing into the turbine rotor.

2.4.2 The Blade Element Momentum Theory (BEMT)

BEMT is a strip theory that combines the momentum theory which annunciates the law of conservation of momentum and the blade element theory which identifies the power in a wind drifted or floated blade as a sum of the resolved forces acting at each small section (element) of the blade. BEMT is considered the most widely used method for wind turbine blade analysis owing to its ease of application (Tangler & Kocurek, 2005). Blade element theory; the complement of the momentum theory in Blade element momentum theory relies on the knowledge of airfoil geometric characteristics which defines the lift and drag coefficients in order to estimate the induction factors. As already discussed in the momentum theory, with respect to equation 2.37, it is evident that if the induction factor is known, evaluating the turbine power and efficiency will be just a step away. The specifics of the blade shape and orientation are important in determining how efficiently a set of the rotor will extract power from the wind. A flat disc for instance placed in the path of the wind rarely extracts any power from the wind. A few folds in the disc may result in its ability to extract some power and ultimately, a well-organized arrangement of blade elements will enable an otherwise inefficient disc to become the ideal turbine.
Figure 2.4 introduces a few properties and terms used in turbine blade/rotor analysis and Figure 2.5 is a three-dimensional outlay of a typical rotor with the two-dimensional force diagram extracted to show how the resolved forces used in the analysis are obtained.

Figure 2.5 describes a typical airfoil viewed in a 2 – dimensional space as part of a 3 Dimensional object. To clearly understand the diagram, the process begins with the force vector $U_2$ which is the wind velocity arriving on the wind turbine as discussed in the previous section. This force vector is slightly less than the free stream wind speed $U_1$ and is consequently multiplied by a fractional factor $(1-a)$. This force vector is perpendicular to the plane of the rotor (since wind turbines are often designed to face the oncoming wind).

It is important to note that although this figure discusses wind energy, a distinction ought to be made by the flow path of the wind and the force imparted by the wind on the turbine blade. The streak lines in the background show that wind flow around the turbine is channeled around the curvature of the blade creating increased pressure on the concave side and lower pressure on the convex side. Blade element method is more interested in understanding the forces at work, and these are represented by the vector lines. $U_2$ is focused at a point on the chord line. When the rotation of the rotor is put into consideration, the effect of the force with magnitude $U_2$ acting on the blade by virtue of the wind is perceived as resolution (subtraction) of the rotary motion force from the incoming wind force. The resultant is called the relative velocity and it acts at an angle $\phi$ from the axis of the rotor. Determination of that angle is a major part of the BEMT.
Figure 2. 4: Schematic Diagram of a Wind Turbine Rotor and Airfoil Features

Figure 2. 5: Diagrams of a Wind Turbine and Forces Vectors Acting on the Airfoil

Source: Francis Agbali Field Analysis 2019

Figure 2. 5: Diagrams of a Wind Turbine and Forces Vectors Acting on the Airfoil
Recall that although the wind hits the blade with a velocity \( U_2 \), the blade itself is in motion at an angular velocity \( \Omega r (1 + a') \). This second velocity \( (U_0) \) occur along the plane of the rotor since the turbine is rotating along its own axis in the x-y coordinate. Therefore, the actual wind force felt by the blade is the vector difference between the incident wind velocity vector and the angular velocity vector. Therefore, the relative wind velocity is the vector subtraction of the two velocity vectors. Thus the vector lines for the angular velocity is conventionally considered reversed (to create a subtraction) and joined tail to the head of the incident velocity so that the resultant force joined the tail of the incident vector to the head of the angular velocity vector becomes the subtraction vector (rather than the addition vector – because of the reserved order). The resultant force vector, which is the net force “felt” by the turbine is known as the “relative velocity” of the wind on the turbine. Thus, although \( U_2 \) was the incident wind velocity, momentum changes occurring in the turbine is considered due to the relative velocity and not directly the incident velocity.

The relative velocity \( U_{\text{rel}} \) induces a drag force represented by the vector \( dF_D \) on the blade in the direction in which the \( U_{\text{rel}} \) force vector is pointing. It also induces a lift force; \( dF_L \), acting at the point where \( U_{\text{rel}} \) and \( U_2 \) hit the blade’s chord line and the lift force point in a direction perpendicular to the relative velocity \( U_{\text{rel}} \). Since the rotor is hinged, these forces are compelled to resolve into their respective components in the coordinates of the rotor plane. Thus, the resultant of the drag and lift forces resolve into a normal force \( dF_N \), acting in the direction of the incident wind and a tangential torque or moment force \( dF_T \), acting to create angular rotational thrust responsible for shaft rotation in the turbine. A major objective of the blade element and momentum method ultimately is the determination of the angular thrust force.
In performing the necessary calculations for determining the thrust force exerted by the wind on the turbine, the angle the relative wind makes with the rotor plane is very important. This angle $\phi$ referred to as the angle of the relative wind can be determined using the tangent relationship:

$$\tan \phi = \frac{U_1(1-a)}{\Omega r (1+a')} \quad \cdots (2.40)$$

The angle of the relative wind is then used to determine the angle of attack (AoA) which is the angle of the relative wind minus the section pitch angle ($\theta$) which is the angle the airfoil chord line makes with the plane of the rotor. Thus:

$$\text{AoA (}\alpha\text{)} = \phi - \theta \quad \cdots (2.41)$$

The farther away from the chord line the angle of relative wind goes, the closer to stall the turbine gets and it has been shown in a particular study on post stall airfoil data, that as the angle of attack exceeded 20 degrees, the airfoil characteristics began to approximate flat plat theory (Tangler & Kocurek, 2005). In using the BEMT procedure, the power generated by the turbine rotor is taken as the sum of the force moments (the thrust at each blade elements multiplied by the local radius of the element) for all the elements on each blade. Stating with the characteristic properties (coefficient of lift and drag) of the airfoil in each element, and knowing the angle of twist of the element with respect to the blade tip or root, calculations of potential $a$ and $a'$ are made.

If the chord of an airfoil within a blade element is $c$, and the wind speed is taken as $U$, the coefficient of lift; $C_l$, for an airfoil is estimated in terms of the amount of Lift force; $L$, per unit length; $l$, of the airfoil as:
\[ C_l = \frac{L/l}{1/2\rho U^2 c} = \frac{\text{Lift Force / Unit length}}{\text{Dynamic Force / Unit length}} \quad \text{...(2.41)} \]

Similarly, the coefficient of drag; \( C_d \), can be estimated in terms of the Drag force. In other words, if the coefficients are known for any airfoil type, it would be easy to determine how much Lift or Drag force is produced at the airfoil at different wind speed.

\[ C_d = \frac{D/l}{1/2\rho U^2 c} = \frac{\text{Drag Force / Unit length}}{\text{Dynamic Force / Unit length}} \quad \text{...(2.42)} \]

Since the turbine at some point within the consideration is effectively in motion under the propelling action of the wind, the wind velocity ‘felt’ by the wind turbine is a wind velocity of the actual freestream wind velocity relative to the velocity at which the turbine is moving; thus a property of moving turbines referred to as the blade tip speed ratio; \( \lambda \), comes into play. The tip speed ratio is the speed of the tip of the blade relative to the freestream wind speed.

When an annular tube with radius, \( r \), and thickness \( dr \) is considered as the element in consideration, assuming that wake rotation occurs beyond the rotor, and the blade angular velocity is denoted by \( \Omega \) while the angular velocity of the wake is represented by \( \omega \), the angular induction factor \( a' \) can be estimated as:

\[ a' = \frac{\omega}{2\Omega} \quad \text{...(2.43)} \]

So that the Thrust can be expressed both in terms of the axial as well as the angular induction factors as:

\[ dT = 4a(1 - a) \frac{1}{2} \rho U^2 2\pi r dr \quad \text{...(2.44)} \]
and \[dT = 4a'(1 + a')\frac{1}{2}\rho\Omega^2r^22\pi rdr\] \quad \ldots(2.45)

So that when equation (2.43) and (2.44) are equated, the tip speed ratio can be established as a function of the induction factors.

\[4a'(1 + a')\frac{1}{2}\rho\Omega^2r^22\pi rdr = 4a(1 - a)\frac{1}{2}\rho U^22\pi rdr\] \quad \ldots(2.46)

\[
\frac{a(1-a)}{a'(1+a')} = \frac{\Omega^2r^2}{U^2} = \lambda^2
\]

\ldots(2.47)

For the blade radius \(r = R\) and the tip speed ratio becomes:

\[
\frac{\Omega R}{U} = \lambda
\]

\ldots(2.48)

And the local speed ratio at each element becomes:

\[
\frac{\Omega r}{U} = \lambda_r
\]

\ldots(2.48a)

The drag \(Q\) is also defined in terms of the induction factors as follows:

\[dQ = d\dot{m} (\omega r) = (\rho U_22\pi rdr)\]

\ldots(2.49)

But \(U_2 = U_1(1 - a)\) and \(a' = \omega / 2\Omega\), thus equation (2.48) becomes:

\[dQ = 4a'(1 - a)\rho U\pi r^3\Omega \, dr\]

\ldots(2.49a)

Since Power = Force x Speed, \(dP = dQ \cdot \Omega\) and from equation (2.47) and (2.47a), the power extracted by the turbine may be calculated as follows:

\[dP = \frac{1}{2}\rho AU^3 \left[ \frac{8}{\lambda^3} a' \, (1 - a)\lambda_\tau^3d\lambda_r \right]\]

\ldots(2.50)

From all the on-going, and especially from Figure 2.4, a few important deductions could be made:

\[dT = 4a(1 - a)\rho U^2\pi rdr\]

\ldots(2.44)
\[ dQ = 4a'(1 - a) \rho U \pi r^3 \Omega \, dr \quad \cdots (2.49a) \]

\[ \tan \phi = \frac{u_1(1-a)}{\Omega r (1 + a')} = \frac{1}{\lambda_r} \frac{(1-a)}{(1 + a')} \quad \cdots (2.40) \]

\[ \sin \phi = \frac{u_1(1-a)}{u_{rel}} \quad \cdots (2.51) \]

\[ dF_L = C_l \frac{1}{2} \rho U_{rel}^2 c dr \quad \cdots (2.52) \]

\[ dF_D = C_d \frac{1}{2} \rho U_{rel}^2 c dr \quad \cdots (2.53) \]

\[ dF_N = dF_L \cos \phi + dF_D \sin \phi \quad \cdots (2.54) \]

\[ dF_T = dF_L \sin \phi - dF_D \cos \phi \quad \cdots (2.55) \]

For B number of blades:

\[ dF_N = B \left( C_l \frac{1}{2} \rho U_{rel}^2 c dr \cos \phi \right) + C_d \frac{1}{2} \rho U_{rel}^2 c dr \sin \phi \quad \cdots (2.56) \]

\[ dF_T = dC_l \frac{1}{2} \rho U_{rel}^2 c dr \sin \phi - C_d \frac{1}{2} \rho U_{rel}^2 c dr \cos \phi \quad \cdots (2.57) \]

Torque can thus be estimated using

\[ dQ = Br \, dF_T \quad \cdots (2.58) \]

\[ dQ = Br \, C_l \frac{1}{2} \rho U_{rel}^2 c dr \sin \phi - C_d \frac{1}{2} \rho U_{rel}^2 c dr \cos \phi \quad \cdots (2.59) \]

\[ dQ = Bc \, r dr \, \frac{1}{2} \rho U_{rel}^2 \left( C_l \sin \phi - C_d \cos \phi \right) \quad \cdots (2.60) \]

If \( \frac{Bc}{2\pi r} \), the solidity of each annular section in which the blade element being considered is factored in, then

\[ dQ = \sigma \pi r^2 dr \rho \frac{U_{rel}^2 (1-a)^2}{\sin^2 \phi} \left( C_l \sin \phi - C_d \cos \phi \right) \quad \cdots (2.61) \]

\[ dF_N = \sigma \pi r \rho \, dr \, U_{rel}^2 \left( C_l \cos \phi + C_d \sin \phi \right) \quad \cdots (2.62) \]

From equation (2.49a) and equation (2.61), where \( C_d = 0; \)
\[ 4a'(1-a) = \sigma \frac{U}{\Omega r} \frac{(1-a)^2}{\sin^2 \phi} = \sigma \frac{1}{\lambda} \frac{(1-a)^2}{\sin \phi} C_l \] \hspace{1cm} \cdots(2.63)

\[ \frac{a'}{(1-a)} = \sigma \frac{1}{4\lambda \sin \phi} C_l \] \hspace{1cm} \cdots(2.64)

Similarly, by equation the normal force equations and (2.56) and (2.62), we get

\[ \frac{a}{(1-a)} = \sigma \frac{C_l \cos \phi}{4 \sin^2 \phi} \] \hspace{1cm} \cdots(2.65)

### 2.4.2.1 The blade element momentum procedure

Beyond all the derivations, the blade element momentum method relies a simple procedure which basically utilizes equation (2.40) to determine the angle of the relative wind after based on some initial guess of axial and tangential induction factors. The iterative procedure follows the order shown below:

a) Obtain airfoil property data for the chosen type of airfoil (plots of coefficients of lift and drag at a different angle of attack)

b) Using equation (2.40), start with some initial guess for \( a \) and \( a' \) then compute the angle of the relative wind.

c) Using the angle of relative wind determined, calculate the angle of attack.

d) From the data on (a) above determine the coefficient of lift and drag which most appropriately matches the determined angle of attack.

e) Use the coefficients to determine the power and coefficient of power for the turbine taking into consideration the number of blades in the rotor and the sum of power for each blade element.
Thus, although the blade element momentum method is a long row of derivation, its application for determination of potential turbine power based on the shape, size, orientation of a wind turbine blade, is procedurally simple and straight to the point. BEMT is, therefore, one of the most commonly used methods among many wind turbine designers and is widely referenced. Much of the derivations used in this section, for instance, were gleaned from standard derivation framework in Manwell and McGowan (2010) with some modifications and mathematical expansion for clarity of idea. Some of the modifications also lend views from works done on specific projects in which BEMT was used. Although BEMT has some limitations including being performed at a specific wind speed and RPM, and the fact that some of the assumptions may not be entirely valid in real life conditions, several modifications have been built into the calculations which refine the performance of the model on specific turbine types (Manwell, 2010; Bobonea, 2013; Schneider, 2016).

2.4.2.2 Choice of the airfoil, lift and drag characteristics

As shown in the last section, the turbine rotor design should be based on specific output expectations. For instance, by anticipating a turbine with efficiency close to the ideal Betz turbine, the iterative procedure for the most appropriate axial inductions factor could start at about 0.3. However, this decision is not entirely a matter of what the designer desire but also a function of the type of airfoil he chooses or will be able to build. Therefore, a great start point for most design has been to choose airfoils from some documented ‘families’ of airfoil whose aerodynamic characteristics have been tested and documented. Much of these data are today available in the public domain and in the archives of several institutions that are often much more than willing to share them. Leading aeronautic laboratories perform airfoil testing and often recommend special airfoils for particular situations.
Low Reynolds Number (LRN) airfoils, for instance, are often recommended in wind turbines operated in low wind speed locations for their ability to perform well under low wind speed situation. For airfoils whose characteristics are not documented, many flow simulation software exists with which most airfoil lift and drag properties may be characterized through some computational dynamics which determine pressure and velocity differences as the fluid flow over the airfoil shape. Common examples include XFOIL 6.3, which is able to take airfoil profile and run their profile based on chosen Reynolds number range that a user supplies. Reynolds number is determined by an equation which takes into consideration the wind speed under which the calculation or simulation is to be carried out as well as the length of the airfoil and the kinematic viscosity of the airfoil which is a ratio of the air viscosity to its density.

\[ Re = \frac{UL}{\vartheta} \]

Where the kinematic viscosity, \( \vartheta = \frac{\mu}{\rho} \) whereas \( \mu \) and \( \rho \) are air viscosity and density respectively. Output includes a graphical display of the airfoil showing streamlines relative to the angle of attack for which the analysis is conducted. XFOIL however, require command line coding for which guidance is however available.

Another platform for evaluating airfoil profile is the Panel Method Based 2D Flow Simulator for MATLAB users. An important feature of Flow Simulator is the availability of a large database of airfoil types provided from the aerodynamic profiles and information at the University of Illinois, Urbana Champaign (UIUC). Generally, modern wind turbine design maximizes lift to drag ratio for a number of reasons including increasing tangential torque forces which results in more powerful shaft rotation which is important in
harnessing most power. Secondly, the more the normal force resulting from drag, the more pressure will be mounted on the turbine blades and tower thus the tendency for a structural failure occurring is higher. Therefore, drag minimization is important. In high drag, low-speed turbines, the turbulent rotational wake is higher and this will mean more land mass will be required if multiple turbines are being installed on a farm since more distance will be required to allow for the restoration of laminar flow needed for effective upstream velocity.

2.5 SMALL WIND TURBINE DESIGN FOR RURAL APPLICATION

Historically, wind turbines have been used in North America since the 1800s for on-farm operations especially water pumping. Wind turbines have also been used Persia since the 9th century (800 AD) for powering water fountain and pounding rice (Sorensen, 1995). The potential for application of small wind systems in addressing challenges in agriculture and in rural areas have been highlighted by researchers. It is suggested that electricity generation and the development of diesel pumps led to a decline in the use of small wind turbines in the 1970s. Wind turbines, however, continue to be used in several places around the world and there is evidence especially in developing countries of the prospects for small mechanical wind systems. A research paper on the renewable energy market in developing countries noted that there are between 500,000 to a million water pumping wind turbines in Argentina, about 100,000 similar ones in South Africa and about 30,000 in Namibia being used for agricultural purposes. (Martinot et al., 2002).

The rise in attention for small wind turbines with the capacity to address uncommon challenges in places where conventional wind systems are not well – suited has driven a
new trend of research with a focus on the use of unconventional turbine types. Building wind systems with indigenous materials as well as the use of technology for engineering novel types of turbines are gaining ground. A turbine with a maple leaf shaped blade was modeled and tested against the conventional type of turbine blades for application in India. The researchers have noted that one of the major challenges to wind energy harnessing in tropical locations is the low energy content resulting from low wind speed in tropic belts especially in the landlocked regions (Gadamsetty, 2015; Karekezi, 2002).

