DEVELOPMENT OF PICO SOLAR CROP DRYER (POD) FOR FARM LEVEL GRAIN DRYING BY SMALL HOLDER FARMERS IN AFRICA

by

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I would like to dedicate this thesis to my parents who have supported me and have taught me important lessons in my life.

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LIST OF ABBREVIATIONS

POD	Picosolar crop dryer
EMC	equilibrium moisture content
PV	photovoltaic
BTU	British thermal unit
HP	horse power
MC	moisture content
ASABE	American Society of Agricultural and Biological Engineers
DR	drying rate
BU	bushels
MR	moisture ratio

SYMBOLS

MC_{wb}	moisture content on a web basis, %
W_w	weight of water, kg
W_d	weight of the dry matter, kg
MC_{db}	moisture content on a dry basis, %
$MC_{initial}$	initial moisture content of the product, %
MC_{final}	final moisture content of the product, %
t	drying time, hour
P	pressure, Pa
P_{static}	static pressure, Pa
Q	airflow rate, m^3/hr
Q_{max}	maximum value of airflow, m^3/hr (m^3/(m^2*s))
a	constant, dimensionless, in equation 6.2 for calculating Q
b	constant, dimensionless, in equation 6.2 for calculating Q
L	drying bed depth, m
n	constant, dimensionless, in equation 6.4 for calculating ΔP
m	constant, dimensionless, in equation 6.4 for calculating ΔP
H	depth of grain, m
v	velocity, m/s
A	drying area, m^2
M_o	initial moisture content on a dry basis, %
M_e	moisture content on a dry basis of the grain when it is in equilibrium, %
T	drying air temperature, °C
RH	relative humidity, %
k	constant, dimensionless, in equation 6.6 for calculating MR
E	constant, dimensionless, in equation 6.8 for calculating M_e
F	constant, dimensionless, in equation 6.8 for calculating M_e
C	constant, dimensionless, in equation 6.8 for calculating M_e
RH_{eff}	effective relative humidity, %
T_{eff}	effective temperature, °C

ABSTRACT

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Title: Development of Pico Solar Crop Dryer (POD) for Farm Level Grain Drying by Small Holder Farmers in Africa
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For African farmers, proper drying is considered to be the biggest single factor in determining whether grain can be effectively stored without deterioration. The primary goal of the project is to develop and test the Pico solar crOp Dryer (POD). The overall goal is to improve the POD's performance, making it acceptable to small holder farmers in Kenya and other developing countries, and positioning it for commercialization. In the POD tests shelled maize was placed in wooden or plastic trays and that were covered with plastic sheets. In the final design, seven small fans of the type used for cooling electronics moved air through the dryer. Power was supplied by a 12 volt, 30 Watt Solar Panel and a 12 volt 7 ampere hour lead acid battery. A charge controller allowed the fans to draw energy from both the solar panel and the battery. The POD was tested at Purdue from 2017 to 2019. The most recent Purdue test on freshly harvested maize was conducted in September 2018. The POD was able to dry 142 kg of 30.1% mc maize to 13.3% in 24.5 hours of drying over 3 calendar days giving an overall drying rate of 0.68 percentage points per hour. The POD dried the maize in 0.84 of the time required to dry maize on a tarp. In the summer of 2018, the components for assembling 5 POD's were prepared and sent to Kenya for testing. The tests were conducted in Nakuru county in November 2018, and in Trans-Nzoia, Uasin Gishu, and Nandi counties in March 2019. Overall average drying rates for the tests varied, depending on weather conditions, from 0.58 to 0.97 percentage points per hour. A thin layer drying equation was adapted for use in investigating the effects of weather conditions and the airflow rate on the POD drying rate. Adoption of the POD by small holder farmers in Kenya and other developing countries should lead to a reduction in post-harvest losses caused by improper drying. Although testing has been primarily focused on drying maize, it could be adapted for drying other crops.

CHAPTER 1. INTRODUCTION

1.1 Importance of Grain drying

Cereal grains are one of the major resources which supply the food industry with essential ingredients and fulfill the protein requirements of people throughout the world. They also play essential roles in feeding animals. Wheat, maize and rice, the three major types of the cereal grains, account for nearly 90% of the world grain production [1] (Figure 1.1). The total world production of cereal grain in 2018 was over 2.98 billion tonnes according to statistics from the Food and Agriculture Organization of the United Nations (FAO) [1]. This illustrates the contribution that cereal grains have made to human needs. In the United States, over 14.4 billion bushels of maize were produced in 2018. It was the cereal grain constituting the largest share of total grain production [2] (Figure 1.2).

Much of the cereal grain harvested is not consumed or processed immediately but is instead stored until it is needed. Sometimes cereal grain is too high in moisture when it is harvested [3]. For example, the maize that is grown in the northern regions of the United States and in many regions in Sub-Saharan Africa is harvested at moistures above those at which it can be safely stored. Wet grain will rapidly spoil because of fungal growth and susceptibility to insect invasion. Wet grain has a higher respiration rate and if the grain is warm and the moisture is sufficiently high it can germinate. Therefore, it is often necessary to dry grain before it is stored. Drying is the most widely and frequently practiced grain-preservation method. Drying wet grain allows the farmers to store it until the price increases or to save it for another use such as feeding livestock [4]. Another advantage of having a grain drying system is that the harvesting schedule can be more flexible. For example, grain can be harvested sooner if the farmer plans to plant another-crop in the same field during the same harvest season. Farmers generally can sell lower moisture grain for a better price when they market their grain.

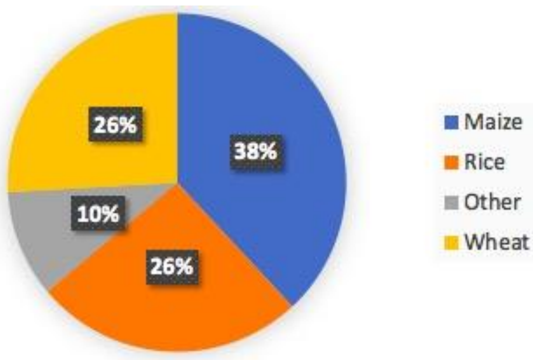

Figure 1.1 World Cereal Production in 2017. Total production in 2017 was 2,980 Million Tons [1]

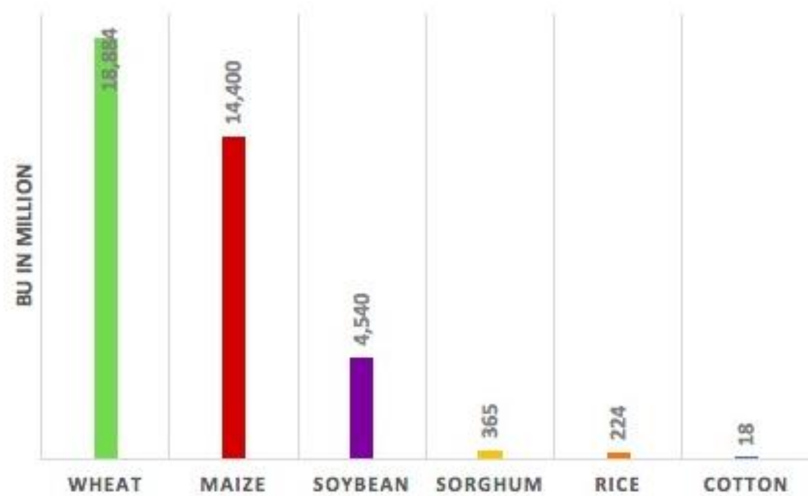

Figure 1.2 Total production of U.S. major crops in 2018 [2]

Grain needs to reach a moisture content that will prevent mold growth. If germination rates need to be maintained at a high level it is also necessary to keep the seed at a lower moisture. The temperature and the relative humidity of the air occupying the space between kernels are two important factors that determine whether fungi can grow. An inter-seed equilibrium relative humidity below 65% is considered “safe” from the growth of microorganisms on maize [5] because there have been no fungi discovered that can grow when the maize is in equilibrium with air at relative humidities below 65%. The safe storage moisture for preventing mold growth depends on the temperature of the grain. Figure 1.3 shows the equilibrium moisture relationships for maize. As the temperature increases, the equilibrium moisture decreases which indicates that it is necessary to dry the maize to a lower moisture content to prevent mold growth in the grain.

For example, for Kenya, which has a warm climate, the storage temperature is higher and therefore the moisture content of the grain that is going to be stored needs to be lower. The safe storage moisture varies slightly among different types of grain (Table 1.1) [6]. In general, 13% moisture content is an accepted value for long term storage [7].

Table 1.1 Equilibrium moisture content (EMC) of cereals at 80 °F (26.7 °C) and 65% relative humidity. Values were calculated using the Modified Henderson Equation [6]

Crop	Moisture (%)
Shelled Maize	13.2
Durum Wheat	13.3
Rice	13.0
Soybeans	11.0
Barley	12.4

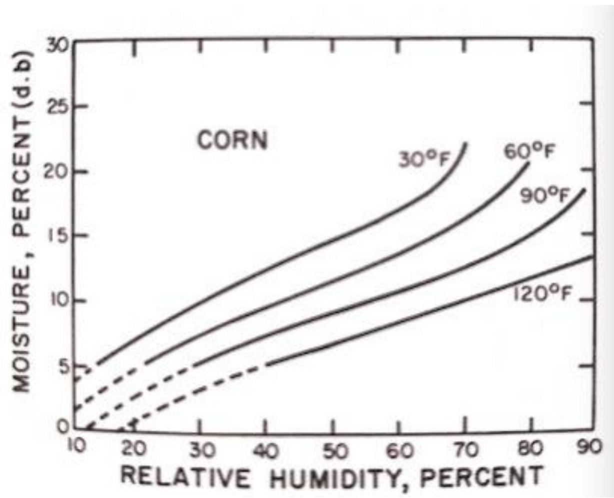

Figure 1.3 Equilibrium moisture relationships for maize [8]

1.2 Solar drying and sun drying

Drying with heated air is the most widely used method of reducing moisture content in industrial and agricultural processes. The energy required for thermal drying is relatively high and the equipment used is relatively expensive. If fossil fuels are used to produce the required heat, the release of carbon dioxide and contaminates (e.g. smoke) can lead to environmental problems. Solar drying, on the other hand, represents a clean and hygienic way to reduce the energy cost and improve product quality [9].

Sun drying consists of spreading the material in a relatively thin layer on a tarp, matt, tray, etc. and exposing it to the sun with frequent stirring or mixing of the material being dried. It is one of the first, if not the first, approach mankind has used and it is different from solar drying. In sun drying, products are placed under the open sky. It is still widely used especially in the rural areas in developing countries. For example, in rural counties of western China, where electricity is not available and the people cannot afford fuel, sun drying is used to dry herbs, grains and vegetables. It is different from solar drying where devices are used to collect and utilize solar radiation.

Although sun drying is the simplest and cheapest, it suffers from several disadvantages [10]:

1. The grain being dried in the open place is exposed to dirt, animals and microbes, which may invade the grain causing a loss of quality or consumption or loss of some of the grain.
2. Adverse weather conditions like unexpected rain may prevent adequate drying and therefore lead to post-harvest losses.
3. A significant amount of labor is required for stirring the grain, which must be done frequently, and for protecting the grain from birds, rodents or other animals. In addition, labor is needed to distribute the grain at the beginning of the day and collect it in the evening.

1.3 Background

Maize is one of the principal foods in Sub-Saharan Africa. The maize harvest season in Kenya starts in October and can continue through December depending on the farmer's preparedness and harvesting resources, market needs and weather conditions. The majority of maize is harvested in November and often left in the field in stacks (stalks placed horizontally on the ground) for about one month. Then it is shelled [11]. According to R. Shreshtra [12], in some African countries, in places like Velingara, Senegal "there was a set time for farmers to harvest their crops before livestock (cattle, sheep and goats), [which] are owned by households in the communities, are released to pasture on crop residues in the field". A few farmers harvest the maize early and sell it to get money for urgent needs such as paying school fees and other bills [13].

Shrestha, in a summary of a survey [12] focusing on drying practices in Kakamega, Kenya and Velingara, Senegal, summarized the practices followed in those communities: “The average moisture content of maize kernels in the ears collected from the field, either from [stacked stalks] or piles was 30-33%. The ears that were brought in from the field that were being dried on the cob outside or inside the house had an average moisture of 24-26%. Furthermore, the moisture content of shelled grains being dried averaged approximately 18%. The stored grains that were collected averaged 14% moisture content.”

Most traders offer low prices to African farmers who harvest early since it is at a higher moisture content and they need to dry the maize to the required 13% moisture content. Therefore, maize that has been dried fetches a higher selling price in the market. Although commercial grain dryers could quickly dry larger amounts of maize, they are often located far away from the smallholder farmers and can be expensive to build and use in Sub-Saharan Africa. Based on the situation, the tradition there is to leave the maize in the field long enough to dry before it is shelled.

According to a 2013 survey conducted by USAID [11] amongst 48 small holder Kenyan farmers in the Rift Valley Province, most of the farmers removed the ears of maize from the stalks and laid the maize ears on the ground for about 8 hours per day, turning them 2-3 times per day for around 4 days. Around half of the farmers placed tarpaulins under maize but the other half did not. After that, the ears were placed in a crib-like structure for around three weeks to allow them to slowly dry.

Significant dry matter losses can occur during post-harvest handling and storage in sub-Saharan Africa. The African Post-Harvest Losses Information System (APHLIS) [14] estimated that 8.5% of maize was lost during post-harvest handling and storage in Kenya during 2013. Studies carried out by the USAID funded Food Process Innovation Lab at Purdue have shown a market demand among smallholder farmers for on-farm grain dryers that cost less than $100, can be disassembled and transported on the back of a motorcycle, and can dry 90 kilograms of grain in one day with one hour or less of manual labor [15]. In addition, the drying rate of the dryers should be higher than the rate that occurs when the shelled grain is placed on a tarp.

The Pico Solar Crop Dryer (POD) was developed by Dr. Arvind Raman and Dr. Richard Stroshine in order to fulfill the needs of African smallholder farmers. The POD was first designed and tested at Purdue in the first several months of 2017 and was subsequently modified several times in succession and tested after each modification. The tests and modifications are discussed in Chapter 3.

1.4 Objectives

The primary goal of the project is to develop and then test the Pico Solar crOp Dryer (POD). Although testing has been primarily focused on drying maize, it could be adapted for drying other crops. The ultimate goal of the project is to develop the POD to the point that it performs well and is acceptable to small holder farmers in Kenya and other developing countries. Its adoption should therefore lead to a reduction in post-harvest losses caused by improper drying. The specific objectives of the research described in this thesis are as follows:

1. Evaluate the performance of the POD including modifications that allow the dryer to perform more effectively and compare the performance of the POD with tarp dying.
2. Explore the use of a thin layer drying equation for simulating the performance of the POD and compare predictions of the adapted equation to results obtained from POD tests.
3. Use the adaptation developed in objective 2 to investigate the effects of air properties and airflow rate on the performance of the POD and use the results of the investigation together with the experimental data to identify approaches to improving the performance of POD.

There are 7 chapters in this thesis. Chapter 2 is a review of publications that describe the development of solar drying, along with an approach to classification of solar dryers and a description of several types of solar dryers that were designed for use in developing countries. Chapter 3 describes the development of the Pico Solar Crop Dryer (POD) including the project background and the working principles and then summarizes performance tests conducted between 2017 and 2019. Chapters 4 and 5 present the results of the dryer performance tests conducted at Purdue University and in Kenya, respectively. The performance and modifications of the POD as well as comparison with tarp drying are also included. Chapter 6 introduces an adaptation of the thin layer drying equation, which can be used to investigate the effect of weather conditions and airflow rate on the drying rate of the dryer. It also discusses the validation of the model. The chapter also includes a summary of the model's predictions regarding the effects of air temperature, air relative humidity, and airflow on drying rate in the POD. Chapter 7 gives conclusions drawn from the research and gives recommendations for continued development.