A technological challenge has been identified with grain drying in hot and humid climates and the conditions underlining postharvest losses in tropical climates have been isolated as the need for rapid removal of moisture in grains immediately after harvest. Energy for grain drying has also been identified as lacking in several developing countries. Wind energy as a renewable source of power for conducting forced convection has been reviewed noting that wind energy science is robustly supported by the theoretical framework for testing and development of different types of wind energy harnessing devices. This thesis is focused on demonstrating the potential of small wind turbines made from materials which can be sourced in most developing countries as tools for generating forced convection using energy in the wind.
CHAPTER 3:

SMALL WIND TURBINE DESIGN FOR MECHANICAL DRYING OF GRAIN
IN LOW WIND SPEED, WARM AND HUMID CLIMATES

3.1 ABSTRACT:

Horizontal and vertical axis wind turbines were tested in a preliminary study to determine the most efficient type of wind turbine for harnessing wind energy under low wind speed conditions. Multi-blade (12 bladed) horizontal axis wind rotor (HAWT) had the best power profile over three other turbine family types including a lift driven 3 blade vertical axis wind turbine (3VVAWT) and two drag driven savonius type vertical axis turbines (4VVAWT and E4VVAWT). A multi-blade, adjustable pitch, 1.4 m diameter wooden wind turbine was subsequently evaluated for its capacity for forced convective drying ear corn in low wind speed, warm and humid climates. The objective of the study was to test the high solidity wind turbine under low wind speed (2.5 – 5.5 m/s) conditions for airflow output using a mechanical coupling of the rotor shaft, and the ventilation fan through a gear or belt drive. The system’s efficiency during wind tunnel testing for airflow power was in the range of 4.2 to 8.61%. Airflow up to 0.52 m$^3$/s was produced at a wind speed of 5.6 ± 0.03 m/s. Psychrometrics chart, fundamental airflow, and resistance equations were embedded into a MATLAB function to calculate the power requirement for designing the turbine considering typical harvest season tropical conditions (25°C and 85% relative humidity). The airflow generated matched the requirement for drying up to 50kg
of ear corn in 2 to 4 days showing that an upscaled system taking reference from this prototype has the capacity for addressing rapid drying needs in warm and humid climates.

3.2 INTRODUCTION:

The use of wind energy harnessing systems for application in drying at the small scale farming and household levels is coming into focus for addressing post-harvest losses especially in developing countries where access to reliable power infrastructures is absent or limited, and the cost of generating electricity for resistance heating and forced convection is exorbitant for farmers in developing countries. In sub-Saharan Africa, 25% of grains harvested are lost annually due to poor and inefficient drying (IBRD, 2017; Mada et al., 2014; Olayemi et al., 2012). In addition to the physical loss of produce, grain staples such as corn and peanut, being high moisture produce at harvest, are pre-disposed to disease-causing, toxigenic molds, and other pathogens when adequate drying is not achieved immediately after harvest. One of such biological systems interaction, which has direct impact on human health is the growing concern of aflatoxin-related liver cancers ravaging many developing countries most of which are in hot and humid tropical climates where rapid drying of grains and staples is a major postharvest challenge (Davies, 2013; Kamala et al., 2016; McMillan et al., 2018).

Mitigating postharvest losses resulting from inefficient drying practices have been advocated by researchers (Bradford, 2018; Karekezi, 2002) and the use of renewable energy by smallholder farmers in crop drying, including solar (thermal and photovoltaic) as well as wind systems for rapid moisture removal and in-storage maintenance, has been identified as a potential solution to reduce quantity and quality loss in hot and humid climates (Shanmugam, 2006; Bolaji, 2008; Bolaji, 2011; Irtwange, 2009). It has also been
noted that there is a connection between the use of renewable energy and sustainable development in general (Dincer, 2000). Although forced convective wind energy applications have been rarely used in mechanical grain drying processes, it is widely used for other high torque mechanical operations like water pumping and grain milling. A novel method using wind energy for grain mixing and conveyor operation in silos has also been reported in a patent documented in the United States of America (Ehlers, 1985). It is estimated that more than 6 million water pumping wind devices were used in the United States of America between 1950 and 1970s (Kaldellis, 2011). At about the turn of the new millennium, there were between 500,000 to a million water pumping wind turbines are in use in Argentina, and South Africa has over 100,000 similar wind turbines for pumping water for agricultural operations (Martinot et al., 2002). Wind energy systems used for high torque mechanical operations are, therefore, not entirely new. Wind systems have also been reported several as a renewable power source next to mini-hydro in terms of power conversion efficiency and wind energy currently supports 3% of the United States total electricity production (Dincer, 2011). Wind energy development since the late 1980s equally shows that total power harnessed from the wind for various applications and the physical size of wind power systems globally has been on the increase.

The design, fabrication, and testing of a wind energy harnessing system suited for low-cost rapid drying of a food product through increased heat and mass transfer are, therefore, is the principal motivation for this study. In this chapter, the potential of a wind energy harnessing system for application in forced convection needed to enhance the rate of grain drying was examined. The research problem includes how to design and test a wind energy harnessing system (turbine) which would function under low wind speed
condition between 2 m/s and 5.5 m/s. The research further sort to determine if the energy extracted from the wind turbine can be coupled into a mechanical forced convection fan which can generate airflow draft suitable for drying grains harvested in warm and humid climates. In other to address the need of smallholder farmers in developing countries, the research aimed at designing a mechanical forced convection system which can be affordable and adopted in low-income countries.

3.3 MATERIALS AND METHODS:

3.3.1 Materials

Materials used in the cause of this study include the following.

a. Balsa Wood: Balsa wood was purchased from Vernier Software and Technologies (Beaverton, OR, USA) an online store that sells specialty items for kid wind projects. The wood where 0.0762 m wide by 0.30 m long wood and 0.002 m thickness per sheet.

b. Sixty (60) pieces of wood planks measuring 0.101 m x 0.76 m and 12 sheets of 0.0127 m thick plywood boards each measuring 1.2192 m x 2.4384 m were purchased from the local building materials shop.

c. 2 units 0.0127 m (internal diameter) bevel gears for building an axle gearbox, 4 units of 0.0127 m (internal diameter) ball bearings, 1 unit of 0.0127 m (internal diameter) needle bearing with 0.01905 m outer diameter, and 2 units of 0.0127 m (internal diameter) cone swivel bearings were purchased from McMaster Carr (Elmhurst IL, USA) an online hardware marketer.

d. Aluminum and soft steel shafts were fabricated at the Engineering Design Centre of the Department of Biosystems and Agricultural Engineering.
3.3.2 Methods

3.3.2.1 Preliminary study using horizontal and vertical axis turbine

Preliminary studies were conducted on four types of wind turbine to determine the wind turbine type that could provide better power profile for forced convection operations. The need for testing each type of turbine arose from 3 major considerations. First, although most common wind turbines used in electricity generation are 3 blades horizontal axis wind turbine (HAWT), mechanical operations involving forced convection would require that the air stream be transferred using ducts or tubing from the fan to the drying point. Unlike electricity which can be transferred through rotary contact mechanisms from the nacelle, ducts from the nacelle will constrain the wind tracking the rotation of the nacelle and vertical axis rotation would be required if the fan would be on the ground. This gave the use of a vertical axis wind turbine (VAWT) more advantage over the HAWT. Secondly, although HAWT are reported to have better energy harnessing efficiency than VAWT, the rated operational conditions for most HAWT are in 12 m/s wind speed. Most tropical locations are known to be low wind speed locations (Karekezi, 2002) and metrological data for the Guinea Savannah region in sub-Saharan Africa show typical historical wind speed between 2 m/s and 5.5 m/s (Ajayi, 2010; Ajayi et al, 2011; Cloutier, 2011). There was the need to, therefore, look at wind turbine types that will show considerable energy harnessing efficiency at low wind speeds. Thirdly, based on the number of rotating parts and ease of
blade fabrication, building a VAWT is economically more viable than HAWT for low-income farmers and there was the need to closely compare the technical and economic advantages in terms of empirical data which were scarcely available.

A 12-blade, fixed pitch, variable chord ornamental windmill rotor with 0.6 m diameter was adopted from the Engineering Design Centre (EDC) of the Department of Biosystems and Agricultural Engineering, University of Kentucky. Three other rotors of the same dimension but having 4, 8 and 10 blades were built at the EDC using 5 mm aluminum sheets in order to test for the effect of solidity. These turbines represented horizontal axis wind turbines (HAWT). Using the swept area of the HAWT as a guide, three VAWT types were built and tested. A three vane vertical axis wind turbine (3VVAWT) was adopted from a do-it-yourself (DIY) plan for the Lynx-60 purchased from Lynxwind.com (Brighton MI, USA). 3VVAWT is a typical lift driven vertical turbine whose principle of wind energy conversion is similar to airfoil based HAWTs.

In order to test drag driven turbines, a 4 vane vertical axis turbine (4VVAWT) having the same swept area as the HAWT was built following the Savonius (half cylinder) method, using aluminum flashing purchased from the local building materials shop. A second drag drove VAWT (E4VVAWT) was built by including a wooden enclosure which funnels wind into the trailing side of the 4VVAWT. This was based on Bernoulli’s principle and the continuity equation which indicates that funneling the path of incompressible fluid flow would result in an increase in fluid velocity as it moves from the zone of the wider aperture to a narrower aperture. Accordingly, it was anticipated that the increase in velocity would result in increased turbine power for the enclosed 4VVAWT.
3.3.2.2 Wind turbine design concept and criteria

Based on results from the preliminary study using the different types of wind turbines design considerations were made for multi-blade horizontal axis wind turbines. The research idea was therefore to build a variable number multi-blade, variable pitch, wooden, horizontal axis turbine whose diameter is expandable through multi-layer cascading. This turbine would be tested under steady state wind speed conditions in a walk-in the wind tunnel. The turbine rotor design considerations were therefore made partially on the basis of power output calculations and partially on the basis of the limited capacity of the testing wind tunnel for steady-state study to evaluate the actual output. The calculations were to guide the designer of the actual power requirement and therefore the potential dimensional requirement of a turbine that would generate the required power, while the testing facility determined the limits of turbine size that could be built for testing within the laboratory at our disposal.

The concept for the pilot scale wind turbine for application in field operations for actual grain drying in developing countries was one in which the turbine rotor would be mounted on a tower at least 10 meters from the ground in open farmlands within the Guinea Savannah grassland region. A horizontal to vertical axis gear system (Figure 3.1) was designed using a set of beveled gears to allow the power harnessed by the wind turbine be transmitted down the tower through the center of nacelle rotation using a transmission shaft which will be connected to a mechanical fan at the base of the tower.
Figure 3.1: 3D Visualization of the HAWT axle design for Horizontal – Vertical (HV) Power Transfer

Figure 3.2: 3D concept of a wind turbine for mechanical forced convection drying

Figure 3.2 shows the original concept for the full-scale turbine with much allowance for modification with respect to the type of transmission device (gears or belt
drive), the type of solar collector and drying chamber which is not a focus of this study at this point. The focus of the current work was to design a study size turbine which could be tested in the laboratory. The limits of the laboratory facility constrained the capacity of drying that could be achieved by the experimental turbine. The structural mechanics of the study turbine were also limited to the scale of the study and pilot scale turbine would be an upscaled version of the current size, strength, and capacity.

The turbine capacity was based on calculations which begin with determining the amount of grain intended to be regularly dried by a small holding farmer. For instance, if a farmer has 50 kg of ear corn at 35% moisture content (wet basis, wb) 12.209 kg of moisture would have to be removed to achieve a target moisture content of 14% (wb). This calculation is the first among a number of successive calculations and if at any stage of the entire calculation any of the parameters at this level changed, the entire procedure will change, hence the calculation was done by using the equation (3.1) fitted into a calculation scheme in a MATLAB Graphical User Interface and the script for the entire module is shown in Appendix B.

\[
x_3 = \frac{M_1}{100} x_1 - \left[ \frac{M_2}{100}(x_1 - \frac{M_1}{100} x_1)/(1 - \frac{M_2}{100})\right] \quad \text{(3.1)}
\]

Where \( x_3 \) is the amount of moisture to be removed from ear corn at initial moisture content \( M_1 \), target moisture content \( M_2 \) and initial weight \( x_1 \) (kg).

Similarly, the amount of air needed to remove \( x_3 \) kg of moisture from the ear corn has to be calculated. Since air at different relative humidity and temperature have different capacity for moisture pick-up, the psychrometric chart is employed to determine how much moisture each kilogram of air at the prevailing temperature and relative humidity would be
able to pick up. The difference between the mixing ratio (humidity ratio) at the prevailing temperature and relative humidity and at the saturation temperature (wet bulb temperature) and relative humidity just before saturation is determined as the moisture carrying capacity of the air. The psychrometrics chart was thus fitted into the MATLAB calculation scheme mentioned earlier to ensure that based on user inputs, the water carrying capacity at the prevailing environmental conditions are computed automatically. The details of this operation are found in 3.3.2.1 and on the script of the MATLAB function on Appendix B.

Other parameters determined include the determination of the appropriate airflow rate for adequate moisture removal and this leads to the determination of fan power requirement for achieving appropriate moisture removal. This calculation requires a number of steps dealing with potentially varied inputs for any particular situation and is therefore prone to potential computational errors. Therefore, a computational scheme which takes inputs from a user and calculates the required power output based on standard verified equations was adopted. The first input set relates to the state of the grain and farmers drying targets. The second set relates to the ambient air conditions and the target condition of the drying air while the third set of inputs relate to airflow rates and fan power requirement. These are discussed in extensive details in subsequent subsections 3.3.2.1 to 3.3.2.3.

Having achieved an insight of the actual power requirement, the preliminary determination of turbine dimension for supplying the target power output at the desired efficiency is calculated using a modified version of equation (2.12a) in which an efficiency term is included.
\[ P_p = \frac{1}{2} \rho A U_1^3 \eta \]  \hspace{1cm} \ldots(2.12a)

where \( \eta \) is the target turbine efficiency for the design and \( P_p \) is target power output.

In other words, the target of the design process would be to choose using some iterations of blade element and momentum theory, set of blade size, and orientations which will provide the desired output. In this way, turbine rotor dimension (radius), wind speed and power are set as an independent variables while the efficiency parameters (number of blades and associated solidity \( \sigma \), blade twist and associated lift and drag coefficients) are set as the dependent variables for determination either empirically with variable pitch as well as cascading blade design or through analytical methods using blade element momentum theory. In this study, both but more of the empirical methods was relied upon.

An adjustable pitch horizontal wind turbine with a variable number of blades was conceived and preliminary calculations for size and maximum power output achievable was limited by the size of the wind tunnel, the wind speeds for which the study is focused and the measure of parasitic losses due to bearing, gears, and nacelle axle effect. Nacelle - axle effect arises from the need to translate the turbine rotation from the horizontal axis to the vertical axis so that air pumping can be achieved while the turbine still tracks the wind. However, the torque in the air pump rotary part is only equal to the amount of maximum torque mounted by the turbine nacelle control or tail. In other words, a measure of power is lost each time the turbine tracks the wind and the turbine moves in the direction in which the air pump is rotating.

Wind speed conditions for testing was determined by reference to average wind conditions in North Central (middle belt region) Nigeria during the months of July –
August when major corn harvest occurs. A lower limit of 2.5 m/s and an upper limit of 5.5 m/s were set and the estimated output was established (Ajayi, 2011). Figure 3.3 shows a CAD draft of a 12-blade balsa wood prototype concept of a wind turbine rotor with adjustable blade pitch and variable blade number suited for testing potential power for mechanical aeration under different wind speed conditions.

Figure 3.3: 3D Representation of the Expandable Turbine with Variable Pitch

The rotor pitch angle is set by laying on a flat surface and using a wooden alignment block slant cut at specified angle placed on the surface and with a slanted edge aligned with the back of the blade.

3.3.2.2.1 Psychrometrics determination of drying power requirement

The psychrometrics chart provides a number of relationships, which are essential to determining drying conditions. Principally, the humidity ratio of air – the amount of moisture present per kilogram of dry air at a particular relative humidity, the dry bulb and wet bulb temperatures, and their relationship to other air-water vapor properties are defined
within the chart. Other important properties that could be gleaned off the psychrometrics chart include the specific enthalpy of air-water vapor mixture. For grain drying, moisture to be removed is assumed to be freely available on the product surface and unbound, and available to be picked up by dry air having psychrometrics quality suitable for drying. Although this assumption has technical limitations with respect to the sorption property of the agricultural product, the effect of the assumption on drying time and therefore energy requirement will be compensated for by the use of ear corn drying rate data obtained from deep bed empirical models derived under airflow and packing formation considerably similar to those in actual practice.

For the purpose of providing design criteria for this project, the middle belt region of Nigeria (within the Guinea Savannah tropical belt in Sub Saharan Africa) was chosen as the field testing region. This decision was based on the fact that Nigeria and South Africa are the largest grain producers of grain in sub Saharan Africa and of the two countries, Nigeria more closely represents a tropical climate through most part of the year and the country is at the center of some of the major postharvest concerns including aflatoxin contamination of grains. Corn was chosen as the study crop being the most cultivated cereal grain in most developing countries. In the middle belt of Nigeria, the major corn harvest occur in the months of July and August in which ambient relative humidity ranges between 75 and 90 % and an average ambient temperature range between 25°C and 27 °C. From the psychrometric chart analysis shown in Figure 3.3, it is shown that ambient air at 25°C and relative humidity of 85% has a mixing ratio of 0.017 kg moisture per kg dry air and 0.018 kg moisture per kg dry air at saturation.
This shows that air under such condition will hardly achieve much drying. Hence, solar heating of air to achieve lowering of relative humidity is recommended and 10°C rise in air temperature has been shown in a number of solar tent dryers reported in the literature. Therefore, design criteria based on environmental conditions are defined to be 25°C, 85% respectively for ambient temperature and relative humidity and a 10°C rise in temperature using a solar thermal collector. As a result, the relative humidity of the air is lowered to about 48% as the temperature increases as shown in Figure 3.4. The initial moisture ratio of the air and the moisture carrying capacity of dry air as it approaches saturation is used to estimate how much air is required for moisture removal from the agricultural produce under the prevailing psychrometrics conditions.
3.3.2.2 Amount of moisture removal required

The weight of moisture to be removed from bulk ear corn of known weight in order to bring the bulk down to the desired moisture content was evaluated using equation 3.1 below:

\[ x_3 = \frac{M_1}{100} \times x_1 - \left[ \frac{M_2}{100} \times (x_1 - \frac{M_1}{100} \times x_1)/(1 - \frac{M_2}{100}) \right] \] \hspace{1cm} \text{…(3.1)}

where \( x_3 \) (kg) is the mass of water vapor (moisture) required to be removed to bring a bulk sample with an initial mass \( x_1 \) (kg) from a moisture content \( M_1 \) (% wb) to a final moisture content \( M_2 \) (% wb). Equation 3.1 determines the mass of water to be removed based on three known parameters – the initial mass of the sample, the initial moisture content and the target moisture content. If the moisture content is expressed as decimals, then the equation becomes far more simplified as:

\[ x_3 = (M_{C1} \times x_1) - \left[ (M_{C2} \times (x_1 - (M_{C1} \times x_1))/(1 - M_{C2})) \right] \] \hspace{1cm} \text{…(3.2)}

where \( M_{C1} \) and \( M_{C2} \) are decimal expressions of initial and target moisture content respectively. No separate determination of dry matter is required. If dry basis moisture content are given, then equation 3.1 becomes

\[ x_3 = \left[ \frac{M_1}{100} \times \frac{x_1}{(1+\frac{M_1}{100})} \right] - \left[ \frac{M_1}{100} \times \left(x_1 - \frac{M_1}{100} \times \frac{x_1}{(1+\frac{M_1}{100})} \right) \right] \] \hspace{1cm} \text{…(3.3)}

and equation 3.2 simplifies to:

\[ x_3 = \left[ \frac{M_{C1}}{1+M_{C1}} \times \frac{x_1}{(1+M_{C1})} \right] - \left[ M_{C2} \times \left(x_1 - \frac{M_{C1}}{1+M_{C1}} \times \frac{x_1}{(1+M_{C1})} \right) \right] \] \hspace{1cm} \text{…(3.4)}
3.3.2.2.3 Minimum amount of dry air required for appropriate drying

The amount of air in kilograms required for achieving the desired drying was computed using the psychrometrics property of air at the prevailing ambient conditions. The difference between the humidity ratio of air at the drying temperature and the humidity ratio at the wet bulb temperature, or along the saturation line, determines the amount of moisture per unit mass of air that is removed by the air. The total mass of air required to remove all the moisture from the grain was computed by multiplying the inverse of the humidity ratio difference by the total amount of moisture to be removed. Once the amount of air required is determined, drying time will be determined either by relying on the drying rate of the product at the prevailing psychrometric conditions or a decision has to be made as to how long the drying is intended to run. By dividing the total air required by the number of hours required for drying will give the minimum drying rate that will guarantee adequate drying of the product. Using the psychrometric chart shown in Figure 3.4, ambient air temperature, elevated air temperature (based on solar thermal heating of the drying air) and relative humidity at ambient and elevated temperatures were used to derive the amount of air required. A psychrometrics function was built in MATLAB and shown in Appendix B to automatically compute the difference between the lower and the upper humidity ratio as the mass of water per kilogram that the air can remove. Saturation vapor pressure was estimated using the formulae:

\[ sP_g = (-1.547411 + 0.1886945)ts + 0.0049126(ts - 25.0002)^2 + 7.3617 \times 10^{-5} (ts - 25.0002)^3 + 6.177 \times 10^{-7} (ts - 25.0002)^4; \]  
\[ \text{...}(3.5) \]

Equation (3.5) can also be evaluated in psi using equation (3.5a)
\[
\ln\left(\frac{sPg}{3206.18}\right) = \frac{-27405.5 + 54.1896(ts) - 0.04513(ts^2) + 0.215321x10^{-4}(ts^3) - 0.462027x10^{-8}(ts^4)}{[2.41613(ts) - 0.00121547(ts^2)]}
\]

...(3.5a)

Where \(ts\) is the air temperature and \(sPg\) is the Saturation vapor pressure of air at the temperature \(ts\). This equation is a regression of the steam table values for the vapor pressure (ASAE, 1976).

Humidity ratio; \((HR)\) is then estimated by the relationship which associates the relative humidity; \(phi\) (in decimal form), the saturation vapor pressure; \(sPg\), the atmospheric pressure; \(patm\) with the humidity ratio.

\[
HR = 622*phi*sPg/(patm-phi*sPg);
\]

...(3.6)

3.3.2.2.4 Power requirement for adequate aeration

Once the dry air volumetric flow rate for achieving adequate drying is estimated, the required fan power was determined as a function of the volumetric airflow required and the flow resistance encountered by airflow as a result of its passage through ducts and grain depth (Bartosik et al., 2009). Shedd’s equation (3.10) was used to compute the pressure difference along the flow path (depth of ear corn) with the associated modifiers and constants particular to ear corn.

Some parameters required for the fan power calculation include:

i. Desired airflow – The amount of volumetric airflow per unit time required is supplied from the previous estimation given in 3.3.2 above. From the previous sections, it has been shown that the calculated airflow thus represents a number of
external variables such as drying temperature, humidity and amount of moisture to be removed since it was calculated taking these parameters into consideration.

ii. **Drying bin configuration** – The geometric configuration of the drying bin is vital for determining the cross-sectional flow area as well as the depth of produce fill. At this point, airflow may be represented in terms of volumetric flow per sec per face area which is essentially a velocity profile. Depth of fill is a function of the bulk density and an important factor in estimating the total resistance to flow within the drying system. For instance, a shallow bed of ear corn at 0.1 m deep will encounter less resistance to airflow and therefore require less force to pump air through the bed than a bed of ear corn one meter deep.

iii. **Grain depth in the drying bin** – Depth of fill was estimated as a function of bin configuration as well as bulk density of ear corn. A semi-empirical regression model obtained by Murphy (2018) for ear corn bulk density in terms of moisture content was used:

\[
BD = -7 \times 10^{-7} (M)^4 - 0.0002(M)^3 + 0.0132(M)^2 + 0.261(M)^1 + 52.792
\]

\[
\ldots (3.7)
\]

This was in agreement with other previous works including Bartosik et al. (2009) in which bulk density for various grains was estimated using equation (3.8)

\[
BD = x_1 - x_2M + x_3M^2
\]

\[
\ldots (3.8)
\]

Where BD is the grain or ear bulk density (kg.m\(^{-3}\)), \(x_1\), \(x_2\) and \(x_3\) are grain specific parameters while \(M\) is the grain moisture content (wet basis).
Depth of ear fill was established in terms of the dimension of the drying bin and the weight of harvested ear to be dried using the bulk density. The depth of grain fill was determined by the equation:

\[
L \ (m) = \frac{w \ (kg)}{BD \ (\frac{kg}{m^3}) \cdot l \ (m) \cdot b \ (m)} \quad \ldots(3.9)
\]

Where \( L \) is the depth of ear corn fill. \( w \) is the mass of ear corn harvested for drying, \( BD \) is the bulk density while \( l \) and \( b \) are the length and width of the drying bin.

iv. **Static pressure** – The amount of resistance to flow of air expected within the volume of ear corn to be dried is estimated using Shedd’s equation and its closely associated parameters for a specific crop.

\[
\frac{\Delta P}{L} = \frac{a Q^2}{\log_e(1+bQ)} \quad \ldots(3.10)
\]

Where \( \frac{\Delta P}{L} \) (Pa.m\(^{-1}\)) is the pressure drop over a unit of depth \( L \) (m) when the air velocity \( Q \) is presented as velocity (m/s) or as a volumetric flow rate per unit area (m\(^3\)sec\(^{-1}\)m\(^{-2}\)). The total pressure drop for the bulk is determined by multiplying \( \frac{\Delta P}{L} \) by the depth of material in the bin. \( a \) and \( b \) are product specific constants which for ear corn are \( 1.04 \times 10^4 \) (Pa.s\(^2\)/m\(^3\)) and \( 325 \) (m\(^2\)s/m\(^3\)) respectively (Shedd, 1945).

v. **Fan Power**: Power required by the fan to achieve adequate drying was calculated using the equation:

\[
F_P = \frac{dP \cdot Q}{63.43 \cdot (\eta)} \quad \ldots(3.11)
\]

Where \( F_P \) is the Fan Power Requirement, \( dP \) is the total Pressure in the airflow and \( Q \) is the volumetric flow rate of the air delivered by the fan for drying. \( \eta \) is the fractional
efficiency of the fan. Fan Power Requirements for aerated drying of 100 kg ear corn was calculated and turbine size estimation was carried out using the calculation scheme whose parameters are discussed in the sessions above.

### 3.3.2.2.5 Determination of wind turbine power using mechanical methods

A prony brake dynamometer was designed at Engineering Design Centre (EDC) of the Department of Biosystems and Agricultural Engineering, the University of Kentucky for the purpose of measuring the torque in a rotating shaft. A disc was machined on the turbine rotor shaft and a braking caliper was fitted at a known radius away from the center of the shaft. An S-type load sensor pre-calibrated with standard weights was fitted at the clamped end of the caliper so that when a light grip is applied to the braking calipers, the clutch of the caliper applies a soft grip on the rotating disc and the disc tends to drag the caliper along its direction of rotation thus putting the load cell under tension. The amount of force exerted on the load cell is measured in kilograms (or pounds) while the rotational speed of the shaft or turbine is measured using a digital tachometer.

In order to ascertain the power in the shaft, the measured force is multiplied by the distance from the clutch of the braking system to the center of rotating shaft to give the moment force (torque) in the shaft. The torque multiplied by the rotational speed (RPM) of the shaft divided by a constant (5252) gives the power (hp) in the turbine as shown by equation (2.15). If the load is measured in the metrics system, then equation (2.15a) can be used for obtaining the power in kilowatts in a way similar to the procedure above by replacing the constant 5252 with 9547 where these constants are related to the definition of the horsepower as explained in section 2.3 (ii).
Determination of turbine using electrical methods

Electrical methods were used for the determination of the power in the turbine. A generator of known efficiency (i.e. the efficiency of the amateur to convert the mechanical power it receives when its shaft is cranked within a range of rotational speed to electrical energy) is required. Since most wind turbines are used for electricity generation, the common practice in which a simple ammeter and voltmeter are used to determine how much power is drawn from the generator failed to provide an accurate result in this case. This was because the rated efficiency of the generator is only reliable at the peak rotational speed for which the turbine rotation even with reverse speed reduction could not attain the rate peak for the generator. Therefore, using electrical methods for estimating wind turbine power at low wind speed can be erroneous if the energy extraction efficiency of the generator at the specific rotational speed is not known. For instance, if a dc generator is rated to produce 40W of electricity at 1400rpm with an internal efficiency of 95% (in other words, whatever power you measure from the generator at 1400 rpm is about 95% of the actual power it extracted), using the generator at some random speed (e.g. 1000 rpm) could produce unreliable values as was observed in this study. If the appropriate efficiencies are known at the operational rotational speed, the procedure involves connecting an ammeter with one end to the positive terminal of the generator and the second end to the positive terminal of an electrical implement of known resistance (for instance a lighting bulb). The negative terminal of the generator is then connected to the negative terminal of the electrical implement. A voltmeter is then connected across the positive and the negative poles of the generator. The power is determined by multiplying the voltage and the current. In order to accurately estimate the power of the turbine at different rotational speed or wind
speed, different implements with increasing resistance were added at the same wind speed and the voltage and current readings taken until additional implement bring the turbine to a stall. In other words, the load force provided is nearly equal to or more than the force exerted by the turbine. This procedure was repeated at different wind speed and some trends were obtained.

3.3.2.2.7 Determination of turbine power using aerodynamic methods

Aerodynamic power may be measured as a net system power output in the way an electrical generator is used to measure turbine power in terms of electrical power output. However, aerodynamic power measures much more than wind turbine power. It measures the system power output by discounting all the losses from the turbine to the point of airflow and pressure measurements. For instance, power losses as a result of duct losses as well as shaft losses have been taken off when the power is measured in terms of airflow rate and total pressure. In this method, mean airflow rate through a point in the duct through which a mechanical air pump or fan powered by the turbine is forcing air through is measured using suitable tools like a calibrated wind speed sensor or airflow meter. If the diameter or cross-sectional area of the duct is known, then the total airflow through the pipe per sec can be determined with respect to the face area and using a suitable pressure measuring device like a pitot tube or a calibrated pressure sensor, the total pressure in the line (flow plus static pressure) can be measured. To ascertain total pressure, while the fan was running at full strength at each wind speed, the bin outlet was sealed until the flow sensor in the plenum recorded a zero flow velocity (in other words, all the dynamic pressure had been transmuted into static pressure).

\[
\text{Power (kg m}^2\text{/s}^3\text{)} = \text{Airflow rate (m}^3\text{/s}) \times \text{Total Pressure (kg/ms}^2\text{)}
\]

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3.4 RESULTS AND DISCUSSION

3.4.1 Results from Power Requirement Calculations

Calculations were conducted to determine the power requirement for forced convective drying of 100 kg ear corn in climates with an average ambient temperature of 27°C and relative humidity between 80% and 85%. Drying air is assumed to be elevated by 10°C elevation over the ambient using solar heating which results in relative humidity depression to between 40% and 45% respectively. Accordingly, the worse drying condition occurs at 27°C and ambient relative humidity of 85% when no solar heating is available and best drying condition occurs at 37°C and 40 relative humidity when upper solar temperature elevation is achieved and ambient relative humidity at 80% is depressed to 40%. The calculations were conducted for drying within 2 days and within 4 days in which initial moisture content is assumed to be significantly depleted over the first two days but lowered to long term storage states over the 4 days period. Table 3.1 shows the values obtained with the MATLAB graphical user function which harnessed all the equations for fan power determination starting with drying load estimation.

Table 3.1 showed that operations with higher relative humidity air at low temperature for a shorter length of time required the most power of 424 W (0.6 hp). The same condition spread over 4 days of drying resulted in a much lower requirement of 62 W (0.1 hp). Raising the air temperature results in the lowering of relative humidity thus conditioning the air for higher moisture pick up capacity and the power requirement reduces as shown between temperatures 27 and 37°C across the board.
Table 3.1: Fan Power Requirements for efficient drying of 100 kg ear corn from 24% to 14% Moisture Content (wb)

<table>
<thead>
<tr>
<th>Air Temperature (°C)</th>
<th>Fan Power (W)</th>
<th>2 Days</th>
<th>4 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RH40</td>
<td>RH45</td>
<td>RH70</td>
</tr>
<tr>
<td>27</td>
<td>0.63</td>
<td>8.67</td>
<td>100.75</td>
</tr>
<tr>
<td>37</td>
<td>1.64</td>
<td>2.42</td>
<td>35.27</td>
</tr>
</tbody>
</table>

Apart from increasing fan power requirements, the drying of agricultural products with high humidity air in tropical locations poses a risk of mold growth. Therefore, the assumption of this study is that ear corn will only be dried with ambient air in which solar heating or some other forms of heating has been impacted to at least 10°C rise in temperature. This assumption allows the design considerations to be limited to a mean 35°C and relative humidity of 45% region with power requirement limited to under 10W for 2 days drying operations and much lower for 4 days drying. A design safety factor of 1.5 was applied and iterations of turbine radius for the required power for operation in different wind speed regions was done using a MATLAB Script for Turbine Radius on Appendix D.

The results are shown in Table 3.2 and were used as design considerations for choosing a 0.7m radius wind turbine. The orange shaded boxes on Table 3.2 represents the design range (40 - 45% RH and Mean Temperature of 35°C; 37°C being the preferred limit) while those in blue and green are sub design range for which the turbine chosen for the design range might be amply suited. A 0.6 m – 0.8 m radius turbine was therefore chosen.
and an adjustable pitch horizontal wind turbine was designed as shown in Figure 3.1 below. A bigger turbine was probably a better choice but was not selected due to the size of the wind tunnel. Wind speed range was determined by reference to average wind conditions in North Central Nigeria during the months of July – August when major corn harvest occurs. A lower limit of 2.5 m/s and an upper limit of 5.5 m/s were set and the estimated output was established as the design test range.

In order to satisfy the requirement for testing the hypothesis that a mechanical wind turbine is suited for drying of grain in a tropical warm and humid, climate, the test turbine must be able to power a fan with airflow capacity corresponding to ear corn airflow needed for drying within 48 hours, in order not to accept the null hypothesis.
Table 3.2: Wind Turbine Radius Requirement for Delivery of Required Fan Power at Different Wind Speed

2 Days Drying

<table>
<thead>
<tr>
<th>Temperature (Degree C)</th>
<th>Relative Humidity (%)</th>
<th>Turbine Radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wind Speed (m/s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5  3.0 3.5 4.0 4.5 5.0 5.5 6.0</td>
</tr>
<tr>
<td>27</td>
<td>40</td>
<td>1.29 0.98 0.78 0.64 0.53 0.46 0.40 0.35</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>1.55 1.18 0.94 0.77 0.64 0.55 0.48 0.42</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>5.28 4.02 3.19 2.61 2.19 1.87 1.62 1.42</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>10.84 8.25 6.54 5.36 4.49 3.83 3.32 2.92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (Degree C)</th>
<th>Relative Humidity (%)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.5  3.0 3.5 4.0 4.5 5.0 5.5 6.0</td>
</tr>
<tr>
<td>37</td>
<td>40</td>
<td>0.67 0.51 0.41 0.33 0.28 0.24 0.21 0.18</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.82 0.62 0.49 0.40 0.34 0.29 0.25 0.22</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>3.13 2.38 1.89 1.54 1.29 1.11 0.96 0.84</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>7.03 5.35 4.24 3.47 2.91 2.48 2.15 1.89</td>
</tr>
</tbody>
</table>

4 Days Drying

<table>
<thead>
<tr>
<th>Temperature (Degree C)</th>
<th>Relative Humidity (%)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.5  3.0 3.5 4.0 4.5 5.0 5.5 6.0</td>
</tr>
<tr>
<td>27</td>
<td>40</td>
<td>0.51 0.39 0.31 0.25 0.21 0.18 0.16 0.14</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.61 0.46 0.37 0.30 0.25 0.22 0.19 0.16</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.04 1.55 1.23 1.01 0.84 0.72 0.62 0.55</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>4.14 3.15 2.50 2.04 1.71 1.46 1.27 1.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (Degree C)</th>
<th>Relative Humidity (%)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.5  3.0 3.5 4.0 4.5 5.0 5.5 6.0</td>
</tr>
<tr>
<td>37</td>
<td>40</td>
<td>0.27 0.21 0.16 0.13 0.11 0.10 0.08 0.07</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0.33 0.25 0.20 0.16 0.14 0.12 0.10 0.09</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>1.21 0.92 0.73 0.60 0.50 0.43 0.37 0.33</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>2.70 2.05 1.63 1.33 1.12 0.95 0.83 0.73</td>
</tr>
</tbody>
</table>
3.4.2 Wind Turbine Testing

In the preliminary study, four small wind turbines (with a swept radius of 0.3m for HAWT) were tested to determine which of the turbines were more feasible for mechanical aeration.