1.5 References

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CHAPTER 2. LITERATURE REVIEW

2.1 Solar radiation and solar energy utilization in Kenya, Africa

Solar energy is renewable and it has great potential for mitigating negative environmental problems such as the global warming caused by the massive burning of fossil fuels to produce energy. With the rapid technological improvements being made and resultant decreasing costs, it has been predicted that solar energy will be an important share of future energy systems [1]. Data on solar radiation and proper design of solar energy systems are essential to progress in utilization of solar energy.

The amount of solar radiation received by a given location can be determined by processing images from satellites or it can be measured by-ground stations [2]. Because of the interference of the earth's of atmosphere, estimating the ground level solar radiation using satellites is not precise [3]. However, the satellites cover large areas of the earth's surface, which makes it more available to areas in which on-ground measuring stations are too expensive [4].

As shown in Figure 2.1, solar energy in Kenya is abundant [5]. The yearly horizontal solar radiation for Kenya ranges between 1800 and 2556 kW/m^2. In northwest Kenya, the solar radiation is around 2400 kW/m^2. The average daily solar insolation for the countries in Africa is compared to values in Lafayette, IN in Table 2.1. The African locations have great potential for development of solar energy. However, there has been less than anticipated development and utilization of solar energy in Africa even though governments there have established policies to promote solar energy businesses [6].

Table 2.1 Average daily insolation for cities in Africa and for Lafayette, IN

Country	City	Latitude	Longitude	Average daily insolation (kWh/m^2 day)
Kenya	Nairobi	1° 16′ S	36° 48′ E	5.62
Nigeria	Abuja	9° 12′ N	7° 11′ E	5.61
Ethiopia	Addis Ababa	9° 20′ N	38° 42′ E	5.84
United States	Lafayette	40.42° N,	86.88° W	4.5

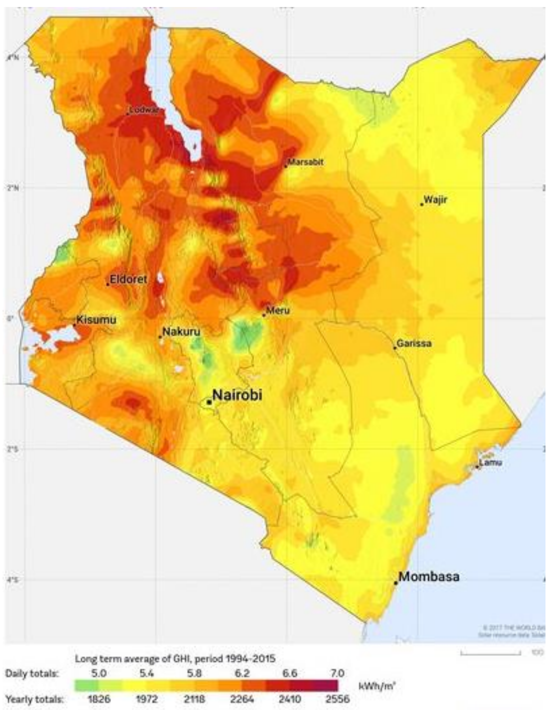

Figure 2.1 Yearly total global horizontal radiation for Kenya [5]

There are two main systems for solar energy utilization being used in Africa: solar thermal systems and photovoltaic (PV) systems. Solar thermal systems are easier to adapt to agricultural drying. In this process, solar thermal plants use mirrors to concentrate the solar radiation that is converted to electricity by using it to drive traditional steam turbines or engines. Ramde and Forson stated that thermal solar drying is desirable for use in drying since it offers free energy with low investment [7]. In PV systems, silicon is typically used in panels to convert solar energy into electricity. Although solar energy has been utilized for decades in many other parts of the world, it is still a recent development in Africa. According to Banks [8], solar technology will be supplying up to 14 per cent of Africa’s energy needs by the year 2050.

2.2 Development of Solar Drying

Crop drying often consumes large amounts of energy. The availability and the cost of that energy directly influence the cost of drying. During cereal drying, a large amount of energy is usually used to power electric fans that move high volumes of air through the dryer. In the United States, combustion of a fossil fuel is usually used to heat the air for high temperature “portable” crossflow dryers and for in-bin dryers, while for low temperature drying systems, electric heat is generally used to heat the air [9]. As the cost of energy increases and people become more concerned about the negative environmental impact of burning fossil fuels there is greater interest in finding alternative energy sources for drying cereal grains.

One of the first investigations of the use of solar heat for agricultural drying was conducted by Buelow in 1958 [10]. Several types of solar air heaters were tested for grain drying and their performance was discussed. Buelow subsequently designed, built, and tested solar collectors in 1962 [11]. In addition, Hall [12] reported on the heating of the ventilation air by placing components it the roofs of swine buildings. Bailey and Williamson [13] published a paper that described grain drying experiments that used solar collectors for grain drying. In their experiments, wheat being dried was either placed on a flat plastic sheet that was not covered or placed on a sloping base 0.75 m^2 in area equipped with a transparent cover. The specific consumption of heat was defined as the solar energy required in Btu’s for removal of 1 pound of water. When grain was placed on a flat plastic sheet that was not covered, the specific consumption of heat available from radiation was 8,000 to 10,000 Btu/lb water evaporated, and 10,000 to 18,000 Btu/lb when grain was placed on the sloping base with a transparent cover. During the experiments, the average solar radiation was 120 to 170 $Btu*h^{-1}*ft^{-2}$. Bailey and Williamson [13] observed that the energy consumption was 3 to 4 times higher than those of farm grain dryers. They suspected that the cooling effect of wind might be responsible for the low utilization of heat. In their report [13] they concluded: “heat utilization in a covered solar drier with uncontrolled air flow is only of the same order as that when material is laid on the ground to dry, but it considerably improved when air flow is controlled and directed downwards through the material to be dried.” They mentioned that only a very small fan was necessary for this type of drying and that as a consequence low static pressures were produced. They also expected that the small scale solar dryer could be of practical use where comparatively small quantities of material have to be dried.

Although many solar collectors were designed and many solar-heated grain drying experiments were proposed, there appear to have been few operational drying systems that used solar energy until 1973 [9]. Interest in research on solar drying increased, apparently as a result of a national fuel shortage and government sponsorship of research on solar drying of maize. In 1973, Peterson [14] proposed a system anticipating that it would be applied to solar crop drying. Peterson and Hellickson [14] concluded in their report that: (1) black bare sheet corrugated collectors could be installed at a low cost and could generate solar energy as efficiently as the plastic covered collectors; (2) solar collectors mounted on a low-temperature drying bin could provide appreciable energy for drying shelled maize; (3) the solar drying bin used 26% less energy than the conventional drying bin. Foster and Peart [15] studied the use of solar energy as an alternative or supplemental source of heat for low temperature grain drying. They claimed that the use of solar energy could decrease the energy costs for drying.

Gayanilo, et al, [16] designed and tested a simple low-cost solar-heated grain drying system in 1979 at the Iowa State University's Woodruff farm. The dryer was equipped with a 2.44 m by 9.75 m bare-plate solar collector and a 58.42 cm diameter drying fan. The dryer capacity was 1.53 m^3 and the system was powered by a 170.9 cm^3 Briggs and Stratton internal combustion engine. The system was capable of drying 1.32 m^3 of shelled maize from 26.3 to 13.9% moisture content in 12 hours over 1.5 days. The total cost of building the system was $1,130.

In 1987, Lutz, et al, [17] developed and tested a multipurpose solar crop dryer for drying various agricultural products. The system consisted of a small radial flow fan driven by a 100 watt AC-motor, a tunnel dryer in which the crop was spread in a thin layer, and a solar collector. The dryer had a flexible capacity varying from 100 kg to 1000 kg. The required drying time varied from 1 to 7 days. The dryer was tested in Greece, Yugoslavia, Egypt, Ethiopia and Saudi Arabia drying several types of vegetables, fruit and some medicinal plants. The results indicated that the dryer typically took 3 to 5 days less than natural sun drying depending on the weather conditions.

2.3 Classification of solar dryers

Generally, solar dryers can be classified on the basis of two criteria. One is the mode of drying, and the other is the energy source. Based on the first criterion, solar dryers can be either direct or indirect. Using the second criterion, solar dryers can be classified as active or passive. [18].
An example of a direct solar dryer is the cabinet dryer. Figure 2.2 shows the configuration of a typical direct solar dryer. The product to be dried is placed in a chamber where it absorbs solar radiation. These dryers are usually covered by glass or transparent plastic that allows radiation to pass through and at the same time reduces direct convective heat losses to the ambient air from the product being dried. Although some of the solar radiation is absorbed by the top surface of the product, part of it is reflected back to the atmosphere. The temperature of the crop inside the dryer increases due to absorption of the solar radiation. There are several limitations of this method including the following: direct exposure to solar radiation may cause discoloration of the product; the capacity of the dryer is relatively small; and finally, sometimes there is only a relatively small temperature rise in the product and this means drying will be slower [18, 19].

Figure 2.3 illustrates the configuration of an indirect solar dryer proposed and analyzed by Goyal and Tiwari [20]. The reflector focuses the solar radiation on the top surface of the collector increasing its temperature. Air passing over this surface is heated and then passes through the sample absorbing moisture from the material that is being dried. The glass cover is inclined at a 45 degree angle so that it intercepts the maximum available solar radiation. Goyal and Tiwari [20] developed a mathematical model of the drying process and calculated that the temperature inside the dryer could be as high as 80°C compared to a normal cabinet dryer that could only reach 55°C. They also claimed that the products in the dryer would be more uniform in moisture compared to a normal cabinet dryer because the products were not directly exposed to sun. Samples dried by this method were considered to have better quality than those dried by a direct solar dryer. In the indirect solar dryer, temperature inside the drying chamber can be controlled whereas there is little control in a direct solar dryer. Sharma, et al., [19] concluded in their review paper that the indirect solar dryer produces a better quality dried product.

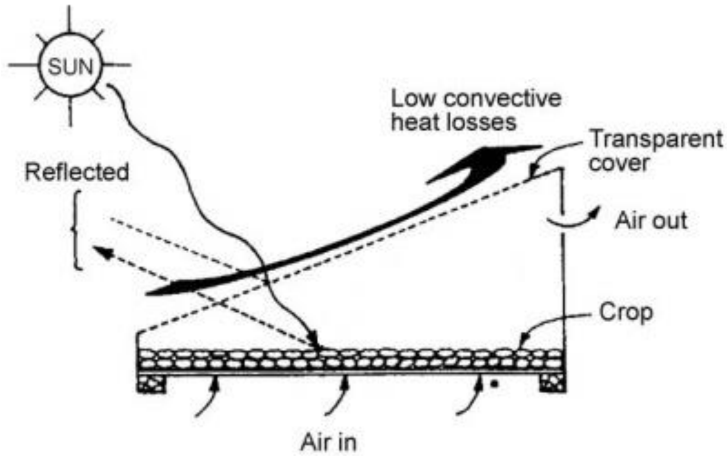

Figure 2.2 Drawing showing the configuration of a typical direct solar dryer [19]

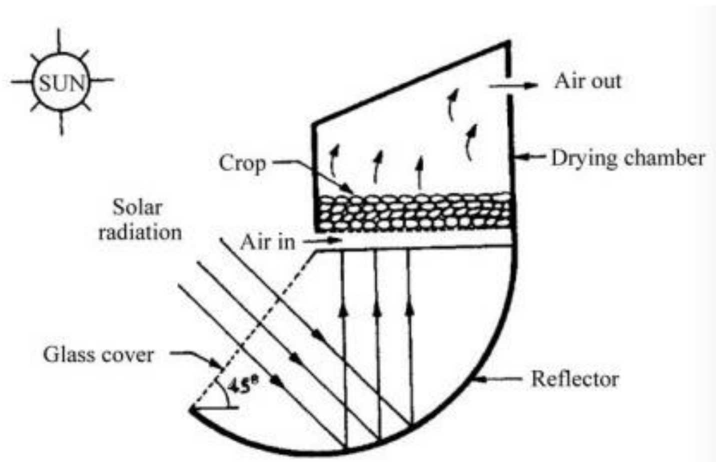

Figure 2.3 Diagram showing the configuration of a typical indirect solar dryer [20]

The passive solar dryer is also known as a natural convection solar dryer. Air movement is driven by the buoyant force that results from heating the air and decreasing its density. Air movement can also be driven by wind pressure or by both buoyant force and wind pressure. This type of solar dryer is more appropriate for small farms than the active solar dryer. It is less expensive to build and can be made from locally available materials [21]. In the active type solar dryer, other types of energy such as electricity or fossil fuel can be used in combination with solar energy to drive fans or pumps. Active dryers are used for drying larger samples and commercial dryers are typically this type of dryer [18].

2.4 Postharvest loss in developing countries

Harris and Lindblad define postharvest as the stage in crop production that begins with the separation of food from its site of immediate growth [22]. The process begins when the harvest is completed and ends at the point where the crop is processed for consumption. Grain loss includes the loss in dry matter or change in availability of nutrients or the quality of the food made from it, which affects its later consumption. Postharvest loss has been a major problem especially in developing countries. For example, in Afghanistan, fruit and vegetables are usually transferred by bags or baskets which bruise or crush the fruit or vegetables at the bottom of the container [23]. In India, inadequate cold chain storage causes considerable losses for livestock products, fruit and vegetables [23]. The World Bank [24] estimated that postharvest losses in Africa for 2011 ranged from 20 to 40 %. The African Post-Harvest Losses Information System (APHLIS) [25] estimated that 8.5% of maize was lost during postharvest handling and storage in Kenya during 2013. The postharvest losses of maize in Ethiopia were worse. They were estimated to be 16.8 % in 2012 by APHLIS [25].

Both farmers and consumers suffer when there are postharvest losses. Consumers have to pay a higher price for the products they purchase due to the qualitative and quantitative losses that occur when drying, storing and transferring the products after harvest. Postharvest losses have a detrimental effect on small scale farmers when they have to sell for a poor price due to the poorer quality of their grain. They also suffer from the loss of revenue which leaves them insufficient funds for necessary purchases. In developing countries, people are impacted by postharvest loss. For example, almost 40 % of the population in West Africa consumes less than half of their daily protein requirements [23]. Almost 20 % of the world's food is produced in China every year while more than 50 million tons of food are lost as the food moves through agricultural supply chains [26].

2.5 Smallholder farmer drying practices

In many developing countries, a popular method of drying is leaving the crop in the field until the grain moisture decreases to an acceptable level. In areas like sub-Saharan Africa, people also place the grain on various surfaces such as the ground, asphalt roads, cemented areas or tables where it is dried by the sun. Disadvantages and limitations of this type of drying were summarized in Chapter 1. In order to achieve better drying, many solar dryers have been developed for use in developing countries but only a few have been successfully commercialized.

Compared to sun drying, the advantages of solar drying can be summarized as follows:

1. Compared to open air sun drying, higher air temperatures and lower relative humidities can be achieved inside the solar dryer, which increases the rate of drying.
2. The grain being dried is enclosed in the dryer and is not exposed to dirt, animals and microbes so that qualitative and quantitative losses can be reduced.
3. Adverse weather conditions, such as an unexpected rain, will have less effect on the grain, because it is protected.
4. Less labor is required since it is not necessary to have a worker protect the grain from pests and animals.

Several solar dryers developed for use in developing countries are reviewed below.

A low cost SRR dryer [27] was designed and developed by the Center for Agricultural Energy and Machinery of Nong Lam University in Vietnam. SRR is a Vietnamese term meaning "Low-Cost." It is a farm-level dryer consisting of a drying bin, a fan and a heater. The drying bin consists of two concentric cylinders with the diameters of 0.4 m and 1.5 m respectively (Figure 2.4). The bin is made from bamboo mats and wire mesh. Its advantages include that it is light in weight and permeable to air. The grain is placed between the two cylinders. The bin can be filled to a depth of 1 m with grain giving it a capacity of around 1 ton. The fan is located on the top of the inner cylinder of the bin. The original design uses a fan rotor from an automobile cooling system to supply air at a rate of 0.35 m^3/s when it is running stably. The fan is driven by a 0.37 kW (0.5 HP), 2800-rpm electric motor. There is a 1000 W resistor located beneath the fan that heats the air. The resistor can be used as needed either at night or when the solar radiation is insufficient because of clouds or rain. Figure 2.4 shows the configuration of the SRR. As shown in the picture on the right, a coal stove can be added to increase the temperate of the air flowing into the dryer. This can reduce the electrical requirements and increase the drying rate [27, 28, 29]. The use of the stove can increase the drying air temperature by 5 to 9 °C above the ambient air temperature.