![Sketches of Vertical and Horizontal Axis Wind Turbines](Figure 3.5)

(a) 3 Vane 0.6 m Vertical Axis Turbine (3VVAWT)

(b) 4 Vane 0.6 m Vertical Axis Turbine (4VVAWT)

(c) Enclosed 4 Vane Vertical Axis Turbine (E4VVAWT)

(d) 12 Blade 0.6 m Horizontal Axis Wind Mill (HAWT)

Figure 3.5 shows the test turbines at the preliminary study stage. Each of the turbines was tested for their power output using mechanical methods in which a prony brake dynamometer made with a calibrated load cell was used to estimate the torque while a calibrated fans unit was used to determine the wind speed and a tachometer determined the rotational speed of the turbine. E4VVAWT with an enclosure was based on the assumption of Bernoulli’s principle and the continuity equation that constricted or funneled path generally increase the velocity of fluid flow. Increasing wind velocity is known to increase the total power that is harnessed by a turbine. Under test, 4VVAWT (Figure 3.5
b) and the enclosed version E4VVAWT (Figure 3.5 c) showed lower power output capacity and rotational speed potentials. The observed low power in 4VVAWT was not unexpected considering that drag driven savonius turbines to utilize only half of their total swept area for the forward draft while the second half is redundant and can actually be counterproductive in poorly designed turbines. The scattered power profile for E4VVAWT suggests high turbulence within the enclosure which significantly supports the fact that increased velocity occurring as a result of the Bernoulli effect and the collision occurring with the blade within an enclosure created a zone of intense turbulence which reduced the turbines’ efficiency to extract energy. While funneling could have reduced backlash effect of the incoming wind on the second half of the blade, funneling also reduced the effective swept area with which the wind impacts the blade and therefore the area component of the turbine power equation was reduced.

Figure 3.6 shows a plot of measured power at different wind speed for each of the four wind turbines under test. Low wind speed zone regime between 2 m/s to 5/5 m/s was of interest since that corresponds to the mean wind speed for the guinea savannah during the months of July and August in which grain harvest is at the peak. Figure 3.4 shows the plots for mean rotational speed for each of the devices.
Results from the turbine power study as shown in Figure 3.6 indicates that 3VVAWT showed the highest power at the upper wind speed limits. It, however, did not start producing power until about 4 m/s wind speed. Its rotational speed profile (Figure 3.7) also shows that it has a steady rising rotational speed which commences a little above 2 m/s. At wind speeds above 5.5 m/s, its power profile shot over the 12 blade windmill making the airfoil type 3VVAWT better than the multi-blade wind turbine in high wind speed operation. The Lynx 6 is engineered for electricity production and must electricity-generating wind turbines have optimum rated wind speed at about 12 m/s. Multi-blade turbines, however, as typified by water pumping windmills run slow but steadily in low wind conditions owing to their high solidity. The poor performance of the 3 blade VAWT (3VAWT) at low wind speed thus disqualifies it for operation in tropical zones where optimum wind speeds are often below 5 m/s.
The 12 blade windmill (HAWT) showed a higher power profile within the mid-low wind speed regime above 2.5 m/s and 5 m/s. Its rotational speed cut in early and stays consistently above all the other types of turbines as shown in Figure 3.5. When the 4 blade HAWT was tested, it recorded no-starts in most of the lower wind speed except at 5.5 m/s pointing to the impact of high solidity in low wind operation of multi-blade turbines.

![Figure 3. 7: Plots of wind speed versus turbine rotational speed for all 4 Turbines](image)

Based on the higher power and rotational speed profile of the 12 blades horizontal axis turbine within the mid-low wind speed zone between 2.5 and 5 m/s, the horizontal axis turbine was selected as the potential turbine for application on the pilot scale actual field study. Subsequently, a 12 – blade, uniform chord, adjustable pitch wooden turbine was built with consideration for ease of replication in developing countries. In other to reduce parasitic bearing losses, lightweight balsa wood was used. However, this had limitations in terms of maximum chord size since the sheets could show structural instability with
increased chord length. Figure 3.8 is a picture of the 0.35 radius wind turbine built with Balsa wood and tested in a 1.2 m x 1.2 m wind tunnel.

Figure 3.8: Wind Turbine Calibration and Wind Tunnel Testing

3.4.2.1 Airflow and Pressure Testing

From Table 3.3 forced convective characteristics of the turbine with its aeration fan under different wind speed conditions, a trend of increasing power from $0.37 \pm 0.02$ W at $1.9 \pm 0.01$ m/s to $5.98 \pm 0.20$ W at $5.6 \pm 0.03$ m/s was reported. Overall system efficiency (convective power output divided by power of wind in the swept area covered by the turbine) however increased from $6.42\% \pm 0.30$ at the lower wind speed limits of the study peaking around $8.61\% \pm 0.32$ at a wind speed around $3.5 \pm 0.02$ m/s after which the efficiency gradually declines till a low of $4.2\% \pm 0.07$ at a wind speed of $5.6 \pm 0.03$ m/s. This trend showed that the wind turbine is more applicable for operation within the mid-range of the wind speed (2.5 to 5.5 m/s) studied. This observation further lends support to the notion that multi-blade wind systems perform better in low wind speed operations such as milling, water pumping and wood sawing where a high drag to lift ratio associated with high torque aerodynamics is known to predominate (Karekezi, 2002). This might equally
explain the low power generation experienced when an electric generator was used to ascertain the efficiency of the wind turbine as shown in Figure 3.9.

There is also the possibility that the decrease in aeration efficiency at the mid-range wind speed could signify that the aeration fan which utilizes the power in the turbine had reached its peak power utilization. Considering that the fan was a vehicle ventilation system fan which was adopted and modified, it is difficult to justify this position and it would be important in any future study to examine the use of a calibrated aeration fan whose aerodynamic properties are documented.

Figure 3.9: Composite Plot of Wind Turbine Power (W) and Efficiency at Different Wind Speed
Table 3. 3:  1.4 m Diameter Turbine Characteristics under Different Wind Speed Conditions

<table>
<thead>
<tr>
<th>Tunnel Wind speed (TWS) (m/s)</th>
<th>Pressure Head (Pa)</th>
<th>Mean DAFV (m/s)</th>
<th>Bin Cross Sectional Area (m²)</th>
<th>Mean Airflow Rate (DAF) (m³/s)</th>
<th>Aeration Power (Airflow * Pressure Head) (W)</th>
<th>Power in Wind (W)</th>
<th>Turbine Power (electrical method**) (W)</th>
<th>Efficiency (wrt power in wind) (%)</th>
<th>Efficiency (wrt to Betz) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6 ± 0.03</td>
<td>11.54 ± 0.38</td>
<td>1.8</td>
<td>0.288</td>
<td>0.52</td>
<td>5.98 ± 0.20</td>
<td>142.54 ± 1.57</td>
<td>2.016</td>
<td>4.2 ± 0.07</td>
<td>7.08 ± 0.11</td>
</tr>
<tr>
<td>5.4 ± 0.02</td>
<td>11.46 ± 0.25</td>
<td>1.7</td>
<td>0.288</td>
<td>0.49</td>
<td>5.61 ± 0.12</td>
<td>128.27 ± 0.89</td>
<td>1.96</td>
<td>4.37 ± 0.08</td>
<td>7.38 ± 0.12</td>
</tr>
<tr>
<td>4.9 ± 0.02</td>
<td>10.38 ± 0.38</td>
<td>1.6</td>
<td>0.288</td>
<td>0.46</td>
<td>4.78 ± 0.08</td>
<td>95.47 ± 0.73</td>
<td>1.624</td>
<td>5.01 ± 0.17</td>
<td>8.45 ± 0.29</td>
</tr>
<tr>
<td>3.5 ± 0.02</td>
<td>7.72 ± 0.25</td>
<td>1.35</td>
<td>0.288</td>
<td>0.39</td>
<td>3.00 ± 0.10</td>
<td>34.86 ± 0.42</td>
<td>1.1984</td>
<td>8.61 ± 0.32</td>
<td>14.52 ± 0.54</td>
</tr>
<tr>
<td>1.9 ± 0.01</td>
<td>2.32 ± 0.14</td>
<td>0.55</td>
<td>0.288</td>
<td>0.16</td>
<td>0.37 ± 0.02</td>
<td>5.72 ± 0.04</td>
<td>0.1344</td>
<td>6.42 ± 0.30</td>
<td>10.84 ± 0.51</td>
</tr>
</tbody>
</table>

* DAFV – Duct Airflow Velocity;  DAF – Duct Airflow;  TWS – Tunnel Wind Speed;

** Electric motor efficiency 88%
<table>
<thead>
<tr>
<th>Tunnel Aperture (%)</th>
<th>100</th>
<th>90</th>
<th>80</th>
<th>75</th>
<th>70</th>
<th>65</th>
<th>60</th>
<th>55</th>
<th>50</th>
<th>45</th>
<th>40</th>
<th>35</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed (m/s)</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>4.9</td>
<td>4.5</td>
<td>3.6</td>
<td>2.7</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Turbine Shaft RPM</td>
<td>473.0</td>
<td>475.7</td>
<td>475.0</td>
<td>474.0</td>
<td>468.9</td>
<td>456.5</td>
<td>455.0</td>
<td>433.4</td>
<td>418.2</td>
<td>255.3</td>
<td>288.0</td>
<td>208.0</td>
<td>179.0</td>
</tr>
<tr>
<td></td>
<td>475.0</td>
<td>476.0</td>
<td>475.2</td>
<td>473.3</td>
<td>469.4</td>
<td>460.4</td>
<td>446.0</td>
<td>432.5</td>
<td>419.0</td>
<td>255.5</td>
<td>287.5</td>
<td>209.0</td>
<td>179.0</td>
</tr>
<tr>
<td></td>
<td>477.6</td>
<td>475.3</td>
<td>476.0</td>
<td>473.8</td>
<td>467.8</td>
<td>458.9</td>
<td>452.5</td>
<td>432.8</td>
<td>420.0</td>
<td>256.5</td>
<td>287.3</td>
<td>207.6</td>
<td>179.8</td>
</tr>
<tr>
<td>Mean</td>
<td><strong>475.0</strong></td>
<td><strong>476.0</strong></td>
<td><strong>475.0</strong></td>
<td><strong>474.0</strong></td>
<td><strong>469.0</strong></td>
<td><strong>459.0</strong></td>
<td><strong>451.0</strong></td>
<td><strong>433.0</strong></td>
<td><strong>419.0</strong></td>
<td><strong>256.0</strong></td>
<td><strong>288.0</strong></td>
<td><strong>208.0</strong></td>
<td><strong>179.0</strong></td>
</tr>
<tr>
<td>Aeration Fan RPM2</td>
<td>963.0</td>
<td>955.6</td>
<td>950.0</td>
<td>947.1</td>
<td>945.1</td>
<td>938.2</td>
<td>918.5</td>
<td>889.0</td>
<td>846.0</td>
<td>528.4</td>
<td>573.0</td>
<td>415.0</td>
<td>358.0</td>
</tr>
<tr>
<td></td>
<td>953.7</td>
<td>953.0</td>
<td>953.2</td>
<td>949.5</td>
<td>946.5</td>
<td>935.4</td>
<td>912.0</td>
<td>886.2</td>
<td>851.0</td>
<td>529.6</td>
<td>572.0</td>
<td>419.0</td>
<td>364.0</td>
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<tr>
<td></td>
<td>957.0</td>
<td>954.9</td>
<td>956.9</td>
<td>950.7</td>
<td>951.0</td>
<td>932.9</td>
<td>916.0</td>
<td>880.2</td>
<td>845.2</td>
<td>528.0</td>
<td>573.4</td>
<td>425.0</td>
<td>359.0</td>
</tr>
<tr>
<td>Mean</td>
<td><strong>958.0</strong></td>
<td><strong>955.0</strong></td>
<td><strong>953.0</strong></td>
<td><strong>949.0</strong></td>
<td><strong>948.0</strong></td>
<td><strong>936.0</strong></td>
<td><strong>916.0</strong></td>
<td><strong>885.0</strong></td>
<td><strong>847.0</strong></td>
<td><strong>529.0</strong></td>
<td><strong>573.0</strong></td>
<td><strong>420.0</strong></td>
<td><strong>360.0</strong></td>
</tr>
<tr>
<td>RPM Measurement accuracy</td>
<td>0.99</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
<td>0.97</td>
<td>1.00</td>
<td>0.99</td>
<td>1.00</td>
</tr>
</tbody>
</table>
The rotational speed profile for the wind turbine was equally tested at different wind speed and reported in Table 3.4. Accordingly, rotations of up to 476 rpm were recorded at a wind speed of 5.4 m/s representing a tip speed ratio of about 2.77, which is more than the average for a 12 blade turbine which is recommended to have tip speed ratio of 2 (Manwell, 2010).

3.4.2.2 Fog testing

Fog test was conducted to demonstrate flow patterns during forced and natural convection airflow through a bin measuring 0.5 m x 0.5 m x 1.0 m (length x width x height) stacked with ear corn. Glycerine vapor was generated using a Chauvet DJ Hurricane 1000 Fog machine (Sunrise FL, USA) and blown across (not into) the suction end of the aeration duct. Turbine powered airflow resulted in low pass movement of air flow as shown in Figure 3.7 (a) while (b) showed stagnant or no air movement when the fan was switched off.

![Fog visualization of forced and natural convective flow using the system](image)

(a) Forced convective airflow (b) Natural convective airflow
3.4.3 MATLAB Function for Calculating Rotor Power Requirement

EarSim is an abbreviation used in this study to denote the use of a script to rapidly calculate the parameters needed for drying ear corn using psychrometric properties of the ambient and drying air as a determinant of drying rate and volumetric requirement. The graphical user interface running background functions removes the need for serial manual recalculation which are error-prone and intensive. For instance, a slight change in ambient or drying temperature can result in immense changes in the amount of air required for drying and consequently the power requirement.

![Figure 3.11: Screenshot of MATLAB GUI for Estimating Drying Power Requirements for Ear Corn (EarSim)](image)

Similarly, differences in corn fill depth or bin dimensions to accommodate changes in the amount of ear corn to be dried will also result in changes in power and pressure requirements. By using EarSim, external call for psychrometrics charts in order to extract important calculation variables is eliminated as psychrometric equations are built into the function.
Table 3.5 shows results of ear corn drying airflow requirements obtained from the MATLAB Script which calculates how much power is required for drying a particular amount of grain. Values ranges between 10 kg (study sample size) and 1000 kg (smallholder maximum harvest capacity) were calculated. Smallholder batch drying capacity was determined based on the total yield of 1000 kg of ear corn per harvest with about 600 kg (the portion that is generally stored and therefore require drying) harvested in 4 to 6 batches of about 100 kg.

Table 3.5: Airflow Power and Flow Resistance Requirements for Drying Ear Corn estimated by Ear Sim

<table>
<thead>
<tr>
<th>Mass of Ear Corn (kg)</th>
<th>Required Fan Power (W)</th>
<th>Airflow Resistance (Pa)</th>
<th>Volumetric Equivalence (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin Depth (m)</td>
<td>Bin Depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2 0.5 1</td>
<td>0.2 0.5 1</td>
<td>0.2 0.5 1</td>
</tr>
<tr>
<td>10</td>
<td>0.0004 0.001 0.002</td>
<td>0.01 0.03 0.06</td>
<td>0.04 0.03 0.03</td>
</tr>
<tr>
<td>50</td>
<td>0.03 0.06 0.14</td>
<td>0.05 0.13 0.27</td>
<td>0.6 0.38 0.52</td>
</tr>
<tr>
<td>100</td>
<td>0.82 2.07 4.14</td>
<td>0.26 0.66 1.32</td>
<td>3.15 3.14 3.14</td>
</tr>
<tr>
<td>200</td>
<td>9.88 24.7 49</td>
<td>0.79 1.97 3.9</td>
<td>12.51 12.54 12.56</td>
</tr>
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<td>298 744 1488</td>
<td>3.62 9.04 18</td>
<td>82.32 82.30 82.67</td>
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</table>

- Values were obtained for 85% ambient relative humidity and air temperature elevated to 35°C from 35°C using a Simulated Solar Thermal Collector

From Table 3.3, the prototype wind turbine with efficiency ranging from 4.2% and 8.6% had a volumetric aeration capacity ranging from 0.16 and 0.52 m³/s and therefore will achieve ear corn drying under 100 kg. It will provide adequate aeration for the
laboratory drying study whose estimated volumetric requirement based on EarSim is 0.03 up to a depth of 1 m.

3.5 CONCLUSION:

A small wind turbine made with a swept diameter of 1.4 m was built using balsa wood flat plate blades whose chord length were 0.076m and 0.3m sub-unit radius. Two subunits were fitted along a full blade length with a separating ring shell 0.82 m wide separating the first set of sub-units from the second set. A total of 12 blades (24 subunits) were used on the rotor. Data from the experiments showed that the turbine had overall efficiency based on airflow to wind power ratio, ranging from 4.2 to 8.6 %. Direct estimation of mechanical power in the system was difficult owing to the absence of a torque measuring tool with desired accuracy and reducibility. Airflow testing using an adapted air conditioning fan (Table 3.3) showed that the turbine could provide aeration up to 0.52 m³/s. Values for static pressure losses in stacked bin were not reported as instrumentation resolution for some boundaries of the study range were contestable but the reading showed consistent trends suggesting that the aeration generated using the turbine, surmounted static losses up to 1m depth filling in a drying bin of dimension 0.5 x 0.5 x 1.0 m stacked with ear corn,. This assertion is supported by the outcome of fog-tests in which low pass airflow was consistently demonstrated through the bin when the ventilation fan was turned on.