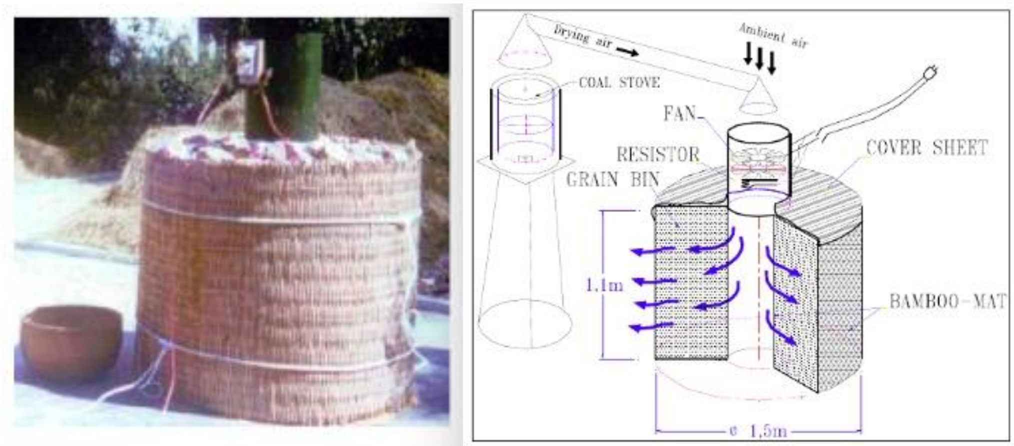

Figure 2.4 The SRR dryer developed by Nong Lam University in Vietnam [27]

The SRR dryer was developed in 1995 and tested by drying rice. Between 1995 and 1998, it was tested with maize, peanuts and other commodities. As of 2004, over 1400 SRR dryers have been used throughout Vietnam and demonstration dryers have been tested in Myanmar, the Philippines, India, Bangladesh and Indonesia [30]. The SRR dryer could dry rice from 24% moisture to 14 % moisture in 4 days (0.1 percentage point per hour drying rate). Its drying rate varies depending on the resistance to airflow and the weather conditions. The cost of the dryer is between 100 and 200 US dollars depending on the height of the bin, the size of the resistor and the local market price of the materials.

The Solar Bubble Dryer (SBD) [31] was designed and developed by the International Rice Research Institute (IRRI), Hohenheim University, and GrainPro USA, Inc. (Concord, Massachusetts, https://grainpro.com/en/) in 2012. The SBD is a portable low-cost solar dryer with a capacity ranging from 0.5 to 1 ton. Figure 2.5 is a picture of the SBD. The drying tunnel is spread out on the ground. The grain is loaded evenly up to the sides of the tunnel. There is a small blower at one end of the dryer which can move the air through the tunnel. The moving air inflates the tunnel and removes water from the grain. A roller is placed beneath the dryer to allow the grain to be mixed every hour without opening the tunnel. The system is powered by a rechargeable battery and a 100W photovoltaic panel. The SBD was tested in several countries in

Asia including Myanmar, Vietnam, Indonesia, Thailand, Nicaragua, the Philippines, and Cambodia between 2012 and 2016. The system drying rate is around 0.5 % point of moisture per hour depending on the weather conditions. Experiments have shown that the SBD could effectively protect grain on a rainy day, which is not usually possible for open sun drying. The cost of the SBD system is around 1500 US dollars [31]. The SBD has been commercialized and can be purchased from GrainPro.

Figure 2.5 Picture of GrainPro's of Solar Bubble Dryer (SBD)

A low cost natural convection cabinet dryer was developed by Patil and Sukla in 1988 [32]. The dryer consists of a steel frame covered with asbestos sheets with wire mesh on the bottom. A heat exchanger effectively transfers heat to the chamber where grain or a food material is placed in trays. It has a valve and chimney which allow smoke to escape (Figure 2.6). Air enters at the bottom of the dryer, goes through the samples and then escapes at the top. The system has a capacity of around 100 kg of wet product. The air is heated by burning agricultural waste. The investment in the dryer is around 400 dollars with an additional energy cost of around 18 dollars per ton. The system was tested in India where it was able to dry split soybeans from 62.8 % to 26.4 % in 15 hours, and soy flakes from 30 % to 11.8 % in 6 hours [32, 33].

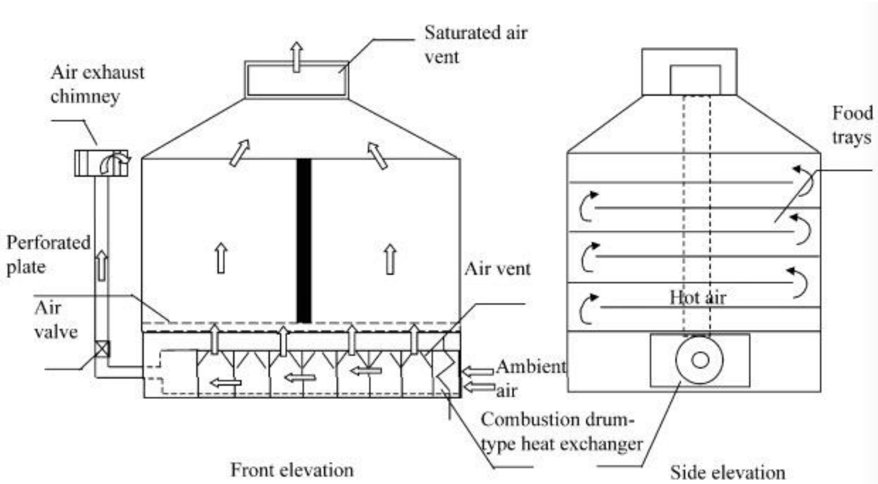

Figure 2.6 Diagram of a low-cost natural convection food dryer [31]

A forced convection solar dryer was developed by Dr. Klein Ileleji and his team at Purdue University (Figure 2.7). The dryer consists of a solar collector supported by an aluminum frame, and a chamber with an approximate volume of 0.68 m^3. Nine stackable trays can be placed inside the chamber. There are 8 small fans that move drying air through the dryer. Two of them are located in the front side of the dryer and the other 6 are on the floor. The system is powered by a 12V deep-cycle battery as well as a 100W photovoltaic solar panel mounted on the top. The temperature inside the chamber was typically be 5°C to 10°C above ambient. Greater temperature rises have been achieved in more recent versions of the dryer. The dryer was tested in West Lafayette, Indiana (United States), in Kakamega, Kenya (East Africa) and Velingara, Senegal (West Africa). The tray at the bottom of the stack of trays performed better than tarp drying [34]. The dryer can also be used for drying fruit and vegetables. It is being produced and marketed by JUA Technologies, International (Purdue Technology Park, West Lafayette Indiana, https://juatechnology.com/).

Figure 2.7 The forced convection solar dryer [34]

2.6 References

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CHAPTER 3. DEVELOPMENT OF THE PICO SOLAR CROP DRYER

This chapter includes an overview of all the tests conducted at Purdue and in Kenya. It includes a description of how the POD was developed and changes that were made in the design of the dryer. It also gives background information about the project and describes the configuration of the dryer.

3.1 Background

In Sub-Saharan Africa, principal foods include maize, beans, and rice. Although some farmers choose to sell their crops immediately after harvesting, most of them use natural sunlight to dry the grain first. Sometimes the crops are spread on tarps to protect them from contamination by dirt and other foreign materials. The disadvantages of natural sun drying have been summarized in Chapter 1. Socio-economic research [1] carried out by the USAID funded Food Process Innovation Lab at Purdue has shown a market demand among smallholder farmers in Kenya for a low cost dryer that they could use to dry their crops. The research indicated that the dryer should be able to dry 90 kg of grain faster than drying on a tarp. In addition, it should be possible to disassemble the dryer and transport it on the back of a motorcycle, because the motorcycle is a major type of transportation used in Africa. The dryer should be low-cost so that the smallholder farmers can afford it. An economic survey conducted by Food Processing Lab personnel indicated that a there would be a demand among some of the farmers for a dryer that would cost 100 dollars or less. This is illustrated by the graph in Figure 3.1. As shown in the figure, if the solar grain dryer costs over $100, less than 20 % of the people surveyed said they would be willing to purchase the dryer. The median price that the farmers were willing to pay for a solar dryer which dries 100 kg shelled maize per day to the safe storage moisture was around 62 US dollars. However, Dr. Stroshine and Dr. Raman anticipate that if the farmers in Kenya see that the dryer works well, there will be more who are willing to pay the greater cost of the dryer.

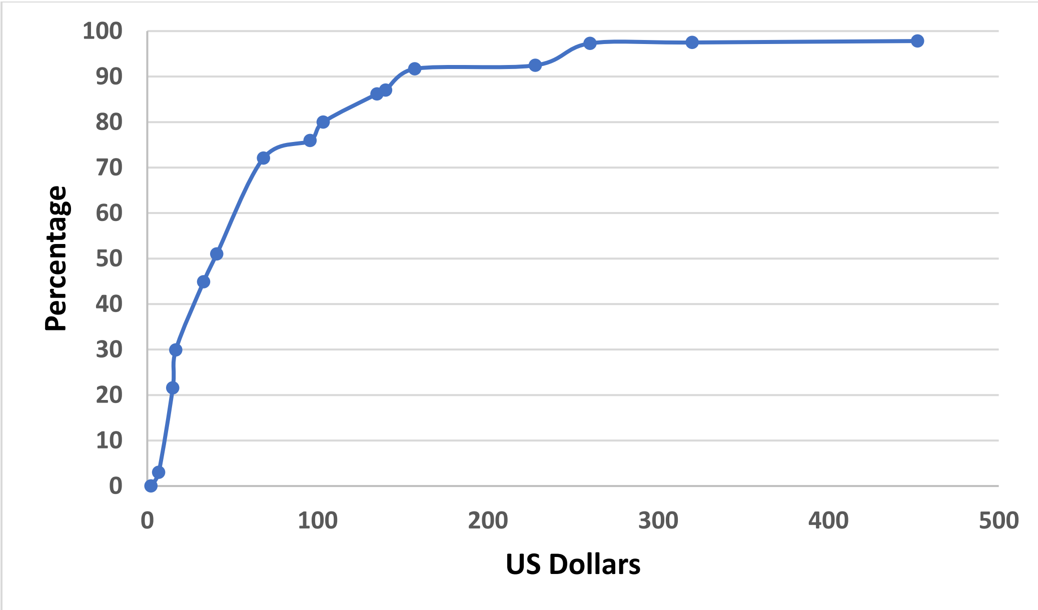

Figure 3.1 Percentage of people not willing to pay when a grain dryer is available at the price given on the horizontal axis [1]

The advantages of the proposed solar dryer were given in chapter 2, section 2.4 They are re-stated with elaboration below:

1. If there is not a heavy cloud cover, the air above the grain is heated reducing its relative humidity. The warmer and lower relative humidity air will dry the grain to a safe storage moisture more rapidly.
2. In some instances the higher temperature and lower relative humidity achieved in the dryer can make it possible to dry the grain to the required 13% moisture content. This low moisture could not be achieved by drying at ambient conditions. The dried grain should fetch a higher selling price when it is marketed.
3. Using the dryer eliminates the additional labor needed to protect grain that is exposed on a tarp from birds, rodents or other pests and animals.
4. The grain is enclosed in the dryer during drying and therefore it is not exposed to dirt, animals, and microbes. Therefore, the quality of the grain dried in the dryer can be better
5. In some regions of Africa in the season when maize is being dried, rain develops during certain times of the day (e.g. the afternoon), and the dryer can protect the grain from the rain. If the grain were on a tarp, it would have to be covered or put back in a bag before the rain arrives.

The Pico Solar Crop Dryer (POD) was designed and developed by Dr. Raman and Dr. Stroshine in an attempt to fulfill the needs of the African smallholder farmers as identified by the Food Processing Lab survey. The term Pico Solar refers to devices that can be powered by small photovoltaic panels having a capacity of approximately20-30 W. Pico-solar photovoltaic applications are becoming increasingly popular in Sub-Saharan Africa. Their development is supported by the government and driven by private firms who supply pico-scale systems to customers that meet their electricity and lighting needs [2]. As shown in Figure 3.2, the annual sales of pico-solar products dramatically increased from about 0.1 million units in 2010 to over 2 million units in 2014. Continued market growth is expected. In their article Scott and Miller [4] estimated that the number of pico-scale solar units sold annually in Africa could reach 17 million by 2030.

Figure 3.2 Annual sales of the pico-solar products in Africa in millions of units [3]. (* "branded" refers to products sold under well-known brand names)

Three countries, Kenya, Ethiopia, and Tanzania accounted for two thirds of the sales of pico-solar products between 2014 and 2015 [3] (Figure 3.3). The reasons for the rapid development of the pico-solar industry in Africa, especially in East Africa were summarized by Nygaard and coworkers [2]. First of all, the increasing price of oil has stimulated the development of an alternative energy industry. The price of crude oil rose from 20 dollars per barrel in 1985 to around 100 dollars per barrel in 2015 [5]. Secondly, the price of the solar photovoltaic modules has dropped from over 12 dollars per Wp in 1980 to 0.4 dollars per Wp in 2014 [6]. The price decrease stimulated expansion in production and installation of photovoltaic panels in the region. In addition, the emergence of a Pay-As-You-Go (PAYG) approach contributed to the popularity of pico-solar systems. The PAYG model allows residents in sub-Saharan Africa to purchase a small amount of electricity as they need it instead of investing in a larger more expensive system. A metering technique that regulates the use of electricity was also developed for the region [2].

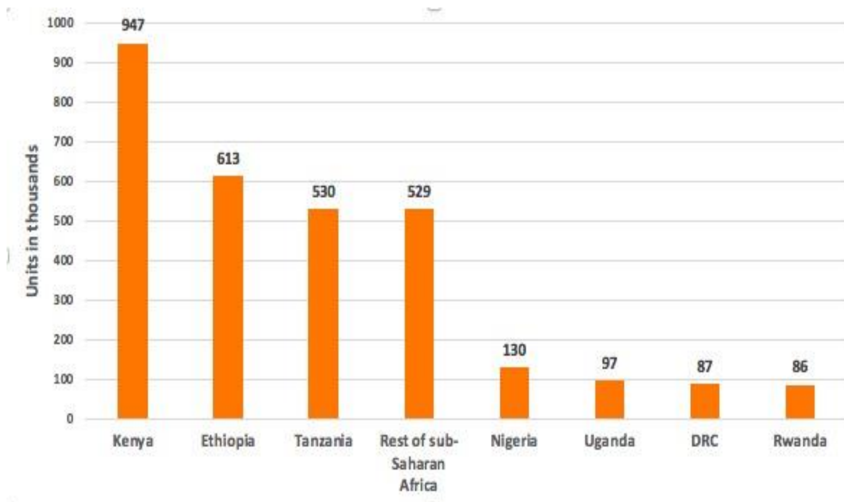

Figure 3.3 Sales of pico-solar products in 2014-2015 in Africa [3]

3.2 The development of the Pico Solar Crop Dryer

The first version of the dryer developed was the Solar Wrap Dryer assembled by Dr. Raman in 2016 at Purdue. The dryer consisted of a tarp, plastic sheets, one or more fans, a 20 W solar panel and a 13 V deep-cycle battery. The solar panel was connected to both the fans and the battery using an inexpensive charge controller. After Dr. Raman developed the dryer, he invited Dr. Stroshine to assist him with evaluating its performance. Maize was placed on a tarp which was covered by a plastic sheet. A small length of the end of the sheet opposite the fan was left open to form a relatively small outlet for air exiting the dryer. The rest of the plastic sheet was sealed by tucking it beneath the tarp so that the air blown into the dryer by the fan inflated the plastic and created a dome or bubble over the drying corn. Tests conducted at Purdue from June to October 2016 indicated that the Solar Wrap Dryer did not dry maize faster than the tarp. It took 4 days to dry 45 kg of maize to 13.8 % moisture content with the solar wrap dryer while it took 3 days to dry the same amount of maize by exposing it to the sun on a tarp. However, the dryer still had the advantage of protecting maize from birds, animals, and airborne contaminants.