A MATLAB function written to calculate the drying parameters required for achieving ear corn drying in 48 hours showed that the aeration power generated by the wind turbine system was sufficient for laboratory scale aerated drying of ear corn up to 50kg.
Data obtained from this study equally suggest that the prototype wind turbine is able to achieve aeration of corn up to a 100 kg as demonstrated by the preliminary aeration tests and comparison with calculations for airflow quality requirements for rapid ear corn drying showed that it is able to support aerated drying activity up to half the regular batch of a small scale farmer. Since this is a prototype and it has demonstrated the capacity to support the simulation level drying test, it is concluded that the wind harnessing system is capable of addressing the drying aeration need of typical smallholder farmer of corn in low wind speed, warm and humid. The result failed to accept the null hypothesis, and it is held that using wind-powered aeration has some potential for enhancing the rate of air flow through small batches (up to 50 kg) of ear corn and therefore should enhance moisture removal and faster drying. A drying study under conditions similar to those in which the turbine was tested is recommended for later study.
CHAPTER 4:

EAR CORN DRYING STUDY IN TROPICAL CLIMATE SIMULATED USING CONTROLLED ATMOSPHERE WITH FORCED CONVECTION

4.1 ABSTRACT

Controlled atmosphere simulation of ear corn drying was conducted under conditions similar to elevated ambient conditions during corn harvest season in a typical tropical grain-belt within north-central Nigeria. The study showed that there was a significant difference at the 5% probability level of error when drying was conducted with airflow between 0.002 m$^3$kg$^{-1}$s$^{-1}$ and 0.08 m$^3$kg$^{-1}$s$^{-1}$. Moisture content was reduced from 22% to 15% within 22.7 hours with the higher airflow level and 40.3 hours with natural convective airflow. These values contrast with 4 to 7 days reported for drying in the tropics indicating that there was some impact of forced convection on drying under the study conditions. However, considering continuous steady state drying in the simulated study, a field trial with a pilot scale wind turbine is recommended for future study. This further identified gaps of research focus in documenting bulk drying of ear corn generally, and especially under critical conditions as are prevalent in tropical climates.
4.2 INTRODUCTION:

Grain postharvest losses (PHL) in developing countries have been identified as a major challenge to global food security. In sub-Saharan Africa (SSA) alone, it is estimated that over four billion dollars (USD 4 billion) are lost annually (World Bank, 2011). Estimates using metadata analysis and from self-reported farmer data (Hengsdijk & de Boer, 2017, Kumar & Kalita, 2017) show that between 19% and 24% of grains harvested in SSA are lost shortly after harvest due to storage and drying inefficiencies among other causes. The Food and Agriculture Organization (FAO) and World Bank data show that beyond controlling field losses, eradicating hunger in SSA would require close focus at the post-harvest level through the development of solutions that have a connection with the social, agricultural and economic realities of the region (Affognon et al., 2015). The ecological uniqueness of the region as a factor which predisposes grain to postharvest spoilage equally require close consideration (Bradford et al., 2018). In identifying the core issue leading to a high magnitude of postharvest losses in developing countries, Bradford et al., (2018) had zeroed in on “humidity” as the culprit. In other words, consideration of losses on the basis of the climatic condition could better motivate solutions that are ecology specific. For instance, corn is the most cultivated staple crop in the developing countries of tropical SSA (Tefera, 2012), and the preponderance of high ambient relative humidity (sometimes up to 85%) and mesophilic temperature (between 25°C and 45°C) are evidently the major factors which support rapid biochemical activities leading to its spoilage, and therefore, make high corn postharvest losses in these locations perennial. In a study in Southeast Asia related to grain drying in the tropics, the researchers state that grain drying is a major problem in wet season tropical climates because sun drying proves insufficient
for rapidly removing the moisture in grains under such high humid climates (Driscoll, 1996).

Agricultural practices and access to technology equally play an important role in grain postharvest associated with developing countries. In several tropical developing countries for instance, up to 69% of grains consumed, come from smallholding farming (Cornia, 1985; Jayne, 2003) where farm sizes range between 0.44 to 1.2 hectares with cultivation, harvest and drying conducted manually. Sun drying in the open is the most common means of grain drying resulting in long exposure to high humid climates prevalent during major harvest seasons. Apart from the increased exposure to pests, such open drying in humid climates results in the growth of molds with the high potentials of contamination with their toxins. A typical example of the role drying practices play on grain postharvest losses is evident in the case of corn drying in tropical countries of SSA. In Nigeria as a case study; most small holding farmers first dry their corn on the cob (ear corn drying) to enable subsequent manual shelling, after which shelled corn is then sun-dried until the kernel moisture content drops below 15% db. (13% wb) to enable long term storage in bags, plastic or metal drums and in other forms of traditional storage systems. Studies on the aflatoxin content in maize products from the region and some abduct studies on human in the sub-region suggest that dietary aflatoxin contamination in the area is high. Reported maize (corn) losses in Nigeria based on the African Postharvest Losses Information Systems (APHLIS) have been steadily between 17.3 to 17.9 % from 2010 to 2015 (NRI, 2017). The facts of both direct losses and contamination of corn products with mycotoxins point to a need for critical evaluation of the efficiency of the common drying and storage methods within the area.
The heightened concern on liver cancers in developing countries and the close association between dietary consumption of mold metabolites in grains further draws attention to the need for freshly harvested grains like corn to be rapidly dried to safe water activity level following harvest in warm and humid climates. Safe water activity level generally varies for different grains and in respect to the specific spoilage agent, and for corn, a common consideration is drying down to moisture content below 15% db where the grain can be held safe for a couple of months. In many developing countries, the means for achieving this threshold and maintaining it during storage remain an on-going challenge based on unavailable or unreliable access to power, and the exorbitant cost of sophisticated drying equipment needed for safe storage. There is, therefore, an ongoing need for solutions that will promote quicker and rapid drying following harvest.

In order to mitigate the effect of high environmental humidity (which creates drying challenges) at mesophilic temperature range, an understanding of the physical, and aero-thermodynamic characteristics of drying systems rapid moisture removal in grains like corn is important. Drying studies provide useful information which is required for equipment design and fabrication. Drying has been described as a common and essential process in the postharvest system but also a complex and least understood phenomenon which is difficult to mathematically describe or simulate and most drying studies rely on empirical validation (Bakker-Arkema et al., 1996; Driscoll, 1996). Empirical studies, on the other hand, are limited in application to situations similar to those under which they were conducted. This brings into closer perspective the need for bulk ear corn drying characteristics for designing systems that can address the challenges found in warm and humid climates.
Bulk ear corn drying studies are scarce. A few reported studies have focused on thin-layer, fully exposed (single layer) ear corn while most of the literature focuses on grain drying systems typically found in developed countries. Furthermore, apart from a narrow range of conditions reported for seed corn drying, the impact of standard and sub-optimal aeration, temperature and relative humidity on deep bed ear corn drying under typical conditions found in warm and humid climates are virtually non-existent. Table 4.1 shows the equilibrium moisture content for ear corn. The red boxes show equilibrium moisture content for ear corn during harvest seasons in the tropical corn belt of SSA. The lowest value (17.2% moisture content), explains the occurrence of postharvest loss and mold contamination in the region. The green boxes show the benefit of temperature elevation.

Table 4.1: Equilibrium moisture content (EMC) for ear corn at different temperature and relative humidity

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<tr>
<th>Temperature (°C)</th>
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<th>35</th>
<th>40</th>
<th>45</th>
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<td>13.0</td>
<td>14.0</td>
<td>15.1</td>
</tr>
</tbody>
</table>

(Source: Calculated from Modified Henderson Equations)
Figure 4.1 shows the average ambient temperature in a typical tropical location. The red highlight boxes show the months of major and minor corn harvest in the Guinea Savannah belt in Nigeria. Between July and August, when the major harvest occurs, ambient temperatures range between 18.3°C in the early hours and 29.4°C in the afternoon. Figure 4.2 equally shows the water activity levels at which various biotic factors including yeast and molds will proliferate and cause damage to biological materials like grains which possess the requisite moisture content.

When water activity is expressed in percentage, it is referred to as equilibrium relative humidity (ERH). In other words, by following the line for mold growth, it can be shown that mold activities begin gradually at about 0.6 Water activity or 60% relative humidity and the reaction or activity increases more rapidly between 0.8 and 1.0. From table 4.1, it can, therefore, be shown that at 35°C (95 F), raising concern for mold growth begins at about equilibrium relative humidity of 60% corresponding to a corn moisture content of 12.9%. In practice, however, major molds of concern also have optimum proliferation range about 70 - 75% ERH and grain moisture content above 14.5% are considered critical and 13.6% moisture content and lower are desirable.

Water activity and temperature generally guide the considerations for drying and safekeeping of grain during storage. The challenge in grain drying equipment design results from the need to know the drying dynamics of the particular grain. Drying rate characteristics are therefore of interest to postharvest system designers and researchers.
Figure 4.1: A Pictographic Chart of Average Ambient Temperature of Lokoja Area – Typical Tropical Grain Belt in Nigeria

Figure 4.2: Water activity Chart showing Reaction Rates for Various Biochemical Activities

Source: Syntilab Activity of Water
4.2.1 Statement of Research Problem and Objective:

The challenges of grain drying in developing, tropical countries have been closely related to high humidity in warm climatic conditions. Different agricultural products dry at different rates under different ambient conditions and drying rates for ear corn at one humidity has been known to differ from the rates at other levels of humidity. It is also generally known that changing airflow rates through agricultural products impacts the rate at which they dry. Data on ear corn drying rates are scarce and the focus on the few studies available are on drying under sub-tropical conditions. Among the few, whereas some attention has been given to the impact of changes in temperature and relative humidity, little focus has been placed on the role that airflow has on ear corn drying.

In a study by Sharaf Eldeen et al. (1980), the drying rate of a single piece, fully exposed ear corn in a tube supplied with excess drying air was measured and modeled. This represents an important empirical and thin layer drying model, which provides useful basic ear corn drying characteristics. Direct practical application of these characteristics, however, without validation, hardly exist. Islam (2004) showed that the assumption in which deep bed ear corn drying is modeled as a series of thin layers could be erroneous. The researcher cited the Barre – Hamdy – Baughman model, in which thin-layer model considerations were extended to deep bed (bulk) drying and resulted in errors with greater than 20 hours standard drying time difference. Friant et al., (2004) identified the need for independent data validation of the Sharaf Eldeen (1980) model and made significant improvements in the drying rate prediction, especially in the latter half of the drying process.
Generally, empirical and even analytical data on ear corn drying are scarce. This might be associated with the fact that only very few commercial systems in developed countries still dry ear corn since mechanized harvesting began to dominate the farming landscape in the 1900s. The second possible reason for low interest in bulk ear corn drying studies could be related to the difficulty involved in characterizing random ear corn filling and the irregularity of void space between ears when bins are filled by funneling or dumping. Among prominent literature on ear corn drying, Islam et al. (2004) reported the optimization of a commercial dryer operated at the upper tropical temperature range (between 35°C and 46°C). The researcher, however, used relative humidity between 16% and 25%, falling far below the practical conditions in warm and humid tropical climates. Other ear corn drying studies commonly cited (Friant, Marks, & Arkema, 2004; Sharaf-Eldeen, Blaisdell, & Hamdy, 1980) generally were conducted under thin layer assumptions in which ample airflow was supplied. Thus, individual ears were fully exposed and dried without consideration of ear corn to ear corn, as well as ear corn to air interaction which occurs in deep bed (bulk) drying.

There is, therefore, a gap in information on drying rate characteristics for ear corn dried at different airflow rates under typical tropical conditions. This study examines ear corn drying at three airflow rates for stacked layers in an environment which simulates the ambient conditions during postharvest drying in a typical tropical climate.
4.3 THEORETICAL BACKGROUND

Drying of agricultural materials is generally considered to be processed which occur under the falling rate regime (Erbay & Icier, 2010). The characteristics of drying processes are very important in equipment design for accurate capacity estimations. The process therefore is often modeled either as distributed models in which simultaneous heat and mass transfer considerations within the drying system are considered using the Luikov’s equations which are extension of Fick’s second law of diffusion or they may be modeled as lumped parameter models in which Luikov’s equation is further simplified by an assumption of uniform temperature gradient within the product.

In the distributed model, Fick’s law is thus presented by Luikov (1994) as a three termed equation in which pressure (P), temperature (T) and moisture changes (\(\partial M\)) are modeled simultaneously. Most common models ignore the pressure term.

\[
\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P \quad \cdots (1)
\]

\[
\frac{\partial T}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P \quad \cdots (2)
\]

\[
\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} T + \nabla^2 K_{33} P \quad \cdots (3)
\]

Where \(\nabla^2\) are partial derivatives with reference to the differentiation entities and K are the coefficients specific to the differentiation entities where \(K_{11}\) for instance, is the effective diffusion coefficient with reference to moisture gradient and \(K_{12}\) effective diffusion coefficient with respect to temperature gradient within the system.
And for lumped parameter models, the terms become simplified as shown below:

\[ \frac{\partial M}{\partial t} = K_{11} \nabla^2 M \]  \hspace{1cm} \text{...(4)}

\[ \frac{\partial T}{\partial t} = K_{22} \nabla^2 T \]  \hspace{1cm} \text{...(5)}

So that the phenomenological coefficient \( K_{11} \) is the effective moisture diffusivity (\( D_{\text{eff}} \)) and \( K_{22} \) is thermal diffusivity (\( \alpha \)) thus for planar geometries the rate of change of moisture content can be rearranged as:

\[ \frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial^2 M}{\partial x^2} \]  \hspace{1cm} \text{...(6)}

\[ \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \]  \hspace{1cm} \text{...(7)}

Equation (6) shows the rate of mass transferred (moisture removal) in terms of a relationship in which the left-hand side of the equation is a time function while the right-hand side is a space-related moisture gradient. In other words, in time \( t \), how fast is moisture moving from one region of the system into the other. This type of relationship has been used by various researchers from understanding various drying processes. As stated earlier, the focus of this chapter is on the impact of airflow on the rate of moisture removal in bulk ear corn. Six models listed below and previously reported in the literature were fitted to the data.
Table 4. 2: List of Model Equations Fitted with the Experimental Data

<table>
<thead>
<tr>
<th>Model Cited by</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis Model (Bruce, 1985)</td>
<td>$MR = e^{-at}$</td>
</tr>
<tr>
<td>Henderson and Pabis (1961) (Henderson, 1997)</td>
<td>$MR = ae^{-bt}$</td>
</tr>
<tr>
<td>Wang and Singh Model (Wang &amp; Singh, 1978)</td>
<td>$MR = 1 + at + bt^2$</td>
</tr>
<tr>
<td>Silvia et al</td>
<td>$MR = e^{(-at-b\sqrt{t})}$</td>
</tr>
<tr>
<td>Peleg model (Turhan, Sayar, &amp; Gunasekaran, 2002)</td>
<td>$MR = \frac{1 - t}{(a + b * t)}$</td>
</tr>
<tr>
<td>(Thompson, Peart, &amp; Foster, 1968)</td>
<td>$t = A \ln(MR) + B (\ln(MR))^2$</td>
</tr>
</tbody>
</table>

4.4 MATERIALS AND METHODS

4.4.1 Materials

About 500 kg of yellow dent ear corn was hand-picked from the University of Kentucky’s Coldstream research center in Lexington Kentucky in September 2018. The kernel moisture content was immediately determined using a rapid grain moisture meter to be an average of 20% (db) and later verified using a modification of ISO 6540 and BS 4317 procedure as reported by Ameobi and Woods (1993) in which whole ear corn was dried at 130°C for 38 hours (Ameobi & Woods, 1993). The ear corn samples were bagged in batches of about 50 kg and stored in sealed polyethylene bags within an environmental chamber maintained at about 1.6°C (35°F) to lower biological activity while waiting for offseason experimentation. This procedure was similar to that adopted by Sharaf-Eldeen et al. (1996) in which fresh single ears were sealed in polyethylene bags and frozen for off-
season examination. It was assumed that bulk bagging helped to achieve equilibration of the bulk ear corn moisture content during the waiting period.

Dehusked ears were carefully selected prior to the drying study and those with kernel defects or malformation was removed from the bulk. Selected ears were rewetted in a controlled environment chamber held at 85% relative humidity and 18°C for at least 73 hours prior to experimentation. This pretreatment was aimed at equilibration under conditions similar to those in a tropical climate but the temperature was lowered below 20°C to minimize microbial and biochemical activity.

4.4.2 Methods

4.4.2.1 Drying Experiment

A walk-in environmental chamber at the Department of Biosystems and Agricultural Engineering, the University of Kentucky with programmable temperature and relative humidity control was used for the drying study. A horizontal and a vertical bin were built in a way that optimally separated the entire environmental chamber from the ear corn during drying. Air flow through the corn was controlled using a set of variable speed, axial fans adopted from a computer server cooling rack. These fans at the inlet of the drying bin pulled warm, conditioned air from the environmental chamber and pushed it through the load unit inside the drying bin. Prior to loading the bin with the ear, a calibrated anemometer was fitted into the plenum of the bin. Using a Hewlett Packard 6205C Dual DC Power Supply, the supply power to the fans was tuned until a precalculate airflow velocity was reached. The precalculation involved dividing the desired volumetric flow rate by the cross-sectional area of the bin to obtain the flow velocity equivalent to the
required volumetric flowrate. The anemometer was then moved around the cross section
to ascertain that the average flow velocity matched with the desired values.

The stack of ear corn was placed in the load unit with a largely perforated false
bottom metal sheet. The air exit at the open end of the drying bin faced the exhaust of the
environmental chamber. The horizontal bin had its load unit open on opposite horizontal
ends to allow the cross flow of air through the bin. The drying bin was mounted on a load
sensor which automatically recorded changes in weight. The vertical bin, on the other hand,
was a square-topped wooden vertical cuboid with inlet air supplied at the base while the
top was directed towards the exhaust of the environmental chamber. The drying bin is
mounted on a set of calibrated load cells such that weight loss was automatically logged at
an interval of one reading every 6 minutes (0.1 hours). This was achieved by adding a
360,000-millisecond delay in the logging code. Weight loss was logged to a memory card
while monitored over the serial port of a computer. The memory device was downloaded
at the end of each drying test and stored on an Excel spreadsheet.