Dr. Raman took the dryer to Kenya in October where he and Dr. Patrick Ketiem conducted tests. During the first day of testing an unexpected rainstorm developed while Dr. Raman and Dr. Ketiem were away from the site. When they returned to the site they discovered that although the storm had disrupted operation of the fan, the maize was dry, protected from the rain by the plastic covering. During that visit Dr. Raman and Dr. Ketiem discussed the possibility of drying the maize in trays and using a fan to force the air through the maize.

After Dr. Raman returned from Kenya, he discussed the possibility with Dr. Stroshine. The conventional method of pushing the air up through the trays did not take advantage of the heating of the air that could be achieved by the sunlight that was intercepted by the plastic covering the dryer. One possibility would be to add a tube that absorbed heat from the sun in front of the fan inlet. Dr. Stroshine proposed that the airflow be directed downward through the maize so that the air trapped beneath the plastic that covered the trays would first be heated by the sun. Dr. Raman constructed trays that could be used to test this approach. After an initial test of the dryer in which, similar to the solar wrap dryer, the trays were wrapped with plastic and air was forced from the end of the dryer opposite the fan, Dr. Raman proposed that the underside of the trays be left open so that air could exit anywhere under the drying trays.

The first prototype of this new version of the dryer was built and tested indoors at the ADM Agricultural Innovation Center in January and February of 2017. The 12 volt battery used for the solar wrap dryer provided power to the fan. During the following summer several tests with the new version of the dryer were conducted outdoors. A solar panel was connected to the fans and battery using a charge controller. More details on these tests are included below. The new approach had the following advantages:

1. The downward airflow permits trapping of solar heat above the drying bed so that the air that is forced through the grain is first heated.
2. The downward airflow takes advantage of evaporative cooling of the air which increases its density so that the natural direction of the airflow is downward.

3. Two layers of plastic sheets are used (black beneath clear) providing more effective trapping of the solar energy, as demonstrated in tests with the solar warp dryer conducted in the Fall of 2016.
4. The fan and the 20 W solar panel are low in cost and affordable by the smallholder farmers in Africa.
5. The addition of the 13 V deep-cycle battery connected to the solar panel with a charge controller allows excess energy produced by the solar panel during the time of the day when solar radiation is at its maximum to be stored for later use when solar radiation levels are lower. The dryer only uses renewable energy which makes the operating cost extremely low.

In the first version of the POD, the maize was placed in 5 trays consisting of a wooden frame with a wire mesh bottom. The frames were made from boards that were nominally 2.5 cm thick and 7.6 cm wide (1 inch by 3 inch). The actual dimensions of the surfaced boards were 1.9 cm thick and 7.0 cm wide (0.75 by 2.5 inches). Therefore, these trays were relatively shallow and could hold only approximately 45 kg of wet maize. They were positioned side by side and any space between adjacent trays was sealed using duct tape. The trays were slightly elevated above the ground by wooden “feet” attached to the corners of the tray so that the air could easily exit the maize beneath the trays.

The new POD design was first tested at Purdue in February of 2017 inside the Purdue ADM Agricultural Innovation Building. The room where the test was conducted was heated so that the air that passed through the maize was warm with a low relative humidity. The indoor temperature was around 20°C and the relative humidity was around 16 to 18 %. The POD test was conducted over two days starting from February 2nd, 2017 using 45 kg of shelled maize rewetted to 18.9 % moisture content. The maize was dried for 6.08 hours on the first day and 4.67 hours on the second day. At the end of drying, the average moisture content of samples in the 5 trays reached 13.4 % and the total drying time was 10.75 hours. The average drying rate was 0.5 percentage points of moisture reduction per hour.

After the initial test was completed at Purdue, the POD was sent to KALRO in Kakamega, Kenya where a test was conducted by Dr. Patrick Ketiem. Figure 3.4 shows the POD test in

Kakamega being conducted in March 2017. Written instructions for setting up the dryer were provided and Dr. Raman and Dr. Stroshine discussed these with Dr. Ketiem during an early morning (in West Lafayette) Skype session. Dr. Ketiem collected and analyzed data from this first POD test. A total of 45 kg of shelled maize was dried from 26% moisture content to 13.5% moisture content in 18 hours. A tarp drying test was conducted at the same time as a basis for comparison. The maize on the tarp was dried from 30.6 % moisture content to 15.8 % moisture content in 18 hours. The tarp drying rate, 0.8 percentage points per hour, was slightly higher than the drying rate of the POD which was 0.7 % per hour. However, the POD dryer was able to dry the maize to 13.5 % moisture whereas the tarp was not able to dry the maize below 15.8 % moisture because the ambient air was humid.

Figure 3.4 POD test set up by KALRO in Kakamega, Kenya, March 2017

3.3 Improvements of the Pico Solar Crop Dryer during the Summer of 2017

Dr. Stroshine and Dr. Raman conducted a series of 4 tests for the purpose of improving the performance of the POD design between June 20th and August 7th of 2017. Table 3.1 summarizes the configurations tested and the test results. It was often cloudy during June and July of 2017 and that reduced the solar radiation levels. Therefore, tests were scheduled when the weather forecast predicted that it would be sunny or partly cloudy.

Table 3.1 Summary of POD tests conducted from June 20, 2017 to August 7, 2017

Date	Configuration	Weight of the wet maize (kg)	Initial MC (% w.b.)	Final MC (% w.b.)	Drying Time (hrs.)	Drying Rate (pts/hr.)
06/20	Small trays, dashboard dual fans	50	21.8	12.8	29.5	0.3
06/27	Small trays, dashboard dual fans	50	27.9	13.3	27.0	0.54
07/18	Larger trays, dashboard dual fans	90	25.5	13.5	28.75	0.41
08/07	Larger trays, five Silent Case Fans	90	26.3	12.2	30.6	0.46

In the first test, which started on June 20th, five wooden trays were used. The trays had a length of 76 cm (30 in.), a width of 46 cm (18 in.) and a depth of 4.4 cm (1.75 in.). The dashboard fans that were used for moving the air through the dryer are made for mounting on an automobile dash board and consist of two adjacent fans secured to a pedestal in such a manner that they can be rotated 360 degrees. Direct current electricity is normally supplied to the fans by plugging them into the automobile's cigarette lighter. However, with an adapter they could be connected to the 12 V battery. The fans were placed at one end of the trays. With the five wooden trays, the POD could hold 50 kg of wet maize with an initial moisture content of 21.8%. The test began at 09:30 on the first day and ran continuously (including through the night) through late afternoon of the second day. The total running time was 29.5 hours and the average drying rate was 0.3 percentage points of moisture per hour.

The second test began in the late afternoon of June 27th and continued through the night to the following day. The same five wooden trays and the dashboard dual fans were used. However, maize to be dried in the test had a higher initial moisture content of 27.9 %. Because of the high initial moisture content, drying occurred during night hours as well when the relative humidity of the ambient air was relatively high. This change also increased the average drying rate to 0.54 percentage points of moisture reduction per hour.

During the third and the fourth tests, five larger wooden trays were used. The trays were 86 cm (34 in.) long and 51 cm (20 in.) wide with a depth of 8.9 cm (3.5 in.). These larger trays allowed the POD to carry over 90 kg of wet maize. The third test started in the late afternoon of July 18th

and continued through the night. It took 28.75 hours to dry the maize from an initial moisture content of 25.2% to 13.5%. The average drying rate was 0.41 percentage points of moisture reduction per hour.

In the fourth test, the airflow rate was increased by replacing the dashboard fans with five Apevia 120 mm Ultra Silent Case fans that utilize 12 V DC power. The fans are made for use in cooling electronic equipment such as computers. More fans were used because more airflow was needed in order to adequately inflate the plastic that covered the trays so that it formed a pocket of air above the trays. Air in this “bubble” is heated by the solar radiation striking the plastic and then the air passes through the maize. The five fans were mounted in a rectangular wooden frame that was positioned in the same location that the dual dashboard fan had been located previously, at one of the ends of the rectangular shaped drying bed formed by the five trays. The fourth test began at 17:00 on August 7th with maize re-wetted to 26.3 % moisture content. The fans were shut off at 21:00 and restarted at 12:30 on August 9th. The final average moisture content of the maize was 12.9 %. As shown in Table 3.1, the average drying rate was 0.46 percentage points of moisture per hour.

3.4 Performance tests conducted from September 2017 to May 2019 at Purdue and Kenya

From September 2017 to May 2019, a total of 5 tests were conducted to further improve the performance of the POD. Table 3.2 summarizes the configurations and the results of the tests. More detailed discussions and results for these tests are included in Chapter 4. The test conducted on September 7th, 2017 adapted the plastic drying trays that Dr. Klein Ileleji was using for tests with the multipurpose solar cabinet type dryer he developed for drying maize and other products in Africa. The trays were smaller than the trays purchased from China. Therefore, six trays were needed to provide enough capacity for 90 kg of rewetted maize.

Table 3.2 Summary of POD tests conducted from September 2017 to September 2018 at Purdue, West Lafayette

Date	Configuration	Weight of the wet maize (kg)	Initial MC (% w.b.)	Final MC (% w.b.)	Drying Time (hrs.)	Drying Rate (pts/hr.)
09/07/17	Adapted Dr. Ileleji's plastic trays	90	27.2	13.9	29.1	0.457
09/15/17	Tested with recently harvested maize	122.9	26.8	12.2	24.9	0.586
07/18/18	Changed the location of the fans from the end of the trays to the middle of the trays	90	21.2	12.2	11.6	0.776
08/09/18	Added wire mesh inside the two trays at opposite ends of the dryer	90	21.0	13.4	12.25	0.620
09/12/18	Tested with freshly harvested maize	110	30.1	13.3	24.5	0.686

In the final test of 2017, which was conducted on September 15th, 123 kg of the freshly harvested maize was dried. The number of fans was increased to 7 to ensure the plastic covering the trays was well inflated. In tests conducted with 5 fans, there was inflation of the plastic, but it could easily collapse or fail to fully inflate without assistance. The seven fans were mounted in a wooden frame similar to the one used in the August 2017 test. At the same time that this drying test was conducted, approximately the same amount of maize was dried on a tarp so that the performance of tarp drying could be compared to the performance of the POD.

In November of 2017, 10 plastic trays (780 cm by 510 cm by 10 cm) meant for use in containing baby chickens were purchased from China. They were manufactured by Linqi Shunda Plastic located in Shandong, China. The trays arrived in late December and in February the trays were set up indoors using dry corn to determine the best way to configure the dryer using the trays. The wooden frame with the 7 fans had a length slightly greater than the longest dimension of the plastic trays. Therefore, the location of the fan was changed from the end of the dryer to along one of the sides of the rectangular shaped array of trays. This also changed the air distribution in the dryer. Prior to this change, the maize in the tray on the end of the dryer opposite the fans dried more rapidly than the maize in the tray to which the fan was attached. A likely explanation is that the air that was forced downward through the maize in the tray furthest from the fans had traveled the entire length of the dryer giving it more time to be heated by solar radiation. At the same time, another approach to creating a seal between the plastic and the side of the tray was developed. The edge of the plastic was folded underneath a long wood lath strip and clamped to the side of the tray with a 5 cm (2 inch) binder clip. Three lath strips were used along the side opposite the fan and one lath strip was placed on each end of the rectangular drying bed. Another lath strip the same length as the top of the fan frame was used to secure the plastic to the top of the fan frame. Two slightly shorter wood lath strips were used to secure the plastic to the vertical sides of the fan frame. Because of the thickness of the wood used to make the fan frame, larger spring clamps were used to secure the lath and plastic sheet to the frame. These clamps could open wider than the binder clips. Most of the wood lath strips were approximately 87 cm (34.25 inches) in length. The strips on either side of the fan frame were sized so that when they were put in place, the fan frame was centered along one of the longer sides of the dryer. The shorter strips of wood lath that secured the plastic to the vertical sides of the fan frame were approximately 23 cm (9 inches) long.

During the first two weeks of March, a set of five trays, a wooden fan frame with the seven fans, a set of 10 wood lath strips, binder clips, clamps, wires, and other components of the dryer were packaged and taken to Kenya by Dr. Jake Ricker-Gilbert, the Principle Investigator for the drying and storage component of the Food Processing Lab project. These were given to Dr. Patrick Ketiem from KALRO who set up a test with the dryer in May of 2018. He used the solar panel and battery previously purchased for the solar wrap dryer. He was also provided with written instructions on setting up the dryer.

Dr. Ketiem, who works for KALRO, conducted a test with the POD on May 15th and 16th, 2018. It took 16 hours to reduce the moisture content of shelled maize from 21 % to an average of 14.7 % over two calendar days. More detailed results are included in Chapter 5. On July 18th, 2018, a test of the dryer constructed using the plastic trays and the wooden fan frame with 7 fans was conducted at the ADM building on Purdue’s campus. The fans were located along one side of the rectangular drying bed, as described above. For this test Hobo sensors (Onset Computer

Corporation, Bourne, MA) were used to measure the temperature and relative humidity of the air entering the fan, the air on the surface of the maize in the tray at the center of the fan frame, the air on the surface of the maize at one end of the dryer, and air exiting beneath the tray that was at the end of the dryer. While this test was being conducted it was decided that the wooden fan frame could be replaced with one made from aluminum. Plans for the frame were prepared and a prototype was constructed in the ABE Department's shop. This aluminum frame was used for the next test that was conducted on August 9th. In addition, wire mesh was placed inside the 2 drying trays on opposite ends of the dryer) in order to increase airflow resistance and slow down the air that was passing through the end trays. It was expected that this might even out the moisture content of the maize in the 5 trays. More details on the test are included in chapter 4.

After testing the aluminum fan frame several slight changes were made to make it easier to tape the frame to the plastic trays and to allow for minor adjustments in the height of the frame above the ground. This newly designed fan frame was used for the last test of the summer, which used maize recently harvested by hand from Purdue's ACRE and shelled at the Indiana Corn and Soybean Innovation Center using a sheller equipped with rubber rollers. The quantity of corn shelled was sufficient to dry approximately 130 kg in the POD and about the same amount on a tarp so that the drying rates of the two methods could be compared. More details on this test are included in chapter 4.

During the summer of 2018 Dr. Stroshine and Dr. Raman felt that the POD had been developed to the point that it was ready to be tested at several locations in Africa. This would allow the project the opportunity to obtain feedback from farmers and others who would want to make use of the dryer. It was also the last year of the Food Processing Laboratory project and the leadership of the project was anticipating that drying tests with the POD would be conducted during that last year. The resources were available to construct five dryers for testing in Kenya and to send the five dryers to Dr. Patrick Ketiem at KALRO for testing. Twenty five trays were ordered from the manufacturer in China and shipped directly to Nairobi. At the same time, the other components needed to assemble the dryers were prepared at Purdue University. Five aluminum fan frames were built, at least 5 sets of plastic sheets were cut, wood lath strips were cut to the proper length, and wires for connecting the fans, batteries and solar panels were prepared. Binder clips, duct tape, and the other supplies were purchased. These were bundled into two packages that were taken to Nairobi by Dr. Jennifer DeBoer, a professor in Engineering Education, who was traveling to Nairobi for a meeting in early September of 2018.

Although the shipment of trays arrived in Nairobi about September 24, 2018 it did not clear customs in Kenya until October 22nd, 2018. The airport charged fees for storing the trays and the total charge for clearing customs was $821.50. The trays were placed in the office of Mr. Hugo DeGroot in the CIMMYT facility in Nairobi. Dr. Patrick Ketiem picked up the trays on October 26th. Dr. Ketiem had visited Purdue University September 21 through the 28th to attend the conference entitled "Innovations in Agriculture: Scaling Up to Reach Millions" sponsored by Purdue University and the African Development Bank. During his visit he met with Dr. Stroshine and Ms. Mingyuan Chen. They demonstrated how to set up the POD. In addition, Dr. Stroshine was able to give Dr, Ketiem a cash advance that allowed him to purchase solar panels and batteries when he returned to Kenya. He was also able to use some of the funds to cover the cost of the first POD test he conducted in Njoro in Nakuru County, Kenya.

The project director gave approval for transfer of additional funds to CIMMYT in December of 2018. However, the necessary approval from CIMMYT Headquarters in Mexico was not provided until February of 2019 and funds were finally transferred on February 21st of 2019. After several days of searching, Dr. Ketiem was able to locate several batches of maize with a moisture content of 26% or above. He began conducting tests the week of March 11th, 2019. He was able to finish three tests before the onset of heavy rains for the 2019 season. In addition, he was no longer able to find high moisture maize. For that reason, the test that he intended to conduct in Bungoma was not conducted.

When Dr. Ketiem conducted the last of the three tests in Nandy County he also dried part of the sample of maize by exposing it to the sun on a tarp. This served as a comparison with a common method of drying maize used in Africa. Table 3.3 summarizes the locations and results of the Kenyan tests. The detailed descriptions and results are given and discussed in Chapter 5 of this thesis.

Table 3.3 Summary of POD tests conducted in November, 2018 and March 2019 in Kenya by Dr. Patrick Ketiem. Tests planned for Bungoma County were not conducted.

Locations	Initial MC (% w.b.)	Final MC (% w.b.)	Drying Time (hrs)	Drying Rate (pts/hr)
Njoro Nakuru (11/18)	30	13.3	20	0.835
Trans Nzoia (3/19)	29	13.9	26	0.581
Uasin Gishu (3/19)	26	12.6	16	0.838
Nandi (3/19)	36.4	13.0	24	0.975

While Dr. Ketiem was conducting tests in Kenya, two tests were conducted at Purdue with the help of Mr. Zifan Zhu, an undergraduate student majoring in Agricultural Systems Management, who was working on a special problems course with supervision by Dr. Stroshine. The first test conducted was a “normal” drying test that was conducted indoors. It was hypothesized that the difference in drying rate between the center trays and the trays on the ends of the POD was caused at least in part by solar radiation striking the plastic at different directions during the course of a day so that the ends received more total solar radiation during a given day than the middle. Also, the air reaching the end trays had more time to be heated by the radiation. By conducting the test inside the effect of solar radiation was eliminated. The moisture content of the trays was nearly uniform. This is evidence that the solar radiation does contribute to the variation in drying rate among the trays. Dr. Stroshine suggested that orienting the dryer with the long dimension in the north-south direction would reduce the moisture variation among the trays.

For the second test, two dryers were set up simultaneously. In this test, two layers of wire screen were put in each tray of one of the dryers. It was hypothesized that the wire screen would increase the airflow resistance and slow down the air that was passing through the trays. It was also expected that the pressure inside the dryer with wire screen would be higher. However, the two layers of screen increased the pressure by a very small amount (from 3.2 Pa to 3.4 Pa) and had no detectable effect on the drying rate.

3.5 References

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CHAPTER 4. EVALUATION OF THE PERFORMANCE OF THE PICO SOLAR CROP DRYER AT PURDUE UNIVERSITY, WEST LAFAYETTE

This chapter documents, analyzes, and discusses five tests conducted at Purdue University from September 2017 to May 2019. It describes how the POD was configured and the test procedures and it summarizes and analyzes the data gathered during and after each of the tests.

4.1 Experiment configuration and procedure

4.1.1 Experiment configuration

Figures 4.1 and 4.2 show the configuration of the POD and illustrate how the POD dries the material. The material to be dried is placed in a series of plastic or wooden trays which are covered with plastic sheets. The edges of the sheets are clamped to the fan frame and the trays using wood lath strips and either spring clamps or binder clips or a combination of the two. The plastic covering consists of two layers with a black sheet on the bottom and a clear plastic sheet on top of that. The black sheet is effective in absorbing solar radiation because of its color. The clear plastic was added as a result of the advice from one of Dr. Raman's colleagues. It reportedly reduces the loss of the energy absorbed from solar radiation by reducing the amount of reflection and re-emission. Solar radiation striking the plastic heats the air in the chamber formed by the plastic sheets and the surface of the shelled maize that is contained by the trays. The trays have holes or openings in the bottom (wooden trays have wire mesh bottoms; plastic trays are manufactured with holes in the bottom) allowing the air that has passed through the maize to escape from the POD. The trays are placed with their longer sides together so that a rectangular drying bed is formed. The wooden trays are 86 cm by 51 cm (34 inches by 20 inches) forming a drying bed that is approximately 86 cm by 255 cm (34 inches by 100 inches). The plastic trays purchased from China are 78 cm by 51 cm (31 in by 20 in) and form a rectangular drying bed 78 cm by 255 cm (31 inches by 100 inches). Any gaps between the trays are sealed by placing a single strip of duct tape over the edges of the two trays that are touching each other. The trays are elevated about 5 cm (1.97 in.) using legs (wooden trays) or, for the plastic trays, by supporting them on wood boards that are nominally 5 cm by 10 cm (2 inches by 4 inches, referred to as two by fours). The air space beneath the trays allows the air that is forced downward through the drying bed to easily escape into the atmosphere.

Seven small fans of the type used for cooling electronics are used to move air through the dryer. The fans are 120 mm Ultra Silent Case Fans made by Apevia Corporation (Taipei, Taiwan). During the tests in 2017 and the first several tests in 2019, the fans were secured in a wooden frame. Since July of 2018, the fan frame has been made from aluminum. The fan frame was attached to the dryer with duct tape which covers any gaps between the frame and the side of the tray. The height of the frame can be adjusted slightly (a little more than 6mm) by loosening wing nuts on the base of the fan frame. The aluminum frame has a metal “lip” on it that is secured to the top edge of the three middle trays of the set of 5 using duct tape to seal any gaps that might allow air to escape instead of being forced through the bed of shelled maize. The air trapped between the plastic and the bed of maize is heated by solar energy. It then moves from the top surface of the maize through the maize and exits below the tray. This air movement is aided by evaporative cooling. The blue line and arrows in Figure 4.1 show the direction of air movement.

Power is supplied by a 12 volt 20 Watt or 30 Watt Solar Panel (Newpowa Corporation, Las Vegas, Nevada) and a 12 volt 7-ampere hour lead acid battery (EXP 1270, Expert Power, Paramount, California). A CMP 12 charge controller (Koneze Corporation, Hong Kong) is used to allow the energy generated by the solar panel to be distributed to both the fans and the battery. If the solar panel produces excess energy, it is used to charge the battery. If the solar panel cannot produce enough energy to drive the fans, then the battery supplies the additional energy that is needed. If the plastic is secured properly with sufficient flexibility, when air is forced through the trays it will inflate the plastic forming a dome or bubble over the trays as shown in Figure 4.2.

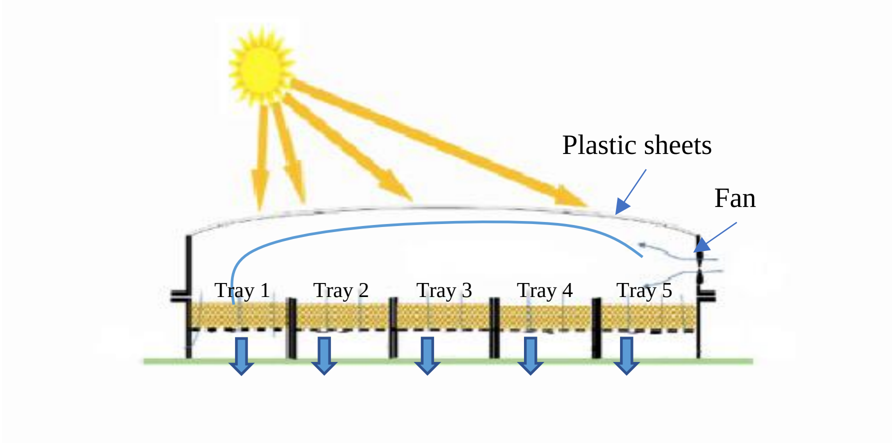

Figure 4.1 Sketch showing solar heating of the air and the direction of airflow in the POD

Figure 4.2 Picture of the POD configured with wooden trays

4.1.2 Experimental procedure

The POD performance tests were set up on the gravel covered driveway and parking area north of the ADM Agricultural Innovation Building. The building is located on Ahlers Drive on the south end of the Purdue campus near the Materials Management and Distribution Center. If the outdoor conditions were not favorable for solar heating of the air in the dryer, such as during the winter, the tests were set up inside the ADM building where the air was relatively warm and had a low relative humidity. Before setting up the test outside, the ground was swept to remove any large stones and to smooth the area where subsequently a tarp was placed on the ground. Five wooden trays were placed adjacent to each other along their longest sides. Any gaps between the sides were sealed by placing a strip of duct tape on top of the sides of both trays. The fan was put in place and attached to the trays with duct tape. Next, shelled maize was added to the trays, an initial sample was taken from each tray (see below) and the plastic was placed over the top of the trays. The plastic was held in place with binder clips and wood lath strips, as described previously. Next, the solar panel and battery were connected to the fans. When the fans started, the plastic inflated forming a dome over the trays.

The tests with freshly harvested maize (Test 20170915 and Test 20180912) used maize harvested by hand from a field at Purdue's Agronomy Center for Research and Extension (ACRE). Maize was shelled using an Almaco Maizer (MAZ T15077) and Almaco Orbital Seed Sizer (SBG T15078) available at Purdue's Plant Phenotyping Facility, which is also located at ACRE. The freshly harvested maize was relatively high in moisture content, between 25 % and 30%. The other tests were conducted using re-wetted maize. Samples were re-wetted in the grain lab located in the one story portion of the ABE building before May 2018 or in room B-124 of Lily Hall after that (when the one story portion of the ABE building was demolished). The re-wetting process involved adding the appropriate weight of water calculated to bring the dry sample to the target moisture, which was usually about 21%. After the water was added, the maize was mixed with a barrel roller for 4 to 15 hours.

Tests began in the morning and were discontinued each evening with the exception of the first three tests conducted in the summer of 2017. Tests were temporarily stopped so that samples could be taken from the trays at intervals of approximately 4 hours. Before taking the samples, maize in each tray was thoroughly mixed by stirring with hands and sometimes arms immersed in the grain occasionally up to the elbows. A small metal scoop was used to remove a sample from each tray. The scoop was pushed into the maize in approximately 8 locations in different regions of the trays (Figure 4.3) so that approximately equal amounts were taken from all the regions. In order to reduce the amount of weight loss due to sampling, only around 300 grams to 400 grams of maize were taken each time. The samples were placed in small double plastic bags (usually a double zipper sandwich bag within a one quart double zipper bag) and sealed until they could be tested using the Steinlite Moisture Meter. The date, time and tray from which the sample was taken were written on a small slip of paper that was subsequently placed between the two bags. After determining the moisture content using the Steinlite Moisture Meter, the samples were stored in the lab, or in a refrigerator if moisture was above 15%, until an oven moisture test could be conducted.

Figure 4.3 Sampling regions for each tray

For each of the tests conducted in September with freshly harvested maize, a sample of approximately the same weight and initial moisture content was dried on a tarp so that the drying rate could be compared to the POD drying rate. The tarp used in the test was 590 cm long (232 in.) and 90 cm wide (35.4 in.). The entire sample that was harvested and shelled was weighed on a platform scale, and placed in a pile on the concrete floor of the ADM building. The maize in the pile was turned and mixed using shovels. Then slightly more than half the sample, as determined by weighing, was placed in 44 gallon plastic trash containers and moved to the dryer. The remainder of the maize was spread evenly in a thin layer on the tarp, which was located next on the POD on the north side of the ADM Agricultural Innovation Center. Figure 4.4 is a photo of a tarp being used to dry maize in September 2018. The tarp was divided into 4 regions of approximately the same size for purposes of sampling. Samples were taken from each region using the small metal scoop and placed in bags along with labels. Their moisture was determined using the Steinlite moisture meter and then they were stored until an oven moisture test could be conducted. The moisture contents of the four samples were averaged to give the moisture content of the maize on the tarp at the time of sampling.

Figure 4.4 Maize drying on a tarp

The oven moisture content tests were conducted according to the procedures specified for whole kernel air oven tests in ASABE Standard S352.2 [1]. The samples were poured into a small spouted sample pan and thoroughly mixed by hand. Three random subsamples of approximately 15 g were taken from the sample pan and placed in small metal moisture dishes that had metal lids. The dishes were weighed on an electronic balance (always with the lid on) before and after the maize was added. Then the lids were removed and the dishes were placed in a forced convection air oven for 72 hours at 103°C. The moisture meter and oven were also used to determine the initial moisture content of the maize on samples taken before drying and from the trash cans in which the maize was placed at the conclusion of the drying test.

To better evaluate the performance of the dryer, temperature and relative humidity measurements were taken and recorded periodically during the drying tests. Temperatures in two of the drying trays and the temperature of the air entering the fans and near the drying trays were determined using indoor-outdoor thermometers. The outdoor sensors of two thermometers were placed inside the dryer on the surface of the shelled maize. Readings were taken at approximately 2-hour intervals.

The relative humidities of the air entering the fans and the air exiting the trays were determined by using a Psychro-Dyne battery operated psychrometer (currently available from Paul N.

Gardner Company, Pompano Beach, Florida) to measure wet and dry bulb temperatures. The Psychro-Dyne was placed first at the fan inlet, and then beneath the middle and two end trays. When it was placed beneath the trays, it was positioned in the gap between the ground and the bottom of the tray. A board was usually placed beneath the Psychro-Dyne so that the inlet to the instrument was closer to the bottom of the tray and was drawing air that was flowing from the bottom of the trays. Measurements were made at approximately 2-hour intervals. Relative humidity was determined from the wet bulb and dry bulb temperatures using a psychrometric chart calculator program found on the web [2]. When the relative humidity measurements were taken, the battery was temporarily disconnected from the charge controller and battery voltage was measured using a digital multimeter. Files containing solar radiation data during the time when the test was being conducted were downloaded from the website supported by the Purdue Applied Energy Laboratory. The laboratory has instruments to measure solar radiation and other weather data on the roof of Purdue's Knoy Technology Building which is located approximately 1 mile from the ADM building [3].

Beginning in July of 2018, four Hobo data loggers were used in the tests to automatically record the temperature and relative humidity at 5 minute intervals during the drying test. One sensor was suspended in front of the fan inlet, another was placed on the surface of maize in the middle tray, the third was placed on the surface of maize in one of the end trays, and the last was placed beneath the end tray. The sensor suspended in front of the fans was shaded with a strip of cardboard so that solar radiation did not strike it directly. The sensor beneath the tray was placed on a board so that it was held closer to the air flowing from the bottom of the end tray. The measurements taken during the tests are summarized in Table 4.1.

Table 4.1 List of measurements involved in performance tests

Measurement	Equipment	Location	Frequency
Air temperature	Thermometers, Thermocouple	Fan inlet, 2 end trays, middle tray.	~2 hours interval
Dry bulb, wet bulb temperature	Psychro-Dyne	Fan inlet, 2 end trays, middle tray	~2 hours interval
Temperature and relative humidity	Hobo Sensor	Fan inlet, 2 end trays, middle tray.	~5 minutes interval
Solar radiation	Data from: http://technrgl.ecn.purdue.edu	Knoy Lab, Purdue	~15 minutes interval
Moisture content	Steinlite, Oven	Representative samples of each tray	~4 hours interval
Battery voltage	Digital Multimeter	Battery	~2 hours interval

4.1.3 Moisture content – definitions and formulas

The moisture content of cereal grains and oilseeds is determined on the basis of the weight of water relative to the total weight and is usually expressed as a percentage [4]. There are two commonly used methods to represent the moisture content: wet basis and dry basis. In this thesis, the wet basis moisture content is used unless otherwise specified. The moisture content on a wet basis is obtained by dividing the weight of water in the material by the total weight of the material [Equation (4.1)].

$$\%\, MC_{wb} = \frac{W_w}{W_w + W_d}\,(100\%) \qquad (4.1)$$

Where, MC_{wb} is the moisture content on a web basis, W_w is the weight of water, and W_d is the weight of the dry matter.