The ear corn was loaded in a structured pattern which allowed for some measure of
reproducibility. Ear corn was stacked laterally at each layer with subsequent layer
staggered or cross rotated to bridge possible air shunting.
Figure 4.3: Cut-Side Section of the Horizontal Drying Bin for Ear Corn Drying

Figure 4.3 shows the horizontal drying bin with Fans installed at A, the load unit at B and the load sensor at D. Section C is the exit of the drying bin. The Bin C is suspended on the rack and is independent of the load sensor D and the load unit B. The load bin sits directly over the load sensors while the Bin C is basically an air flow tube enclosing the load bin. The weight of the empty load bin is recorded at the start of each experiment and the sensor tarred after which the ear corn is loaded. With the load cell programmed to log every 6 minutes, the user has a mean 5 minutes process to load the ear corn from the time the sensors are tarred till the first reading is taken thus attempting that there is uniform loading time for each session.

Although pointed-loading in which the circular end of the cobs is arranged facing the airflow was initially considered in the horizontal bin, it created free shunt passages at the walls where circular ear corn geometry lapped with flat wall surfaces on the side. The
load unit in the horizontal bin could hold up to 20 kg of ear corn while the bin in the vertical bin could hold up to 10 kg of ear corn.

**4.4.2.2 Experimental Design:**

A 2x2x3 factorial study involving 2 temperature levels, 2 relative humidity levels, and 3 airflow rates was originally designed for the study. However, in view of time limitations and the futility of non-elevated temperature drying at 25°C, the study was refocused to a 1 x 2 x 3 with the stated assumption that solar temperature elevation of 10°C was made. Attempt at the pretreatment stage to equilibrate the ear corn at 85% relative humidity and 25°C resulted in mold growth and some loss of materials indicating that conducting such drying as part of the study was not feasible.

**Table 4.3:** A 1 x 2 x 3 experimental design code for studying the impact of airflow on the drying rate of ear corn

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>80% Relative Humidity</th>
<th>85% Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35°C</td>
<td>35°C</td>
</tr>
<tr>
<td>No Forced Convection</td>
<td>A03580</td>
<td>A03585</td>
</tr>
<tr>
<td>0.002 m³kg⁻¹s⁻¹</td>
<td>A13580</td>
<td>A13585</td>
</tr>
<tr>
<td>0.008 m³kg⁻¹s⁻¹</td>
<td>A23580</td>
<td>A23585</td>
</tr>
</tbody>
</table>

In this code system, the first digit represents the level of airflow, and the second and third digit represents the relative humidity condition under study.
Table 4.4: Table of Actual Controlled Atmosphere Chamber Conditions at 35°C.

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>80% Relative Humidity</th>
<th>85% Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Forced Aeration (0.025 m³/s)</td>
<td>45%RH</td>
<td>48%RH</td>
</tr>
<tr>
<td>0.02 m³/s</td>
<td>45%RH</td>
<td>48%RH</td>
</tr>
<tr>
<td>0.08 m³/s</td>
<td>45%RH</td>
<td>48%RH</td>
</tr>
</tbody>
</table>

*25°C studies were not implemented as mold growth during drying was imminent

Relative humidity levels selected for the study were obtained from the psychrometric chart at prevailing ambient conditions (25°C and 80 or 85% RH) after heated along the constant humidity ratio line by 10°C to 35°C.

4.4.2.2 Data Analysis

The experimental data were analyzed for mean, standard deviation and t-tests for statistical significance between means of groups using JMP while evaluation of drying rates, moisture ratio as well as data fitting to models was conducted using MATLAB since large numbers of data collected through logging tend to make conventional spreadsheet unusually slow.
4.5 RESULTS AND DISCUSSION:

4.5.1 Drying Experiment Observations:

Ear corn drying using the horizontal drying bin proved to be fairly problematic because as the drying proceeded, ear corn shrinkage occurred which increased the space at the top of the bin and allowed airflow shunting and interfered with measurements of the drying rate. On this account, a horizontal bin with lateral cross flow of air along a plane perpendicular to the material is discouraged. Instead, vertical bins in which airflow passes through the bulk irrespective of shrinkage tend to be better suited for this type of study. In order to continue using a horizontal bin dryer, a load unit modification which will ensure that the airflow is supplied at the base rather than across the stack needs to be made.

4.5.2 Data Collection:

Logged ear corn weight at different airflows as well as temperature and relative humidity were collected at an interval of 6 minutes until loss of weight over time became consistent over about 3 to 4 readings.

4.5.2.1 Moisture Ratio:

The observed weight loss during the drying was processed using the equation for moisture ratio to obtain mean values of moisture ratio of ear corn dried under the different conditions. The results are plotted in Figure 4.4 below.
Figure 4.4: Moisture Ratio for Ear Corn Dried at Three Airflow Levels

The analysis of variance for moisture ratio after target drying time (48 hours) showed that A03585 (no forced convection) and sample (A13585 at 0.002 m$^3$kg$^{-1}$s$^{-1}$) were significantly different A23585 (0.008 m$^3$kg$^{-1}$s$^{-1}$). This showed that low aeration (0.002 m$^3$kg$^{-1}$s$^{-1}$) will have no significant consequence on how fast the moisture is removed from the grain. However, aerating at 0.008 m$^3$kg$^{-1}$s$^{-1}$ was shown to impact the rate of moisture removal as reflected by a reduction of drying time from 40 hours to 22.7 hours. The moisture ratio values obtained were used to fit the test data to a number of drying models.

4.5.2.2 Drying Rates:

Figure 4.5 shows the drying rate versus time curve for no forced convection, low (0.002 m$^3$kg$^{-1}$s$^{-1}$) and high (0.008 m$^3$kg$^{-1}$s$^{-1}$) airflow rates. The plot depicts ear corn drying as showing a rapid decrease in drying rate over the first 6 to 9 hours after which it enters a steady decrease in drying rate over the next 78 hours. This trend is similar to those reported in thin layer drying of ear corn (Sharaf-Eldeen et al., 1980) where the drying was noted to
consist of two drying stages both characterized by falling rate trends but joined by a transition and was consistent with other previous studies.

![Plot of mean drying rate versus time](image)

**Figure 4.5:** Plot of mean drying rate versus time (for ear corn dried at 35°C and 45% relative humidity and three airflow levels - Zero Forced Convection, 0.002 m³kg⁻¹s⁻¹ and 0.008 m³kg⁻¹s⁻¹)

Several reasons have previously postulated for the shift or change that occurs in the drying of ear corn among which is the possibility of differing moisture transfer characters corresponding to kernel and cob drying characteristics. Others include the likelihood of temperature difference at the different layers of the composite product being dried. Importantly, it had been noted that “ear corn dries in a falling rate period of two distinct phases” (Sharaf-Eldeen et al., 1980) and this is confirmed by the current study under bulk or deep bed consideration. The close relationship between the No Forced Convection and the 0.02 m³/s airflow is possibly an indicator that very low pass airflow has no significant impact on drying rate of ear corn under the conditions studied. This fact accentuates the fact that increased airflow rate is a significant factor in rapid moisture removal and hence postharvest loss control in during ear corn drying in humid climates.
Figure 4.6: Plot of moisture content changes over drying time at the three airflow levels (0.002 m³kg⁻¹s⁻¹ and 0.008 m³kg⁻¹s⁻¹)

The higher airflow condition (0.008 m³kg⁻¹s⁻¹) showed significantly higher drying rates over the two lower rates initially (up to about 24 hours of drying) as expected, then fell below those of the other two levels. This could indicate different drying mechanisms between corn kernels and the cob material. In the non-aerated drying, the shift towards equilibrium with the environment predominates the mode of moisture loss explaining the gradual rate at which the drying rate for the lower aerated and non-aerated levels progressed. Equilibrium driven drying is predominantly a function of diffusion, which is based on differences in vapor pressure between ambient (temperature and relative humidity) and grain (temperature and moisture content) conditions. In contrast, forced convection results in an increased rate of evaporation leading to a higher temperature gradient between the grain and the environment as a result of evaporative cooling. The gradient encourages faster migration of heat and associated mass transfer till the lowering
of internal free water will naturally reduce the rate of mass loss which results in the lower rate after about 24 hours.

Analysis of variance for mean time to 15% moisture content is shown in Appendix E and indicates that whereas the time for achieving 15% moisture content was not significant between the low (39.9 ± 3.5 hrs) and non-aerated study (46.3±6.4 hrs), the high aeration study was significantly different (p < 0.0032) at the 0.05 levels with a mean of 23.6±0.5 hrs. Figure 4.5 shows the actual moisture content drop in the ear corn to 15% moisture content was reached. The standard deviation showed that drying in non-aerated and low aerated studies are unpredictable with a wide margin in time to desired moisture content across replicate studies while the high aeration level had a fairly more consistent drying rate as reflected by a standard deviation of 0.5 hours. This shows that the rate of aeration had an impact on the rate of drying and can be beneficial for better predictability of drying irrespective of associated factors such as ear corn packing. This trend is in contrast with those reported for thin-layer drying in which it was concluded that aeration levels do not show a significant difference in the rate of drying. This is probably as a result of the fact that thin layer drying is characterized by saturated airflow rates around the fully exposed ear. In contrast, for deep bed drying, the loss of full exposure of ear corn play a significant role in how well air is able to reach a larger area of the corn. Moreover, the presence of a larger amount of moisture to be removed from within the interstices of the stacked bin creates a potential for saturated air remaining in the bin in stagnant, non-forced convective drying. Aeration may thus be playing a role of displacing already equilibrated air from within the bin much more than the actual inter-corn-air moisture removal mechanism at the initial stage of the aerated drying near when there is abundant moisture
in the grain. This may be supported by the higher drying rate in the lower aerated drying over the non-aerated study.

The difference in drying rate as expressed by time to desired moisture content show that the rate or level of aeration impacts the rate of deep bed ear corn drying under high humidity conditions and therefore the results failed to reject the hypothesis that aerated drying at the test level impact the drying rate of the corn in warm, humid climate.

4.5.2.3 Model Equations:

The data obtained in the drying study were fitted to six empirical model equations using MATLAB and the results are shown in Table 4.5.2. The model root means squared error show that the Peleg model as well as the Wang and Singh models best fitted the data and could be used to predict the moisture ratio and consequently, the instantaneous moisture content of during the drying of the ear corn under conditions similar to those used in this study.
Table 4.5: Summary of Models Fitted to Empirical Data for Ear Corn Drying at three airflow rates

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
<th>Airflow Rate (m³/s)</th>
<th>Parameters</th>
<th>$R^2$</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis</td>
<td>$e^{-at}$</td>
<td>0.0</td>
<td>$a = 0.003047$</td>
<td>0.9452</td>
<td>0.01235</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>$a = 0.01274$</td>
<td>0.9965</td>
<td>0.004784</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>$a = 0.01679$</td>
<td>0.9924</td>
<td>0.01744</td>
</tr>
<tr>
<td>Henderson and Pabis</td>
<td>$ae^{-bt}$</td>
<td>0.0</td>
<td>$a = 0.9795$</td>
<td>0.9835</td>
<td>0.00691</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>$a = 0.9955$</td>
<td>0.9974</td>
<td>0.004328</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>$a = 0.9854$</td>
<td>0.9941</td>
<td>0.01591</td>
</tr>
<tr>
<td>Wang and Singh</td>
<td>$1 + at + bt^2$</td>
<td>0.0</td>
<td>$a = -0.00376$</td>
<td>0.9686</td>
<td>0.009533</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>$b = 1.734*10^{-5}$</td>
<td>0.9997</td>
<td>0.001489</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>$b = 0.0001461$</td>
<td>0.999</td>
<td>0.006435</td>
</tr>
<tr>
<td>Silvia et al</td>
<td>$e^{(-at-b/\sqrt{t})}$</td>
<td>0.0</td>
<td>$a = 0.02691$</td>
<td>0.4252</td>
<td>0.04076</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>$b = -0.08138$</td>
<td>0.8993</td>
<td>0.0271</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>$b = -0.1279$</td>
<td>0.9937</td>
<td>0.01655</td>
</tr>
<tr>
<td>Peleg</td>
<td>$\frac{1-t}{(a+b*t)}$</td>
<td>0.0</td>
<td>$a = 231.4$</td>
<td>0.9747</td>
<td>0.008557</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>$b = 2.336$</td>
<td>0.9996</td>
<td>0.001677</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>$b = 1.045$</td>
<td>0.9999</td>
<td>0.002438</td>
</tr>
<tr>
<td>Thompson</td>
<td>$t = A \ln(MR) + B (\ln(MR))^2$</td>
<td>0.0</td>
<td>$A = -223.7$</td>
<td>0.9871</td>
<td>2.599</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>$B = 645.7$</td>
<td>0.9997</td>
<td>0.1348</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.08</td>
<td>$B = 45.88$</td>
<td>0.9998</td>
<td>0.2791</td>
</tr>
</tbody>
</table>
4.6 CONCLUSION:

The study showed that there was no significant difference at the 0.05 level in the effect of airflow at 0.02 m$^3$/s and at the zero levels. However, there was marked statistical significance at the 0.08 m$^3$/s level. Application of wind-powered drying at the airflow higher level would, therefore, offer rapid removal of moisture from ear corn. The study suggests that although ear corn drying at the lower airflow levels was relatively unpredictable with high standard deviations in time to desired moisture content (which could be associated with factors including the nature of packing and bin filling), there were no such inconsistencies at the higher airflow level. This implies that higher airflow favors more predictable drying which could mean that associated factors such as how reproducible the packing of ear corn was in the bin could be considered negligible.
CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSIONS

An attempt was made to demonstrate the potential of utilizing a wind energy harnessing device locally fabricated, for mechanical drying of ear corn in warm and humid climates. A high solidity wind turbine rotor with the capacity to supply pre-calculated power needed for forced convective drying of ear corn under low wind speed conditions (2.0 – 5.0 m/s) was built and tested. The wind turbine system was tested in a subsonic wind tunnel under low wind speed (2.0 – 5.5 m/s) conditions which simulate wind speed in the guinea savannah belt of sub-Saharan Africa. The system’s capacity to achieve ear corn drying was tested in a controlled environment chamber which simulated typical tropical ambient temperature and relative humidity. These simulated parameters were the same as those used in estimating the airflow requirements used in the turbine design. Drying was considered to be efficient when the ear corn at a known moisture content (about 23%) under the study conditions were dried to moisture content levels below 13% - a safe level for subsequent dry storage, within a 48 hours period.

This study, therefore, represents steady-state considerations of ear corn drying in typical tropical climate condition including wind speed levels. Although steady state test conditions do not guarantee actual operation viability in real life, it provides the premise for making a conclusion on the potentials of the wind turbine to function fairly well under similar conditions. The study showed that with the fans used, the turbine had highest wind utilization efficiency at wind speeds about 3.5 m/s and air flow rates as much as 0.52 m$^3$/s
was achieved at 5.6 m/s. The centrifugal fan used in the cabin ventilation unit of a Honda Pilot – 2007 model purchased from a scrap yard was modified to function as the mechanical blower connected to the wind turbine drive train and the volumetric air output from the system satisfied the requirement for the drying of up to 50kg sample weight.

The drying study compared drying at an ambient temperature of 35°C, which is the equivalence of the harvest season ambient temperature in the guinea savannah belt elevated by a 10°C rise in temperature using a solar thermal collector. The drying rate was significantly different between the non-convective as well as the lower forced convective (0.02 m³/s) level and the higher forced convective (0.08 m³/s) level at a 5% probability of error level. Moisture content reduction in the aerated study from 22% to 15% moisture content in an average of 23.6±0.5 hrs, 39.9±3.5 hrs and 46.3±6.4 hrs respectively for 0.08 m³/s, 0.02 m³/s and no aeration in control atmosphere study.

This study shows that there is strong potential that higher level forced convection from low wind speed turbine systems could address the need for increased moisture removal rates during drying in tropical climates. It was, however, important to note that the current study represents steady-state drying under simulated tropical conditions enhanced by the use of solar or other forms of air heating and therefore field testing would be required to determine how much wind flow downtime and transient changes in ambient environment conditions (temperature and relative humidity) would impact the actual operation of wind-powered grain aeration.
5.2 RECOMMENDATION

Field testing is needed to validate the feasibility of the wind-powered solution proposed by this study in real life conditions. There is also a need for detailed bulk ear corn drying study under different conditions in view of the observed gap resulting from the limited focus given previously by researchers to typical warm and humid climate drying conditions which are very much dissimilar to conditions in a temperate climate. The current study was conducted using reconstituted (rewetted) corn under assumptions which allowed for the conduct of a simulation study that provides some insight into the role of convective air drying of agricultural materials, specifically, ear corn. A study using fresh corn is needed to compare with the current data.
APPENDIX A: Calculation Scheme for Deriving the Turbine Zone Wind Speed

Mass flow rate, \( \dot{m} \)  

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
\rho A_1 U_1 & \dot{m}(U_1 - U_4) & \rho A_3 U_3 & \rho A_4 U_4 \\
\end{array}
\]

Thrust, \( T \)  

\[
\begin{array}{cccc}
1 & 2 & 3 & 4 \\
\dot{m} U_1 & \dot{m}(U_1 - U_4) & \dot{m} U_4 \\
\end{array}
\]

Bernoulli  

\[
\begin{array}{cccc}
p_1 + \frac{1}{2} \rho U_1^2 & p_2 + \frac{1}{2} \rho U_2^2 & p_3 + \frac{1}{2} \rho U_3^2 & p_4 + \frac{1}{2} \rho U_4^2 \\
\end{array}
\]

Pressure, \( p \)  

\[
\begin{array}{cccc}
p_2 = p_1 + \frac{1}{2} \rho U_1^2 - \frac{1}{2} \rho U_2^2 & p_3 = p_4 + \frac{1}{2} \rho U_4^2 - \frac{1}{2} \rho U_3^2 \\
\end{array}
\]

Blade Zone Pressure  

\[
\begin{array}{cccc}
p_2 - p_3 = p_1 + \frac{1}{2} \rho U_1^2 - \frac{1}{2} \rho U_2^2 - p_4 - \frac{1}{2} \rho U_4^2 + \frac{1}{2} \rho U_3^2 \\
\end{array}
\]

\[
p_2 - p_3 = \frac{1}{2} \rho (U_1^2 - U_4^2) \\
\]

Thrust on Turbine  

\[
T_{(2-3)} = \frac{1}{2} \rho A_2 (U_1^2 - U_4^2) = \dot{m}_2 (U_1 - U_4) \\
\]

Since \( \dot{m}_2 = \rho A_2 U_2 \)  

\[
U_2 = \frac{\rho A_2 (U_1^2 - U_4^2)}{\dot{m}_2} = \frac{(U_1 + U_4)}{2} \\
\]
APPENDIX B: MATLAB function for EarSim

function varargout = corn_hyper_bin(varargin)

% Graphical User Interface built by Francis Agbali © and deployed
% for use in partial fulfilment of the requirements for the award
% of Master of Science in Biosystems and Agricultural Engineering
% at the University of Kentucky, USA.
% CORN HYPER BIN MATLAB code for corn_hyper_bin.fig
% CORN HYPER BIN, by itself, creates a new CORN HYPER BIN or raises
% the existing singleton*.
% H = CORN HYPER BIN returns the handle to a new CORN HYPER BIN or
% the handle to the existing singleton*.
% CORN HYPER BIN('CALLBACK',hObject,eventData,handles,...) calls
% the local function named CALLBACK in CORN HYPER BIN.M with the
% given input arguments.
% CORN HYPER BIN('Property','Value',...) creates a new
% CORN HYPER BIN or raises the existing singleton*. Starting from
% the left, property value pairs are applied to the GUI before
% corn_hyper_bin_OpeningFcn
% gets called. An unrecognized property name or invalid value
% makes property application stop. All inputs are passed to
% corn_hyper_bin_OpeningFcn via varargin.
% *
% See GUI Options on GUIDE's Tools menu. Choose "GUI allows only
% one instance to run (singleton)".
% See also: GUIDE, GUIDATA, GUIHANDLES
% Edit the above text to modify the response to help corn_hyper_bin
% Last Modified by GUIDE v2.5 18-Apr-2019 09:02:16
% Begin initialization code - DO NOT EDIT

gui_Singleton = 1;

gui_State = struct('gui_Name', mfilename,...
           'gui_Singleton', gui_Singleton,...
           'gui_OpeningFcn', @corn_hyper_bin_OpeningFcn,...
           'gui_OutputFcn', @corn_hyper_bin_OutputFcn,...
           'gui_LayoutFcn', [], ...
           'gui_Callback', []);

if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end

% End initialization code - DO NOT EDIT
% --- Executes just before corn_hyper_bin is made visible.
function corn_hyper_bin_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn. hObject handle to
% figure eventdata reserved - to be defined in a future version of
% MATLAB handles structure with handles and user data (see GUIDATA)
% varargin command line arguments to corn_hyper_bin (see VARARGIN)
% Choose default command line output for corn_hyper_bin
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes corn_hyper_bin wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = corn_hyper_bin_OutputFcn(hObject, eventdata, handles)
% varargout cell array for returning output args (see VARARGOUT);
% hObject handle to figure eventdata reserved - to be defined in %
% a future version of MATLAB handles structure with handles and user %
% data (see GUIDATA)
% Get default command line output from handles structure
varargout{1} = handles.output;

function x1_Callback(hObject, eventdata, handles)
% hObject handle to x1 (see GCBO) eventdata reserved - to be %
% defined in % a future version of MATLAB handles structure with %
% handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of x1 as text %
% str2double(get(hObject,'String')) returns contents of x1 as a %
% double

% --- Executes during object creation, after setting all properties.
function x1_CreateFcn(hObject, eventdata, handles)
% hObject handle to x1 (see GCBO) eventdata reserved - to be %
% defined in a future version of MATLAB handles empty - handles not %
% created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows. %
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function M2_Callback(hObject, eventdata, handles)
% hObject handle to M2 (see GCBO) eventdata reserved - to be %
% defined in a future version of MATLAB handles structure with %
% handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of M2 as text
%    str2double(get(hObject,'String')) returns contents of M2 as a
double

% --- Executes during object creation, after setting all properties.
function M2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to M2 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles empty - handles not
% created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in wb.
function wb_Callback(hObject, eventdata, handles)
% hObject    this is the handle to the location wb (see GCBO) eventdata
% reserved - to be
% defined in a future version of MATLAB handles structure with
% handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of wb

% --- Executes on button press in db.
function db_Callback(hObject, eventdata, handles)
% hObject handle to db (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)

function M1_Callback(hObject, eventdata, handles)
% hObject handle to M1 (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of M1 as text
%    str2double(get(hObject,'String')) returns contents of M1 as a
double
% --- Executes during object creation, after setting all properties.
function M1_CreateFcn(hObject, eventdata, handles)
% hObject handle to M1 (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles empty - handles not created until
% after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
% --- Executes on selection change in wbdb.
function wbdb_Callback(hObject, eventdata, handles)
% hObject handle to wbdb (see GCBO)
eventdata reserved - to be defined
% in a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)
handles=guidata(hObject);

% Hints: contents = cellstr(get(hObject,'String')) returns wbdb contents
% as cell array contents(get(hObject,'Value')) returns selected
% item from wbdb

% --- Executes during object creation, after setting all properties.
function wbdb_CreateFcn(hObject, eventdata, handles)
% hObject handle to wbdb (see GCBO) eventdata reserved-to be defined
% in a future version of MATLAB handles empty - handles not created
% until after all CreateFcns called

% Hint: listbox controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function T1_Callback(hObject, eventdata, handles)
% hObject handle to T1 (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of T1 as text
%       str2double(get(hObject,'String')) returns contents of T1 as a
%       double

% --- Executes during object creation, after setting all properties.
function T1_CreateFcn(hObject, eventdata, handles)
% hObject handle to T1 (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles empty-handles not created until
% after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function RH_Callback(hObject, eventdata, handles)
% hObject handle to RH (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of RH as text
%       str2double(get(hObject,'String')) returns contents of RH as a
%       double
function RH_CreateFcn(hObject, eventdata, handles)
% hObject handle to RH (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles empty - handles not created until
% after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function T2_CreateFcn(hObject, eventdata, handles)
% hObject handle to T2 (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of T2 as text
% str2double(get(hObject,'String')) returns contents of T2 as a
double

function wbCalc_Callback(hObject, eventdata, handles)
% hObject handle to wbCalc (see GCBO) eventdata reserved-to be defined in
% a future version of MATLAB handles structure with handles and user
% data (see GUIDATA)

% T is temperature
% RH is relative humidity
handles=guidata(hObject);
a = str2num(get(handles.T1,'string'));
b = str2num(get(handles.RH,'string'));

Patm = 101325;  % standard atmospheric pressure (kPa)
T = a+273.15;  % Converting temperature to Kelvin
RH = b/100;  % converting the Relative humidity to decimals
if T>255.37 && T<=273.16
    P = exp(31.9602 - (6270.3605/T)-(0.46057 * log(T)))
elseif T>273.16 && T<459.69
    R = 22105649.25;
    A = -27405.526;
    B = 97.5413;
C = -0.146244;
D = 0.00012558;
E = -0.00000048502;
F = 4.34903;
G = 0.0039381;
P = R*exp((A+B*T+C*T*T+D*T*T*T+E*T*T*T*T)/(F*T - G*T*T))
elseif T>=459.69 && T<491.69
P = exp(23.3924 - (11286.6489/T) - (0.46057 * log(T)))
else
R = 3206.18;
A = -27405.5;
B = 54.1896;
C = -0.045137;
D = 0.0003215321;
E = -0.0000000048502;
F = 2.41613;
G = 0.00121547;
P = R*exp((A+B*T+C*T*T+D*T*T*T+E*T*T*T*T)/(F*T - G*T*T))
end
Pv = RH*P
H = (0.6219*Pv)/(Patm - Pv)
if T >255.37 && T <273.16
hfg=(283663.144-(212.56384*(T - 255.38)))
elseif T >273.15 && T <338.73
hfg = (2502535.259 - 2385.76424*(T-273.16))
elseif T >338.72 && T <459.69
hfg = ((732915978000 - 15995964.08 * T * T)^0.5)
elseif T >459.68 && T <491.70
hfg = (1220.844 - (0.05077*(T - 459.69)))
elseif T >491.68 && T <609.70
hfg = (1075.8965 - (0.56983*(T - 491.69)))
else
hfg = (1354673.214 - (0.9125275587*T*T)^0.5)
end
ts = a
if ts < 17 && ts >5
DryWetBulbDifference = 11.324174 - (0.11695138*RH*100)
elseif ts >16 && ts < 20
DryWetBulbDifference = 12.363868 - (0.1271087*RH*100)
elseif ts >19 && ts < 22
DryWetBulbDifference = 13.167053 - (0.1354603*RH*100)
elseif ts >21 && ts < 25
DryWetBulbDifference = 13.724697 - (0.1405931*RH*100)
elseif ts > 24 && ts < 27
DryWetBulbDifference = 14.872264 - (0.1528917*RH*100)
elseif ts >26 && ts < 30
DryWetBulbDifference = 15.554792 - (0.1603635*RH*100)
elseif ts > 29 && ts < 33
DryWetBulbDifference = 16.514064 - (0.1697082*RH*100)
else
DryWetBulbDifference = 17.551274 - (0.1804083*RH*100)
end
wb = T - DryWetBulbDifference \% Expresses the wet bulb relative to T1

Twb = wb - 273.15 \% Reconvert the wet bulb to Celsius

set(handles.resMCC,'string',Twb)
set(handles.hrDisplay, 'string',H)
set(handles.text16, 'string',Pv)
guidata(hObject, handles);

% --- Executes on button press in rh2Calc.
function rh2Calc_Callback(hObject, eventdata, handles)
% hObject handle to rh2Calc (see GCBO) eventdata  reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)
handles=guidata(hObject);
c = str2num(get(handles.T2,'string'));
d = str2num(get(handles.hrDisplay,'string'));
f = str2num(get(handles.text16,'string'));

T2 = c+273.15
Patm = 101325; \% standard atmospheric pressure (kPa)
if T2>255.37 \& T2<=273.16
P2 = exp(31.9602 - (6270.3605/T2)- (0.46057 * log(T2)))
elseif T2>273.16 \& T2<459.69
R = 22105649.25;
A = -27405.526;
B = 97.5413;
C = -0.146244;
D = 0.00012558;
E = -0.000000048502;
F = 4.34903;
G = 0.0039381;
P2 = R*exp((A+B*T2+C*T2*T2+D*T2*T2*T2+E*T2*T2*T2*T2)/(F*T2 - G*T2*T2))
elseif T2>=459.69 && T2<491.69
P2 = exp(23.3924 - (11286.6489/T2)- (0.46057 * log(T2)))
else
R = 3206.18;
A = -27405.5;
B = 54.1896;
C = -0.045137;
D = 0.0000215321;
E = -0.000000048502;
F = 2.41613;
G = 0.00121547;
P2 = R*exp((A+B*T2+C*T2*T2+D*T2*T2*T2+E*T2*T2*T2*T2)/(F*T2 - G*T2*T2))
end
H1 = d;
Pv2 = (H1*Patm)/(H1+0.6219)
RH2 = (Pv2/P2)*100;
H2 = (0.6219*Pv2)/(Patm - Pv2)
set(handles.rh2Display, 'string',RH2)
if T2 >255.37 \& T2 <273.16
hfg2=2839683.144-(212.56384*(T2 - 255.38))

125
elseif \( T_2 > 273.15 \) && \( T_2 < 338.73 \)
hfg2 = (2502535.259 - 2385.76424*(T2-273.16))
elseif \( T_2 > 338.72 \) && \( T_2 < 459.69 \)
hfg2 = ((78329155957800 - 15995964.08 * T2 * T2)^0.5)
elseif \( T_2 > 459.68 \) && \( T_2 < 491.70 \)
hfg2 = (1220.844 - (0.05077*(T2 - 459.69)))
elseif \( T_2 > 491.68 \) && \( T_2 < 609.70 \)
hfg2 = (1075.8965 - (0.56983*(T2 - 491.69)))
else
hfg2 = (1354673.214 - (0.9125275587*T2*T2)^0.5)
end

ts2 = c
if ts2 < 17 && ts2 > 5
DryWetBulbDifference2 = 11.324174 - (0.11695138*RH2)
elseif ts2 > 16 && ts2 < 20
DryWetBulbDifference2 = 12.363868 - (0.1271087*RH2)
elseif ts2 > 19 && ts2 < 22
DryWetBulbDifference2 = 13.167053 - (0.1354603*RH2)
elseif ts2 > 21 && ts2 < 25
DryWetBulbDifference2 = 13.724697 - (0.1405931*RH2)
elseif ts2 > 24 && ts2 < 27
DryWetBulbDifference2 = 14.872264 - (0.1528917*RH2)
elseif ts2 > 26 && ts2 < 30
DryWetBulbDifference2 = 15.554792 - (0.1603635*RH2)
elseif ts2 > 29 && ts2 < 33
DryWetBulbDifference2 = 16.514064 - (0.1697082*RH2)
else
DryWetBulbDifference2 = 17.551274 - (0.1804083*RH2)
end
wb2 = T2 - DryWetBulbDifference2
Twb2 = wb2 - 273.15
set(handles.text15,'string',Twb2)
guidata(hObject, handles);

% --- Executes on button press in mccCalc.
function mccCalc_Callback(hObject, eventdata, handles)
% hObject handle to mccCalc (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

handles=guidata(hObject);
w = str2num(get(handles.resMCC,'string')); % Wetbulb of Moist Air
z = str2num(get(handles.text15,'string')); % Wetbulb of Dry Air
lhr = str2num(get(handles.hrDisplay,'string')); % Wetbulb of Dry Air
% RH is assumed to be 100 at Saturation / Wetbulb line

Patm = 101325; % standard atmospheric pressure (kPa)
a = [w z]
RH4 = 0.98;
for o = 1:2
    T4 = a(o)+273.15;
    if T4>255.37 && T4<=273.16
        P4 = exp(31.9602 - (6270.3605/T4)- (0.46057 * log(T4)))
    elseif T4>273.16 && T4<459.69
        P4 = 22105649.25;
    else
        A = -27405.526;
B = 97.5413;
C = -0.146244;
D = 0.00012558;
E = -0.000000048502;
F = 4.34903;
G = 0.0039381;
P4 = R*exp((A+B*T4+C*T4*T4+D*T4*T4*T4+E*T4*T4*T4*T4)/(F*T4 - G*T4*T4))
elseif T4>=459.69 && T4<491.69
P4 = exp(23.3924 - (11286.6489/T4)-(0.46057 * log(T4)))
else
R = 3206.18;
A = -27405.5;
B = 54.1896;
C = -0.045137;
D = 0.0000215321;
E = -0.000000048502;
F = 2.41613;
G = 0.00121547;
P4 = R*exp((A+B*T4+C*T4*T4+D*T4*T4*T4+E*T4*T4*T4*T4)/(F*T4 - G*T4*T4))
end
Pv4 = RH4*P4;
H4(0) =(0.6219*Pv4)/(Patm - Pv4)
end
format short
wetHup = (H4(1))
dryHup = (H4(2))
mcc = (dryHup - lhr)
set(handles.text18,'string',dryHup)
set(handles.text20,'string',mcc)
function edit8_Callback(hObject, eventdata, handles)
    % hObject handle to edit8 (see GCBO)
    % eventdata reserved to be defined in a future version of MATLAB
    % in a future version of MATLAB handles structure with handles and
    % user data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit8 as text
    str2double(get(hObject,'String')) returns contents of edit8 as
    % a double

    % --- Executes during object creation, after setting all properties.
    function edit8_CreateFcn(hObject, eventdata, handles)
        % hObject handle to edit8 (see GCBO)
        eventdata reserved - to be defined
        % in a future version of MATLAB handles empty - handles not created

        % Hint: edit controls usually have a white background on Windows.
        % See ISPC and COMPUTER.
        if ispc && isequal(get(hObject,'BackgroundColor'),
            get(0,'defaultUicontrolBackgroundColor'))
            set(hObject,'BackgroundColor','white');
        end

function edit9_Callback(hObject, eventdata, handles)
    % hObject handle to edit9 (see GCBO)
    eventdata reserved to be defined
    % in a future version of MATLAB handles structure with handles and user
    % data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit9 as text
    str2double(get(hObject,'String')) returns contents of edit9 as
    % a double

    % --- Executes during object creation, after setting all properties.
    function edit9_CreateFcn(hObject, eventdata, handles)
        % hObject handle to edit9 (see GCBO)
        eventdata reserved - to be defined
        % in a future version of MATLAB handles empty - handles not created

        % Hint: edit controls usually have a white background on Windows.
        % See ISPC and COMPUTER.
        if ispc && isequal(get(hObject,'BackgroundColor'),
            get(0,'defaultUicontrolBackgroundColor'))
            set(hObject,'BackgroundColor','white');
        end

function edit10_Callback(hObject, eventdata, handles)
    % hObject handle to edit10 (see GCBO)
    eventdata reserved - to be defined
    % in a future version of MATLAB handles structure with handles and user
    % data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit10 as text
str2double(get(hObject,'String')) returns contents of edit10 as a double

% --- Executes during object creation, after setting all properties.
function edit10_CreateFcn(hObject, eventdata, handles)
    % hObject handle to edit10 (see GCBO) eventdata reserved - to be
defined in a future version of MATLAB handles empty - handles not
created until after all CreateFcns called

    % Hint: edit controls usually have a white background on Windows.
    %       See ISPC and COMPUTER.
    if ispc && isequal(get(hObject,'BackgroundColor'),
        get(0,'defaultUicontrolBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end

function edit11_Callback(hObject, eventdata, handles)
    % hObject handle to edit11 (see GCBO) eventdata reserved - to be
    % defined in a future version of MATLAB handles structure with handles
    % and user data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit11 as text
    %        str2double(get(hObject,'String')) returns contents of edit11 as
    %        a double

    % --- Executes during object creation, after setting all properties.
function edit11_CreateFcn(hObject, eventdata, handles)
    % hObject handle to edit11 (see GCBO) eventdata reserved - to be
    % defined in a future version of MATLAB handles empty - handles not
created until after all CreateFcns called

    % Hint: edit controls usually have a white background on Windows.
    %       See ISPC and COMPUTER.
    if ispc && isequal(get(hObject,'BackgroundColor'),
        get(0,'defaultUicontrolBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end

function edit12_Callback(hObject, eventdata, handles)
    % hObject handle to edit12 (see GCBO) eventdata reserved - to be
    % defined in a future version of MATLAB handles structure with handles
    % and user data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit12 as text
    %        str2double(get(hObject,'String')) returns contents of edit12 as
    %        a double

    % --- Executes during object creation, after setting all properties.
function edit12_CreateFcn(hObject, eventdata, handles)
    % hObject handle to edit12 (see GCBO) eventdata reserved - to be
    % defined in a future version of MATLAB handles empty - handles not
created until after all CreateFcns called