The moisture content on a dry basis is the weight of water relative to the weight of dry matter in the material. It can be calculated from MC_{wb} using Equation 4.2.

$$\%\, MC_{db} = \frac{MC_{wb}}{100 - MC_{wb}}\,(100\%) \qquad (4.2)$$

Where, MC_{db} is the moisture content on a dry basis.

The average drying rate was used to quantify the drying rate of the POD. The average drying rate for a period of time, t, was calculated using Equation 4.3.

$$DR = \frac{MC_{initial} - MC_{final}}{t} \qquad (4.3)$$

Where, DR is the average drying rate of the product in percentage points per hour, $MC_{initial}$ is the initial moisture content of the product, MC_{final} is the final moisture content of the product, and t is the drying time in hours.

4.2 Results and Discussion

4.2.1 Test conducted on September 7th 2017 at Purdue (Test 20170907)

4.2.1.1 Introduction

The objective of Test 20170907 was to adapt the dryer configuration so that it used trays already available from the market. The trays used in this first test were purchased from Willow Way LLC in Hagerstown, Indiana by Dr. Klein Ileleji for use in testing the multi-purpose solar dryer he developed [5]. The trays were 77 cm (30.3 in.) long and 41.3 cm (16.3 in.) wide, with a height of 11.8 cm (4.6 in.) (Figure 4.5). These stackable trays were originally made for drying soaps, chocolates and other products. Six trays were used in order to provide sufficient capacity for 90 kg of wet maize. As shown in Figure 4.5, the sides of the tray were shallower in the middle than on the corners which limited the capacity of the tray and would have made it more difficult to secure the plastic to the sides of the trays. Therefore, modifications were made to the trays. Wooden inserts were fashioned to fit into these “notches” giving the trays a depth of 11.8 cm (4.6 in.) on each side.

Five of the Apevia 120 mm Ultra Silent Case fans which utilize 12 V DC power were used in the test. A wooden frame was made in which to mount the fans. The wooden inserts placed in the “notches” of the trays also facilitated attachment of the wooden fan frame and the plastic sheets that covered the trays.

Figure 4.5 Soap drying trays used in Test 20170907

Drying was started at 18:05 pm on September 7th, 2017 with 90 kg of maize that had previously been rewetted to 27.2% moisture content. The test continued through the next day at 18:30. At this point, the fans were turned off and samples were taken from each tray. The average moisture content of the 6 trays was 16.1%. Fans were restarted at 10:40 on September 9th and drying continued until 16:30 when the average moisture content of the maize was 12.9%. The total drying time was 29.08 hours and the average drying rate was 0.45 percentage points of moisture reduction per hour.

4.2.1.2 Results and discussion

Figure 4.6 is a plot of the moisture contents of the shelled maize in each of the trays at the times when samples were taken. The horizontal axis only shows the hours the dryer was operating. The vertical line in the plot shows the break where the drying was stopped in the evening hours of September 8th. The plot also shows the variation of the moisture content among different trays. The samples taken from Tray 1, which are plotted in dark blue, had the highest final moisture content of 14.7%, while the samples in Tray 6, plotted in green, had the lowest final moisture content of 12.9%. The final average moisture content was 13.9% with a standard deviation of 5.49.

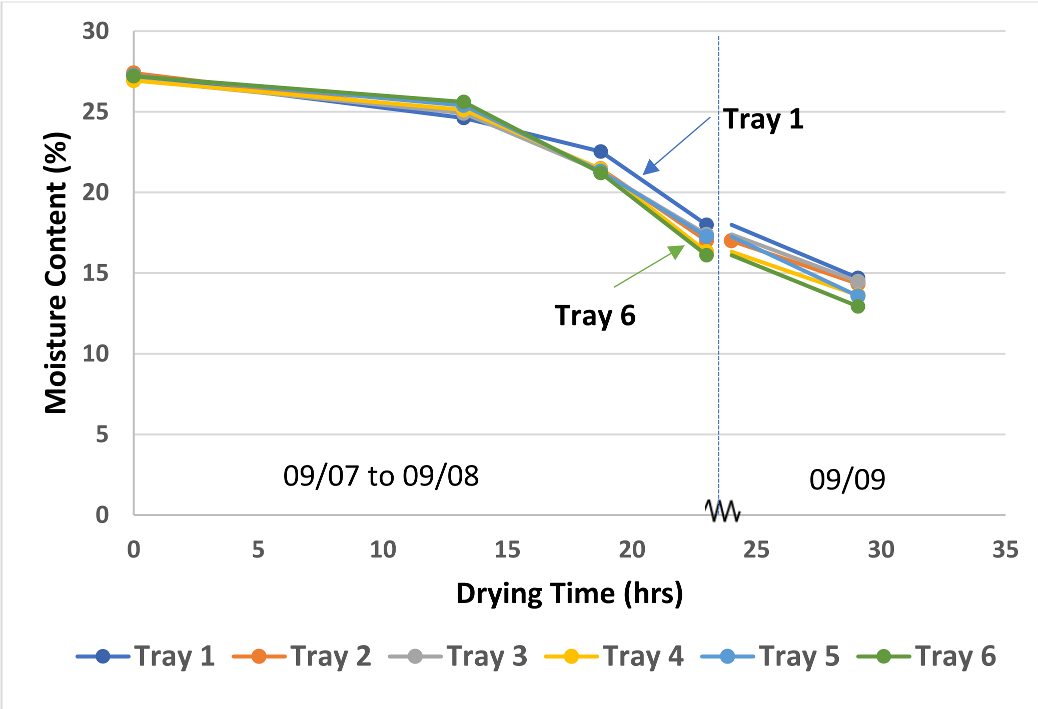

Figure 4.6 Plot of the moisture contents of samples from the six trays during Test 20170907

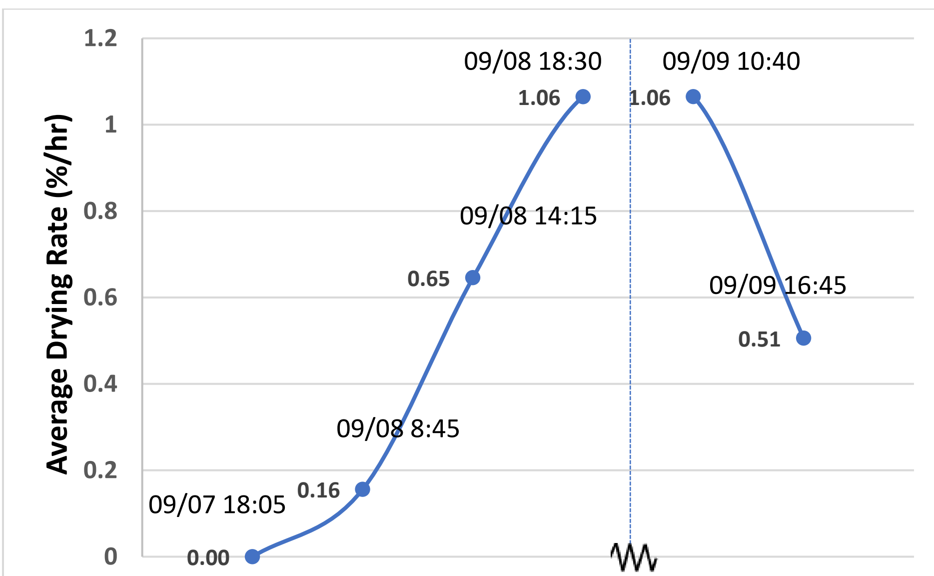

Figure 4.7 Drying rates for time intervals between collection of samples for Test 20170907

Figure 4.7 shows the average drying rate for each period between samplings. The drying rate reached its maximum value during the afternoon when the ambient air temperatures and solar radiation were near their maximum values for the day. One interesting observation is that the maize dropped from 27.2% to 25.1% between September 7th at 18:05 and 08:45 on September 8th giving a drying rate of only 0.16 percentage points per hour. During this period, the ambient air relative humidity reached 100 % on September 7th at 24:00 and remained at 100 % until 09:00 on September 8th. This illustrates the importance of running the fans only when the relative humidity of the drying air is low enough to achieve drying. Less battery power would have been consumed if the fans had been stopped between 23:00 on September 7th and 09:00 on September 8th.

4.2.2 Test 20170915 conducted on September 15th 2017 at Purdue

4.2.2.1 Introduction

The objective of Test 20170915 was to evaluate the performance of the POD with freshly harvested maize and compare it with drying on a tarp. The maize was harvested by hand from a field at Purdue's Agronomy Center for Research and Extension (ACRE). Maize was shelled using an Almaco Maizer (MAZ T15077) and Almaco Orbital Seed Sizer (SBG T15078) available at Purdue's Plant Phenotyping Facility, which is also located at ACRE.

Ears were harvested during the evening of September 14th and shelled the morning of September 15th. As soon as shelling was completed, the samples were transported to the ADM Agricultural Innovation Center, where the drying test was conducted. The total weight of maize was 240.8 kg. The maize was placed in a pile on the concrete floor in the ADM building and mixed with a shovel by pushing the shovel into the pile and then lifting it upwards and dumping the contents of the shovel on the top of the pile. After the sample was mixed, approximately half, 118 kg, was weighed in a 44 gallon plastic trash container on a platform scale and placed on a plastic tarp in the sun for drying. The remaining 122.9 kg were placed in the 5 wooden trays of the POD.

The 5 wooden trays used in this test were the same as those used in tests 20170718 and 20170807. Those tests are not discussed in this thesis because they were conducted before the author joined the project. The trays were 86 cm (34 in.) long and 51 cm (20 in.) wide with a depth of 8.9 cm (3.5 in.). The POD and the tarp are shown in Figure 4.8. The tray that was closest to the fans was assigned the number 1, and the tray furthest from the fans was assigned the number 5. In this test, a total of seven 120 mm Ultra Silent Case fans were used to provide a greater air flow rate. A wooden frame was constructed to enclose them so they could be held in place at the end of the dryer and so there could be more effective sealing of the plastic around the fans. It was relatively easy to clamp the plastic to the wooden frame.

Figure 4.8 The 123 kg of maize in 5 wooden trays (left); maize drying in POD (foreground) and on a tarp (right background)

The tarp test was started at 11:30 on September 15th and the POD test began almost an hour later, at 12:20. The initial moisture content of the maize was 26.8%. The maize on the tarp was stirred by hand at intervals of 2 to 4 hours. Stirring continued at these intervals all the time the maize was being dried on the tarp. Drying on the 15th stopped at 20:30 at which time the POD fans were stopped and the maize on the tarp was collected and placed in a 44 gallon plastic trash container that was moved inside the ADM building overnight, while the POD filled with maize remained outside the building. The next morning, September 16th, the maize in the plastic trash containers was returned to the tarp and drying was resumed at 09:30. Drying continued through 18:30. At this point, the average moistures of maize on the tarp and in the POD were 16.9% and 14.9%, respectively. Rain was predicted for the next several days, and after the rainy period was supposed to be over, personnel were not available to conduct the test. Therefore, the maize in the trays was placed in a 44 gallon plastic trash container and the maize from the tarp was placed in another 44 gallon plastic trash container. Drying was not resumed until September 21st at 9:30

(Tarp) and 10:15 (POD). Drying stopped at 19:00 (Tarp) and 19:15 (POD). The maize in the POD trays had an average moisture content of 12.2%, while the maize on the tarp was at 14.5% moisture content. Therefore, although the POD test was completed, drying on the tarp was resumed on September 22nd at 10:15 and stopped at 16:40. The final moisture of maize on the tarp was 12.5%.

4.2.2.2 Results and discussion

Figure 4.9 shows the moisture contents of the shelled maize in each of the trays and on the tarp at the times when samples were taken. The vertical lines show the approximate times when the test was stopped overnight. The sampling points for the trays and tarp occurred at nearly the same time on the first day of drying, September 15th. However, on the second day, September 16th, the samples were taken at different times, so there is a difference in the number of hours of drying at which a moisture content is shown on the graph of the results.

From the end of September 16th to September 21st, there was a slight incremental increase in the moisture content of the samples taken on the 21st compared to the moisture content of the samples taken for the tarp at the conclusion of drying on the 16th, when the maize was collected and stored in the plastic trash containers. The test was resumed almost a week later. For the samples taken from the POD, the maize equilibrated so that moistures of samples taken from each of the POD trays were nearly identical when the test was resumed on September 21st. The lines for tray 4 are dashed between hours 8.5 and 15.9 because it was suspected that the sample labels were exchanged when their moisture content was being determined using the Steinlite moisture meter shortly after the samples were taken. It was assumed that the sample moisture contents were switched so that the drying curve showed a steady decline in moisture that was similar to the decline observed for the other trays.

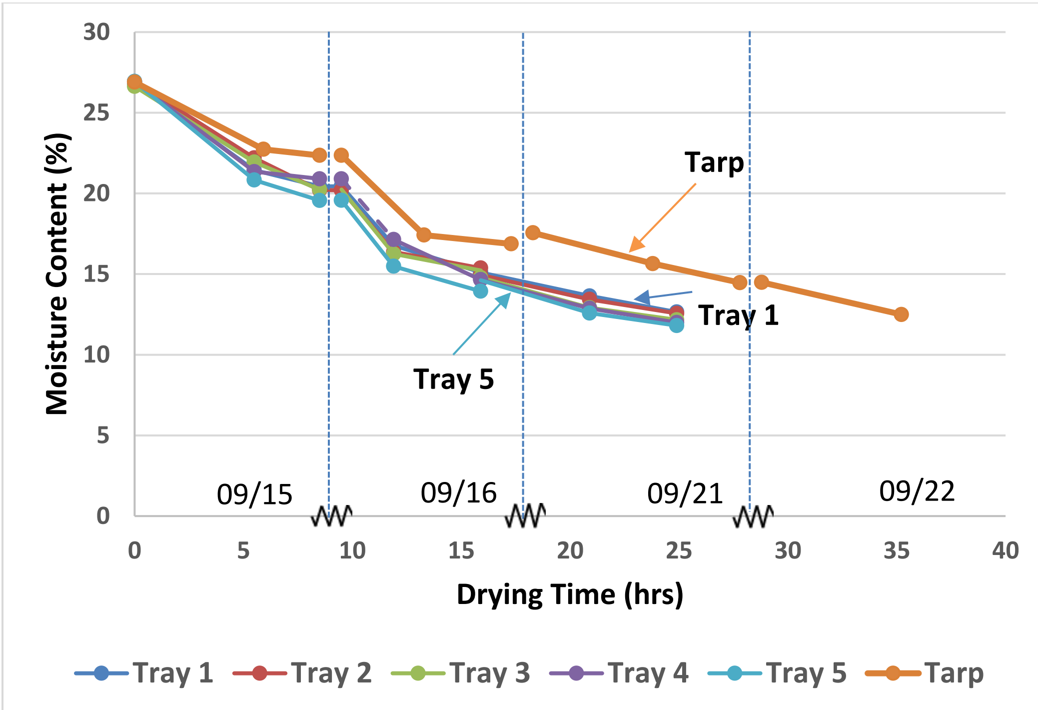

Figure 4.9 Moisture contents for Test 20170915

It took a total of 24.9 hours of drying for the maize in the POD to reach a final average moisture content of 12.2% from an initial moisture content of 26.8%. The average drying rate was 0.59 percentage points per hour. It took a total of 33.2 hours for the tarp to reach its final moisture content of 12.5% with an average drying rate of 0.43 percentage points per hour. The average drying rate of the POD was 1.37 times the drying rate on the tarp disregarding the fact that the final moisture content of the maize from the POD was 0.3 percentage points lower.

A variation in moisture content of the samples taken from the different trays can be observed in Figure 4.9. Tray 1, which is designated with a dark blue line, had the highest final moisture content of 12.6%, while Tray 5 which is plotted in light blue, had the lowest final moisture content of 11.8%. The standard deviation for the final moisture contents of the 5 trays was 0.36. The temperatures in and near the dryer were measured with indoor-outdoor thermometers. The sensors at the ends of the thermometer wires (outdoor sensors) were placed inside the dryer on the surface of the maize in the centers of trays 1 and 5. The ambient temperature was also recorded from the indoor reading of each thermometer and from another thermometer positioned in the shade near the air inlet for the fans. The temperatures are shown in Figure 4.10. The temperature of the air above the maize in Tray 5 was heated between 0 and 8.5 °C during the time when the POD was drying the maize. Heating was only 0 to 4 °C in the morning when the test was started and was greater during the afternoon. Most of the time the temperature on the maize surface in tray 5 was between 2.0 and 4.5 °C higher than the temperature on the surface of the maize in tray 1. A possible explanation is that Tray 5 was the furthest from the fans so that the air had to travel further to the reach Tray 5 and there was more time for it to be heated by the solar radiation. Tray 1 was near the fan and there was little time for solar heating of this air before it traveled through the bed of shelled maize. Near the end of the day when the angle of the sun was such that the end of the dryer near the fans received more solar radiation than the rest of the dryer, the temperatures on trays 1 and 5 were nearly the same. The higher temperature of the drying air apparently contributed to the faster drying rate for tray 5, which is shown in Figure 4.10. For measurements taken early or late in the day, the temperature of the maize inside the dryer was lower than the ambient temperature, presumably because the air temperature dropped slightly as a result of evaporative cooling.

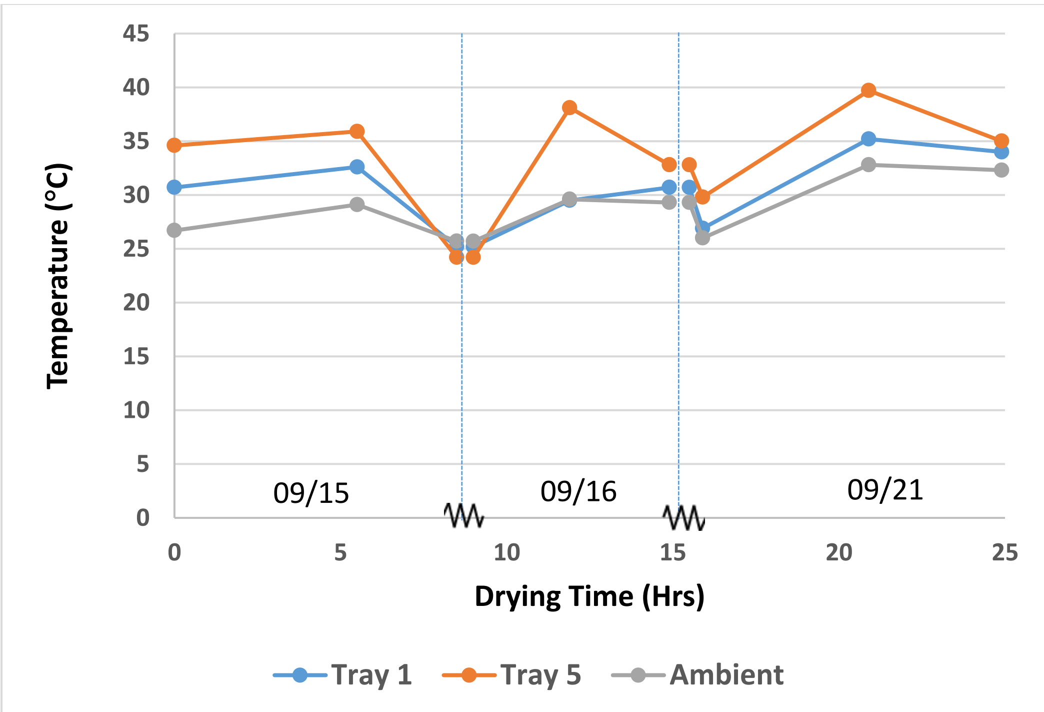

Figure 4.10 Graph of temperatures at various drying times during POD Test 20170915

The relative humidity of the air entering the fans and the air exiting the trays was measured using a Psychro-Dyne battery operated psychrometer. The instrument was placed under both sides of trays 1, 3 and 5. The relative humidities were determined from the wet bulb and dry bulb temperatures using a program available on the internet (http://sugartech.co.za/psychro/) and are plotted versus drying time in Figure 4.11. The relative humidity of the exhaust air was between 2 and 8 percentage points greater than the relative humidity of the ambient air entering the trays. This observation confirmed that the air passing through the system was able to remove moisture from the maize and that drying was taking place in the POD.

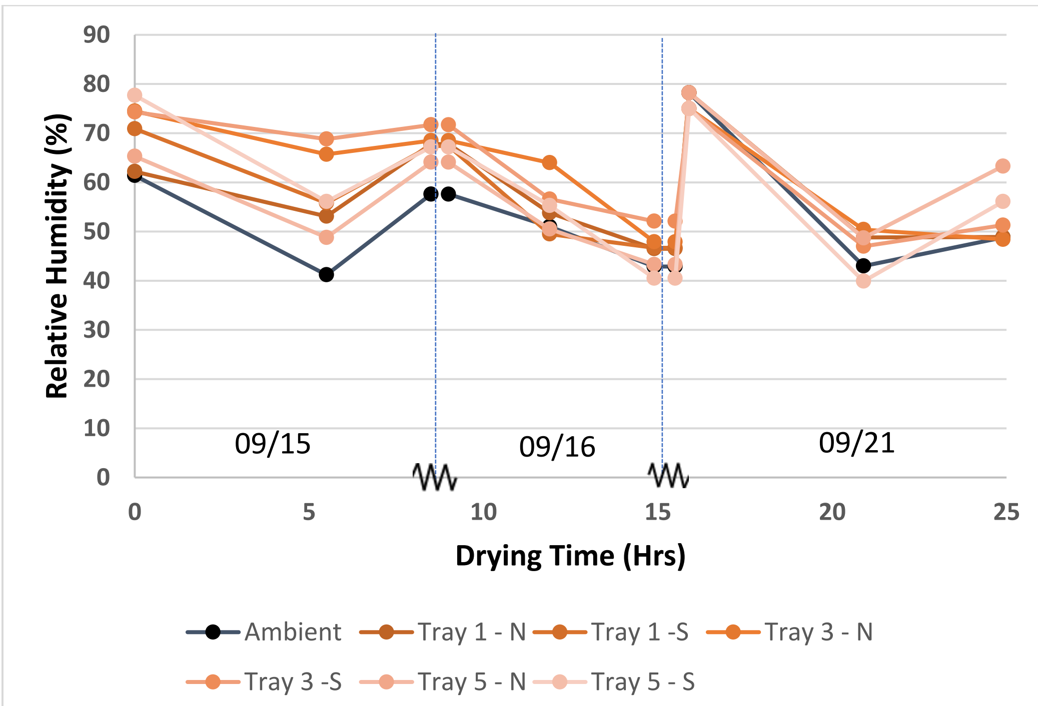

Figure 4.11 Graph of relative humidity versus drying time for POD Test 20170915

Figure 4.12 shows the ambient temperatures and relative humidities of the ambient air recorded at the drying site along with the data collected from Purdue Applied Energy Laboratory with sensors located on the roof of Purdue's Knoy Hall of Technology. Results showed that the measured data (referred to as "Recorded" below) were consistently slightly higher than the Knoy Hall data.

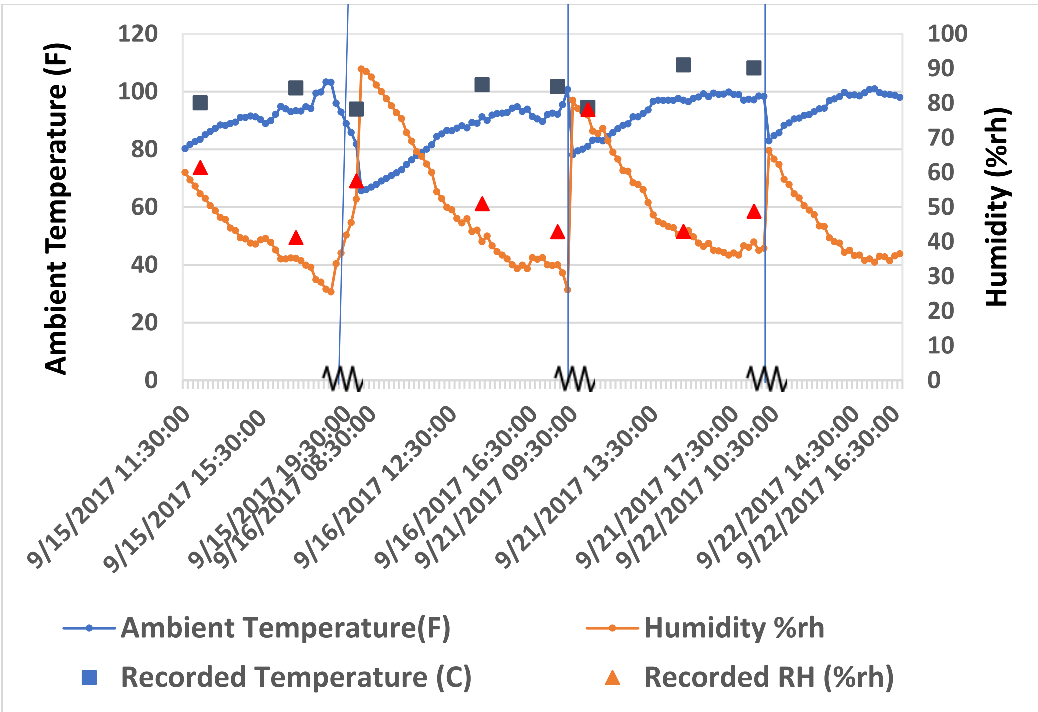

Figure 4.12 Temperatures (blue squares) and relative humidities (orange triangles) measured on the site of the drying test and at the Knoy Hall Applied Energy Laboratory (blue lines and orange lines, respectively)

Figure 4.13 shows the drying rates for the average of the 5 trays and for the tarp calculated for the time intervals between sampling times. Drying was fastest for both the POD and the tarp during the morning through afternoon of the first and second drying days when the maize moistures were high and air conditions were excellent for drying (low RH and elevated temperatures). Drying rate slowed considerably after the second day of drying when moistures were below 16%. The drying rate of the POD was between 1.09 and 1.28 times the rate for the tarp except when the end of the drying period was approached.

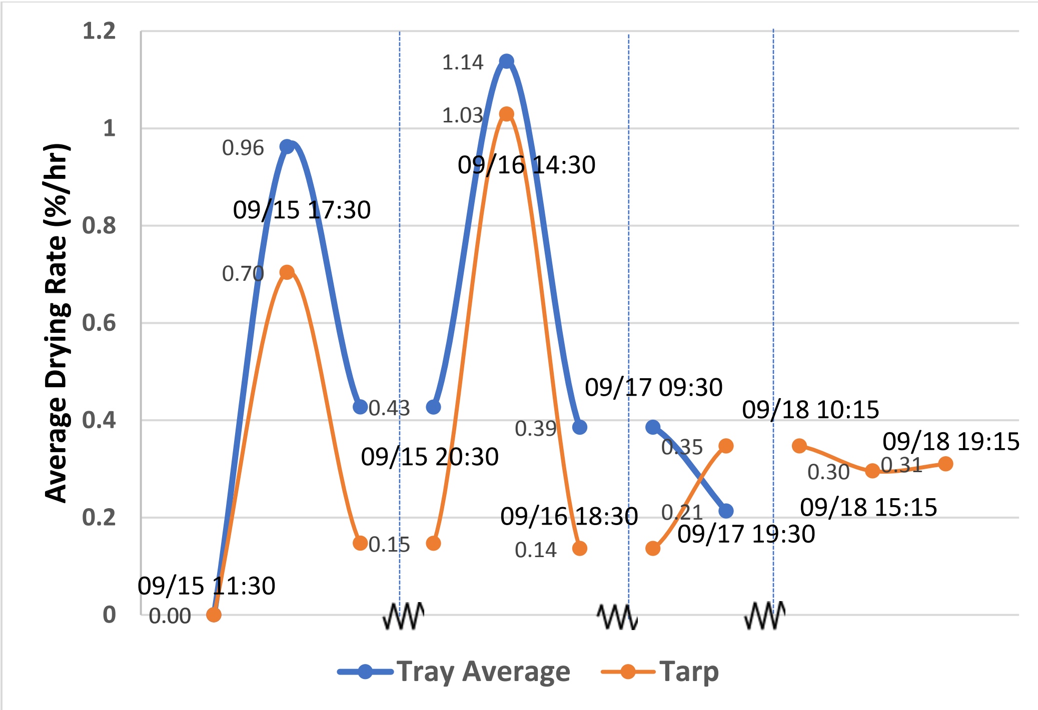

Figure 4.13 Average drying rates for time intervals between sample collections for the trays and the tarp for Test 20170915

The solar radiation data obtained from Purdue's Applied Energy Laboratory for the days of September 15th and 16th, 21st and 22nd, when the drying test was being conducted, are shown in Figure 4.14. Only times when drying was occurring are included in the plot. Note there were sharp drops in solar radiation during the afternoons of September 15th and September 16th. It is likely that these drops were caused by clouds blocking a significant portion of the solar radiation. There were also some variations in sunlight on September 21st. Solar radiation was the most consistently high on September 22nd when drying was only being done on the tarp.

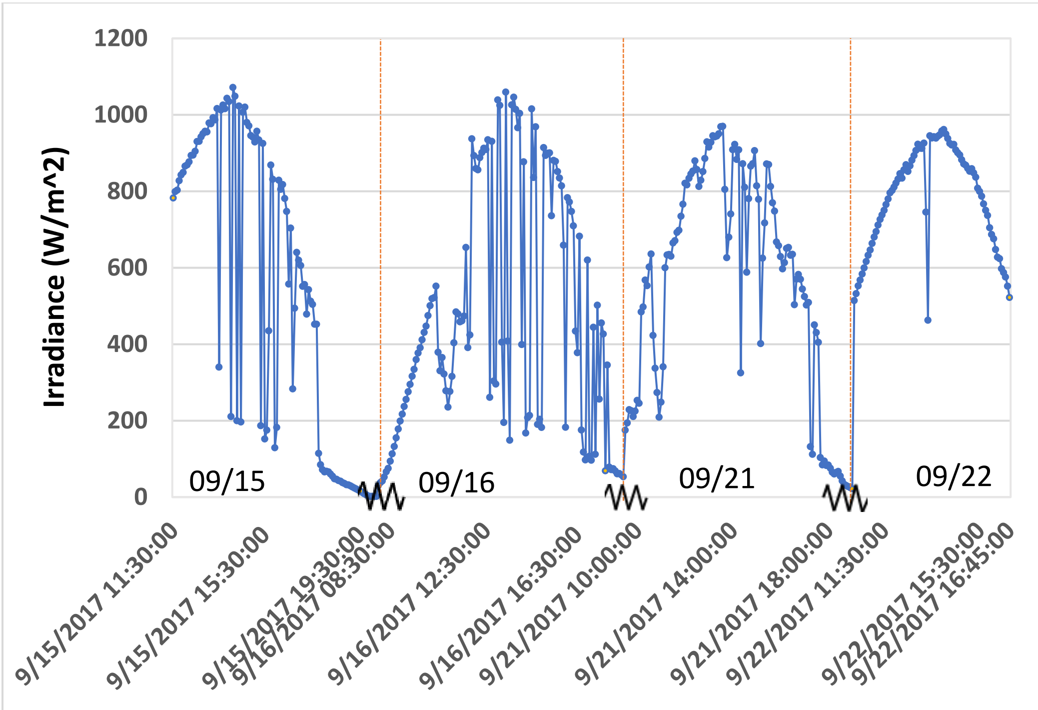

Figure 4.14 Graph of solar irradiance for Test 20170915 versus time while drying

4.2.3 Test conducted on July 18th 2018 at Purdue

4.2.3.1 Introduction

Based on the performance of the POD during tests conducted in September 2017, it was determined that the more recent version of the POD was ready for testing in Kenya, if trays and other components could be provided to our Kenya partners. Estimates of the cost of making a dye to produce plastic trays using injection molding were approximately $8,000. Because funds were not available to make the dye, the alternative of purchasing trays was pursued. In early November of 2017, project personnel were able to locate plastic trays manufactured by Linqi Shunda Plastic, Shandong, China that were suitable, after modification, for use in the POD. The tray is 78 cm (31 in.) long by 51 cm (20 in.) wide with a depth 10 cm (4 in.). Five trays provided a volume of 0.20 m^3 (7.06 ft^3) with a surface area of 1.989 m^2 (21.41 ft^2). This gives enough capacity to hold over 130 kg of wet maize which would give approximately 100 kg of dry (13%) maize. The trays cost approximately $5 each and are marketed for use for incubation of baby chickens. There are slots in the sides of the trays which had to be covered to ensure that the air flows through the dryer properly (Figure 4.15). The bottoms of the trays are perforated with small holes. Each hole has an area of 0.36 cm^2 (0.056 in^2).