    % Hint: edit controls usually have a white background on Windows.
    %       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
            get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in pushbutton8.
function pushbutton8_Callback(hObject, eventdata, handles)
% hObject handle to pushbutton8 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

handles=guidata(hObject);
imec = str2num(get(handles.edit8,'string')); % Mass of Corn (kg)
imcwb = str2num(get(handles.edit9,'string')); % MC Wet Basis (%)
tmcwb = str2num(get(handles.edit10,'string')) % MC wb (%)
%   a1 =  imec  % Corn Bulk Weight (kg) obtained from the storage array (answer)
%   b1 =  imcdb  % Corn Initial MC(db) obtained from the
%   storage array (answer) c1 =  tmcdb  % Ear Corn Target Moisture
%   Content obtained from the storage array (answer)

%% Wet Basis (i.e. If the Moisture Content supplied was Wet Basis)
set(handles.text30,'string',imec)
set(handles.text32,'string',imcwb)
set(handles.text36,'string',tmcwb)

% Mw = b % Wet basis moisture content of sample
x1 = imec % weight of sample
x2 = imec * (imcwb/100) % moisture in sample x1
x3 = x1 - x2 % dry matter dm (weight of sample minus Moisture)
Md = (x2/(x3))*100 % Dry basis equivalence of the MC of sample

%Tw = c % Wet basis target MC when the dry basis moisture is M2
cope = str2num(get(handles.text32,'string'));
dope = str2num(get(handles.text36,'string'));

x4 = ((tmcwb/100)*x3)/(1 - (c/100))% wt of moisture in sample at M2
x5 = (x4 + x3) % wt of samples plus moisture at M2
Td = (x4/x3)*100 % db equivalence of target MC based on dm

%% To bring the sample from M1 to M2, the moisture of weight x6 would
% be
% removed from the sample. This weight is equivalent to the mass of
% moisture in M1 minus the mass of moisture in M2.
x6 = x2 - x4
set(handles.text34,'string',Md)
set(handles.text38,'string',Td)
set(handles.text40,'string',x6)

% Md = b1
% db mc of sample x11 = a1
% weight of sample x21 = (a1 * (b1/100))/(1+(b1/100))
% moisture in sample x1 x31 = x11 - x21
% dm (weight of sample minus moisture) Mw1 = (x21/(x31+x21))*100;
% wb equivalence of initial mc if value given for mc was db

% Target Moisture properties Td1 = c1 x41 = ((c1/100)*x31)
% Actual mass of moisture that resulted in M2%(db) Tw1 =
% (x41/(x31+x41))*100
% Wet basis equivalence of Target Moisture when
% initial values supplied by client were in dry basis. x61 = x21 - x41
% amount of moisture to be removed to reduce the sample from M1 to M2
% if initial M’s supplied where in dry basis. x51 = x31 + x61
% Weight of sample with moisture in it at M2 (db).

% h = msgbox(['Mass of Moisture to be removed = ' num2str(x6),'kg
% Initial Moisture Content wb = ' num2str(Mw),'
% Target Moisture Content wb = ' num2str(Tw),'
% Initial Moisture db = ' num2str(Md),'
% Target Moisture Content db = ' num2str(Td),'
%]);

guidata(hObject, handles);

function pushbutton9_Callback(hObject, eventdata, handles)
% hObject handle to pushbutton9 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB

guidata(hObject, handles);

% Dry Basis (i.e. If the Moisture Content supplied was Wet Basis)

% --- Executes on button press in pushbutton10.
function pushbutton10_Callback(hObject, eventdata, handles)
% hObject handle to pushbutton10 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
 handles=guidata(hObject);

guidata(hObject, handles);

function edit14_Callback(hObject, eventdata, handles)
% hObject handle to edit14 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
 % Hints: get(hObject,'String') returns contents of edit14 as text
 % str2double(get(hObject,'String')) returns contents of edit14 as a double

% --- Executes during object creation, after setting all properties.
function edit14_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit14 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles empty - handles not
% created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes during object creation, after setting all properties.
function axes1_CreateFcn(hObject, eventdata, handles)
% hObject handle to axes1 (see GCBO) eventdata reserved-to be defined
% in a future version of MATLAB handles empty - handles not created
% until after all CreateFcns called

% Hint: place code in OpeningFcn to populate axes1

function edit15_Callback(hObject, eventdata, handles)
% hObject handle to edit15 (see GCBO) eventdata reserved-to be defined
% in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit15 as text
%        str2double(get(hObject,'String')) returns contents of edit15 as a double

% --- Executes during object creation, after setting all properties.
function edit15_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit15 (see GCBO) eventdata reserved-to be defined
% in a future version of MATLAB handles empty - handles not created
% until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit16_Callback(hObject, eventdata, handles)
% hObject handle to edit16 (see GCBO) eventdata reserved-to be defined
% in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit16 as text
%        str2double(get(hObject,'String')) returns contents of edit16 as a double

% --- Executes during object creation, after setting all properties.
function edit16_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit16 (see GCBO) eventdata reserved-to be defined
% in a future version of MATLAB handles empty - handles not created
% until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
   get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end

function edit17_Callback(hObject, eventdata, handles)
% hObject handle to edit17 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit17 as text
%    str2double(get(hObject,'String')) returns contents of edit17
%      as a double
% --- Executes during object creation, after setting all properties.
function edit17_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit17 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles empty - handles not
% created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
   get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end
% --- Executes on button press in pushbutton11.
function pushbutton11_Callback(hObject, eventdata, handles)
% hObject handle to pushbutton11 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB
_handles=guidata(hObject);
int = str2num(get(_handles.edit15,'string'));
wdt = str2num(get(_handles.edit16,'string'));
hgt = str2num(get(_handles.edit17,'string'));
days = str2num(get(_handles.edit18,'string'));
vol = int*wdt*hgt;
set(_handles.text48,'string',vol);
moist = str2num(get(_handles.text32,'string'))
BD = (-7*(100^-7)) * (moist^4) + (0.0002 *(moist^3)) + (0.0132 *(moist^2)) + (0.261*(moist)) + (52.792)
volk = str2num(get(_handles.text30,'string'))
convol = volk/BD
moistreq = str2num(get(_handles.text40,'string'))
% Total amount of water to be removed from the ear corn
mccreq = str2num(get(_handles.text20,'string'))
% Moisture Carrying Capacity of Air
dareq = (moistreq/mccreq)/1.225
% 1.225 is the density of air to convert to m3 from kg
airflra = (dareq/(24*days*60))
% Shedd's Equation
L\alpha  =  (v\text{olk})/(BD*\text{int}*\text{wdt} )
Q_s = \text{airflra/convol}
asae = 1.04*10^4  \% Shedd Curve parameter \( b \) for Ear Corn
bae = 325 \% Shedd Curve parameter for Ear Corn
DPoval = (asae*Q_s^2)/(\log(1+bae*Q_s)) \% Shedd's Equation given Pressure
\% Drop per unit depth change in bin fill height.
DP = DPoval*hgt
Toafl = (Q_s*\text{int}*\text{wdt})
FP = (Toafl * DP)/(63.43 *.45)); \% Uncomment 745.7 to change to hp

set(handles.text50,'string',BD); \% Ear Corn Bulk Density
set(handles.text52,'string',convol); \% Corn Volume to be Dried (m3)
set(handles.text56,'string',daleq); \% Air Volume for Drying (m3)
set(handles.text60,'string',airflra*60); \% 48 Hours Airflow(m3/min)
set(handles.text54,'string',DPoval); \% Pressure Loss (Pa/meter)
set(handles.text58,'string',FP); \% Fan Power
set(handles.text62,'string',DP); \% Total Pressure Loss in Bin
guidata(hObject, handles);

% --- Executes when figure1 is resized.
function figure1_ResizeFcn(hObject, eventdata, handles)
% hObject handle to figure1 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

function edit18_Callback(hObject, eventdata, handles)
% hObject handle to edit18 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit18 as text
% str2double(get(hObject,'String')) returns contents of edit18
% as a double

% --- Executes during object creation, after setting all properties.
function edit18_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit18 (see GCBO) eventdata reserved - to be
% defined in a future version of MATLAB handles structure with handles
% and user data (see GUIDATA)

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
For Wet Basis Calculations:

If original sample weight = x₁ at a Moisture content of M₁ % or MC₁ (fractional MC). And if M₂ is the target moisture content (%) or MC₂ (fractional).

\[
M₁(\%)_{wb} = \frac{x₂}{x₁} \times 100
\]  \hspace{1cm} (1)

Where \( x₂ \) is the mass of water inside the sample to make it M₁% MC wb.

\[
x₂ = \frac{M₁(\%)_{wb}}{100} \times x₁
\]  \hspace{1cm} (2)

or

\[
x₂ = MC₁ \times x₁
\]  \hspace{1cm} (3)

Note that \( x₂ \) is the total moisture in Sample x₁, therefore Dry Matter denoted as x₃ in Sample x₁ will mass of x₁ minus the mass of water in x₁.

\[
x₃ = x₁ - x₂
\]  \hspace{1cm} (4)

Recall (3)

\[
x₃ = x₁ - MC₁ \times x₁
\]  \hspace{1cm} (5)

When the sample is dried to Moisture Content M₂ (%) wb, and x₄ is the mass of moisture in Sample at moisture content of M₂(%)

\[
M₂(\%)_{wb} = \frac{x₄}{x₃ + x₄} \times 100
\]  \hspace{1cm} (6)

\[
x₄ = \frac{M₂(\%)_{wb}}{100} \times (x₃ + x₄)
\]  \hspace{1cm} (7)

\[
x₄ - \left(\frac{M₂(\%)_{wb}}{100} \times x₄\right) = \frac{M₂(\%)_{wb}}{100} \times x₃
\]  \hspace{1cm} (8)

Recall x₃ = x₁ - x₂ (Equation 4) and x₂ = \( \left(\frac{M₁(\%)_{wb}}{100} \times x₁\right) \) (Equation 2)

\[
x₄\left(1 - \frac{M₂(\%)_{wb}}{100}\right) = \frac{M₂(\%)_{wb}}{100} \times (x₁ - \left(\frac{M₁(\%)_{wb}}{100} \times x₁\right))
\]  \hspace{1cm} (9)
\[ x_4 = \left[ \frac{M_2(\%)_{wb}}{100} \times (x_1 - \left( \frac{M_1(\%)_{wb}}{100} \times x_1 \right)) \right] / \left( 1 - \frac{M_2(\%)_{wb}}{100} \right) \]  

...(10)

Equation (10) is the same as

\[ X_4 = \left[ MC_2 \times (x_1 - \{ MC_1 \times x_1 \}) \right] / [1 - MC_2] \]  

...(11)

Amount of Water removed from sample to bring it from Moisture Content of M1 to M2 is the full amount of water in a sample at M1 minus the Mass of Water left after drying has ended at M2.

\[ x_5 = x_2 - x_4 \]  

...(12)

\[ x_5 = [MC_1 \times x_1] - \left[ MC_2 \times (x_1 - \{ MC_1 \times x_1 \}) \right] / [1 - MC_2] \]  

...(13)

or

\[ x_5 = \left[ \frac{M_1}{100} \times x_1 \right] - \left( \left[ \frac{M_2}{100} \times (x_1 - (\frac{M_1}{100} \times x_1)) \right] / [1 - \frac{M_2}{100}] \right) \]  

...(14)

Where \( x_5 \) is the mass of moisture removed to reach target moisture content.

**For Dry Basis Moisture Content:**

\[ M_1(\%)_{db} = \frac{x_2}{x_1 - x_2} \times 100 \]  

...(15)

\[ \frac{M_1}{100} \times (x_1 - x_2) = x_2 \]  

...(16)

\[ x_2 + \frac{M_1}{100} \times x_2 = \frac{M_1}{100} \times x_1 \]  

...(17)

\[ x_2 \left( 1 + \frac{M_1}{100} \right) = \frac{M_1}{100} \times x_1 \]  

...(18)
\[ x^2 = \frac{M_1 x_1}{100} \left(1 + \frac{M_1}{100}\right) = \frac{MC_1 \times x_1}{1+MC_1} \] ... (19)

Dry Matter will be \(x_1 - x_2\)

\[ x^3 = x_1 - \frac{M_1 x_1}{100} \left(1 + \frac{M_1}{100}\right) = x_1 - \frac{MC_1 \times x_1}{1+MC_1} \] ... (20)

For the Grain to be at Moisture Content \(M_2\) (db), then mass of water \(x_4\) will be resident in it

\[ M_2(\%)_{db} = \frac{x_4}{x_3} \times 100 \] ... (21)

\[ x_4 = \frac{M_2(\%)_{db}}{100} \times x_3 \] ... (22)

\[ x_4 = \frac{M_2(\%)_{db}}{100} \times \left( x_1 - \frac{MC_1 \times x_1}{1+MC_1} \right) \] ... (23)

\[ x_4 = MC_2 \times \left( x_1 - \frac{MC_1 \times x_1}{1+MC_1} \right) \] ... (24)

Again, \(x_5\); the mass of water to remove is \(x_2 - x_4\)

\[ x_5 = \left[ \frac{MC_1 \times x_1}{1+MC_1} \right] - \left[ MC_2 \times \left( x_1 - \frac{MC_1 \times x_1}{1+MC_1} \right) \right] \] ... (25)
%% Script for Evaluating Turbine Blade Size Using Aeration Data stored on Excel file wattshall.csv
%% Written by Francis A Agbali BAE, University of Kentucky

clc;
clear;
close all;

%% Power Requirements input from a csv file of output of Appendix A.
%% (wattshall.csv) is the csv version of Appendix D
power = xlsread('wattshall.csv');
pow2 = power(5:6,2:5);
pow4 = power(5:6,7:end);
P2 = [pow2(1,:) pow2(end,:)];
P4 = [pow4(1,:) pow4(end,:)]
u = 2.5
meg = 0.18
rho = 1.225
for i = 1:1:8
    u = 2.5
    for j = 1:1:8
        P = P2(i)*1.5;
        Q = P4(i)*1.5;
        R2(i, j) = sqrt((2*P)/(rho * 3.142 * u^3 * meg));
        R4(i, j) = sqrt((2*Q)/(rho * 3.142 * u^3 * meg));
        u = u + 0.5;
    end
end
APPENDIX E: ANOVA for Drying to 15% MC (%wb)

One-way Analysis of MOISTURE CONTENT By SET

Summary of Fit
- R-squared: 0.069708
- Adj R-squared: 0.06003
- Root Mean Square Error: 1.691383
- Mean of Response: 18.49786
- Observations: 998

Analysis of Variance
- Source: Set
- DF: 1
- Sum of Squares: 130.6481
- Mean Square: 130.6481
- F Ratio: 4.34
- Prob > F: 0.0305

Means and Std Deviations
- Level 1: Mean: 17.6837, Std Error: 1.92966, Lower 95%: 16.8079, Upper 95%: 18.5594
- Level 2: Mean: 16.6462, Std Error: 1.34013, Lower 95%: 15.1789, Upper 95%: 18.0034

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile
- t Alpha: 1.96209, 0.05

LSD Threshold Matrix
- Abs Diff LSD
- 2,1: 0.32647
- 2,3: 0.64030
- 3,1: 0.31868

Positive values show pairs of means that are significantly different.

Missing Rows: 122
APPENDIX F  ANOVA Table for Moisture

Oneway Analysis of Column 2 By Column 1

Oneway Anova
Summary of Fit
- R-Square: 0.213725
- Adj R-Square: 0.211304
- Root Mean Square Error: 0.14837
- Mean of Response: 0.683344
- Observations (or Sum Wgts): 602

Analysis of Variance
- Source: Column 1
  - DF: 2
  - Sum of Squares: 3.390248
  - Mean Square: 1.79512
  - F Ratio: 81.3451
  - Prob > F: <0.0001

- Source: Error
  - DF: 596
  - Sum of Squares: 18.389158
  - Mean Square: 0.03028

- Source: Total
  - DF: 598
  - Sum of Squares: 21.779397

Means for Oneway Anova
Level | Number | Mean | Std Error | Lower 95% | Upper 95%
1    | 201    | 0.79250 | 0.01047 | 0.77188 | 0.81319
2    | 201    | 0.63172 | 0.01047 | 0.61072 | 0.65273
3    | 201    | 0.62520 | 0.01047 | 0.60478 | 0.64568

Std Error uses a pooled estimate of error variance.

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile
- t Alpha: 1.9630, 0.05

LSD Threshold Matrix
Abs(DF)-LSD
1 2 3
1 0.02907 0.13209 0.13703
2 0.13209 0.00907 -0.02413
3 0.13703 0.02413 -0.02907

Positive values show pairs of means that are significantly different.

Connecting Letters Report
Level | Mean
1    | A 0.79250
2    | B 0.63172
3    | B 0.62520

Levels not connected by same letter are significantly different.

Ordered Differences Report
Level - Level | Difference | Std Err Diff | Lower CL | Upper CL | p-Value
1 2 | 0.1651001 | 0.0145000 | 0.13703 | 0.19316 | <0.0001
1 3 | 0.1651001 | 0.0145000 | 0.13703 | 0.19316 | <0.0001
2 3 | 0.0040000 | 0.0145000 | 0.03397 | 0.03407 | 0.7386
APPENDIX G: The Development of Table 4.1

(Using Modified Henderson Equation. (Chen, 1989))

The Modified Henderson equation for determination of Equilibrium Moisture Content was given as

\[ 1 - RH = \exp(-A \cdot (T + C) \cdot M^B) \]  

\[(1)\]

Where RH is the relative humidity given as decimals and T is the temperature. The variables A, B, and C are constants specific to different products. For Ear Corn, using the Henderson equation A = 6.4424 \times 10^{-5}, B = 2.0855 and C = 22.150.

Taking the natural logarithm of both sides of the equation removes the exponential factor on the right-hand side of equation (1) and rearranging the equation, making M, the equilibrium moisture content become the subject, the equation becomes:

\[ M = \left(\frac{\ln(1-RH)}{-A \cdot (T+C)}\right)^{1/B} \]  

\[(2)\]

Equation (2) is then used in an Excel Spreadsheet to determine the set of EMCs for a range of relative humidity from 20 to 85 % and temperatures from 20 to 80°C since the Henderson equation was based on fitting a set of data obtained between 11 – 87 % relative humidity at temperatures between 20 and 80°C
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