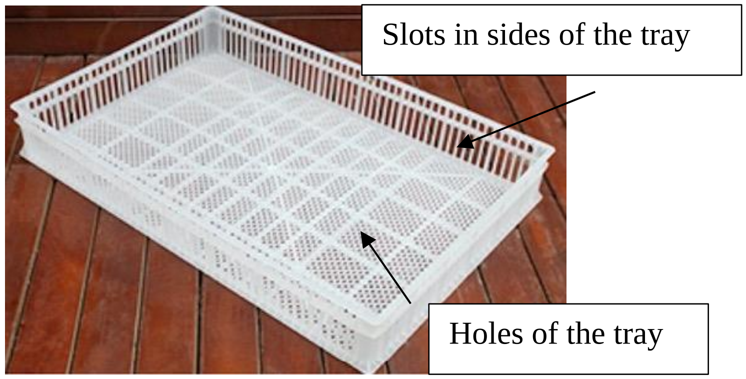

Figure 4.15 Picture of the trays purchased from China

Several wood "two by four" boards, which are nominally 2 in. thick and 4 inches wide, were used to support the trays. The actual dimensions of the boards were smaller because of the wood removed during finishing and shrinkage during drying of the boards. They were actually 1.5 in. (38 mm thick) thick and 3.5 in. (89 mm) wide. There are ribs on the bottoms of the trays which add strength to the trays (Figure 4.16). The two by fours were placed under the third rib from each end of the tray in order to provide better support.

Figure 4.16 Boards aligned to support trays (left); bottom of Tray showing "ribs" that add strength to the trays (right)

As shown in Figure 4.17, the sides of the trays were sealed by applying flashing tape around the inside of some of the trays. Flashing tape is used to form an airtight and watertight seal around windows chimneys, doors, and other building envelope penetrations of houses and other structures. When the tape is applied to the inside of the sides the sticky side of the flashing tape is exposed through the slots in the sides of the trays. Maize kernels and debris could stick to the exposed sticky surface. Therefore, the slots were covered by applying the backing that was peeled from the tape when the tape was prepared for application to the inside sides of the tray. The backing was applied to the outside surface of the sides. There was usually sufficient sticky area exposed through the slots in the side of the tray to hold the backing in place. If necessary, duct tape was used to secure the backing in place. One roll of flashing tape costs approximately $12 US and about 1.5 rolls would be needed to cover all sides of the five trays used in a POD. Therefore, as a lower cost alternative, some of the sides of the trays were sealed by cutting strips of cardboard to the appropriate size and fastening the strips to the inside surface of the sides of the trays using duct tape.

When the five trays were placed next to each other to form the bed of the dryer, duct tape was used to fasten the trays together and to seal any space between adjacent trays. The longer side of the plastic tray at each end of the drying bed was slightly shorter than the side of the wooden tray (78 cm versus 86 cm) and it was also shorter than the length of the fan frame That meant that the fan frame could not be easily attached to the end of the rectangular drying bed formed by the five trays and there would be air leakage. Therefore, the fans were relocated to the middle of one of the long sides of the drying bed (Figure 4.17). It was also anticipated that this would facilitate more uniform drying among the trays. In other words, when samples were taken for moisture content measurements during a test, there would be less variation among the moisture contents of the samples taken from each of the trays at a given sampling time.

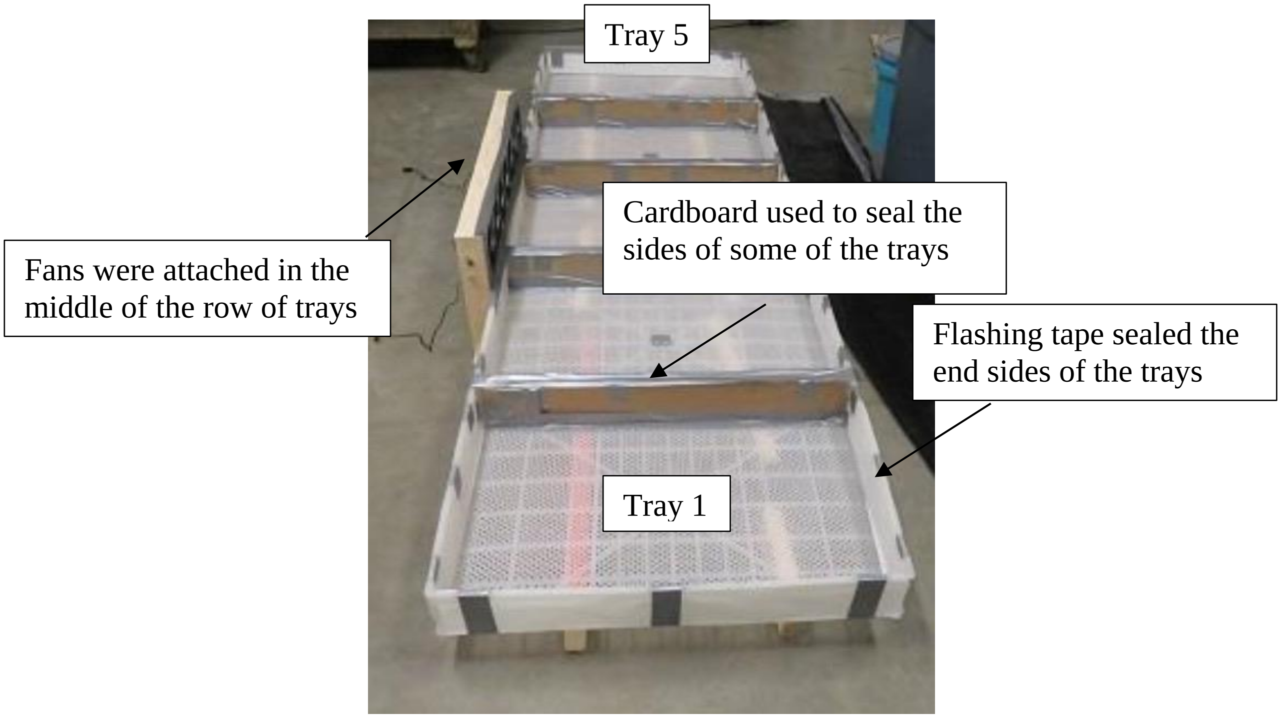

Figure 4.17 POD configuration showing the boards beneath the 5 plastic trays

The test was started at 11:30 am on July 18th, 2018 and stopped at 19:10 on the first day, after 7.67 hours of drying. It was resumed at 09:45 on the second day and stopped at 13:40 on that day thereby providing another 3.92 hours of drying. The 90 kg of maize was re-wetted to an initial moisture content of 21.2% and the final moisture content achieved was 12.23% on average.

4.2.3.2 Results and discussion

Figure 4.18 shows the moisture contents of the shelled maize in each of the trays at the times when samples were taken. The vertical line shows the time when the test was stopped overnight. The total drying time was 11.59 hours and the average drying rate was 0.77 percentage points of moisture content reduction per hour. After the location of the fans was changed, Tray 3 (middle tray) which is in grey, had the highest final moisture content, 12.90%, while Tray 5 (the leftmost tray when facing the fans from the side opposite the fans), which is plotted in a light blue color, had the lowest final moisture content of 11.71%. The standard deviation for the final moisture was 0.53. An explanation for the difference in moisture is that Tray 3 was closest to the air inlet so that air had a shorter time to interact with the solar radiation that was coming through the plastic covering before the air went through the maize. However, the standard deviation of the final moisture content of the trays, 0.53, was 0.79 times the standard deviation for Test 20170907. It had a standard deviation of 0.67 when the fans were located at one end of the drying bed that was comprised of 5 trays. This indicates that re-locating the fans helped to achieve a better uniformity in moisture content of the maize among those trays.

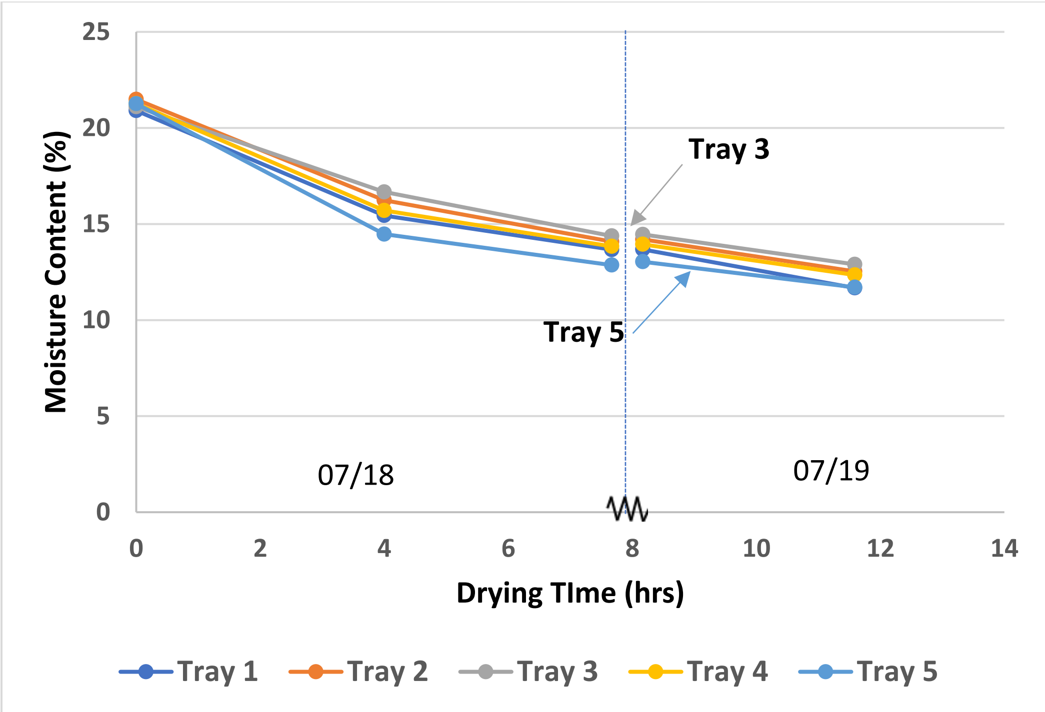

Figure 4.18 Moisture contents for Test 20180718 conducted at Purdue

Starting from this test, four Hobo sensors were used to record more precise and frequent temperature and relative humidity data. The loggers were set to read the data at 5 minute intervals. They were labeled as Sensor 1, 2 3 and 4, respectively. Table 4.2 summarizes the locations of the Hobo sensors. Sensor 1 was suspended with a wire from a short strip of wood lath that was clamped to the top of the fan frame. A piece of cardboard was cut to a length slightly shorter than the wood lath and attached to the lath. This shielded the sensor from direct sunlight and held it at approximately the same height as the fan inlet. Sensor 4 was placed on a 38 mm thick board (a short piece of two by four) beneath Tray 4.

Table 4.2 Locations of the Hobo sensors

Sensor No.	Location
1	Suspended in front of the inlet of the fans
2	Surface of maize in the center of Tray 3
3	Surface of maize in the center of Tray 1
4	Under Tray 1 approximately 38 mm above the ground

Figure 4.19 and Figure 4.20 are plots of the Hobo data for relative humidity (in percent) and temperature (in °C), respectively. The vertical dashed line in the plots indicates the time when the test was stopped overnight. Figure 4.19 shows that air exiting from Tray 1 (yellow line) had a higher relative humidity than the inlet air (blue line). Therefore, as expected, it picked up moisture as it passed through the maize. The exiting air relative humidity increased from approximately ambient conditions of 28% to exhaust air conditions of approximately 35% during the morning of the first day when the grain still had a high moisture content. The air absorbed more water at the beginning of the test and that probably contributed to the faster drying rate. As shown in Figure 4.21, the average drying rate from the beginning of the test at 11:30 through the time when the first sample was taken, 15:30, was the highest observed during the test. It was 1.37 percentage points of moisture reduction per hour. For the beginning of the second day, when the ambient air relative humidity was highest, the air exiting from Tray 1 was only about 2 percentage points higher than the inlet relative humidity. According to Figure 4.20, the air above the maize in Tray 1 (gray line) was heated by 5 °C to 20 °C above the inlet air temperature. However, air above the maize in Tray 3 was only heated between 2 °C and 10 °C above the inlet air temperature. The greater increase in the air temperature for the air above tray 1 is a likely explanation of why the maize in Tray 1 dried faster than the maize in Tray 3.

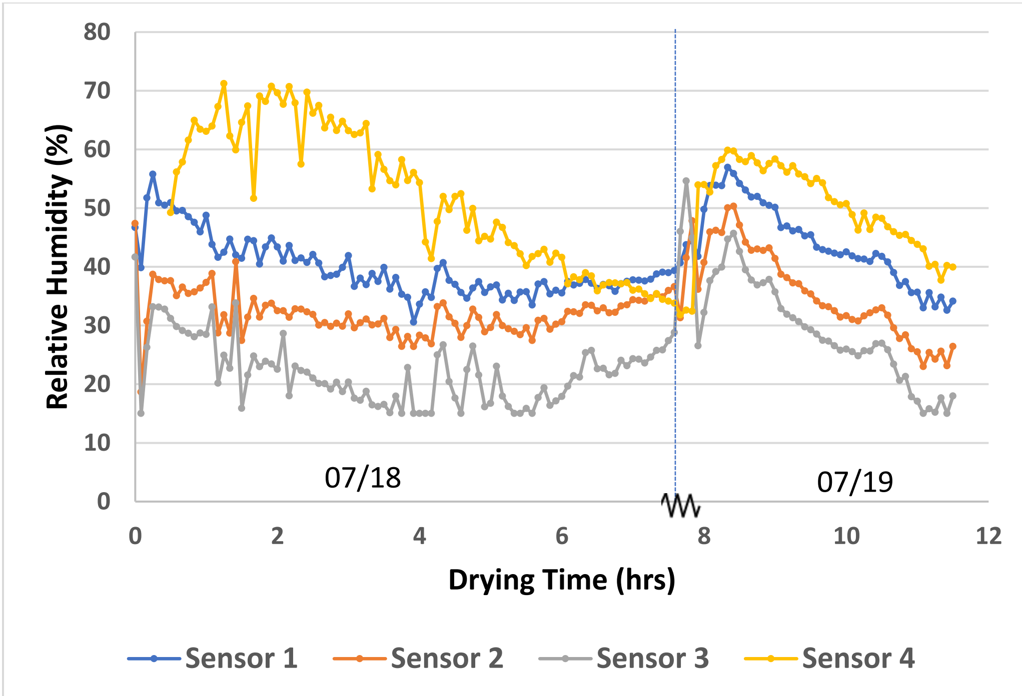

Figure 4.19 Graph of relative humidity (Hobo sensor data) verses drying time for POD test 20180718

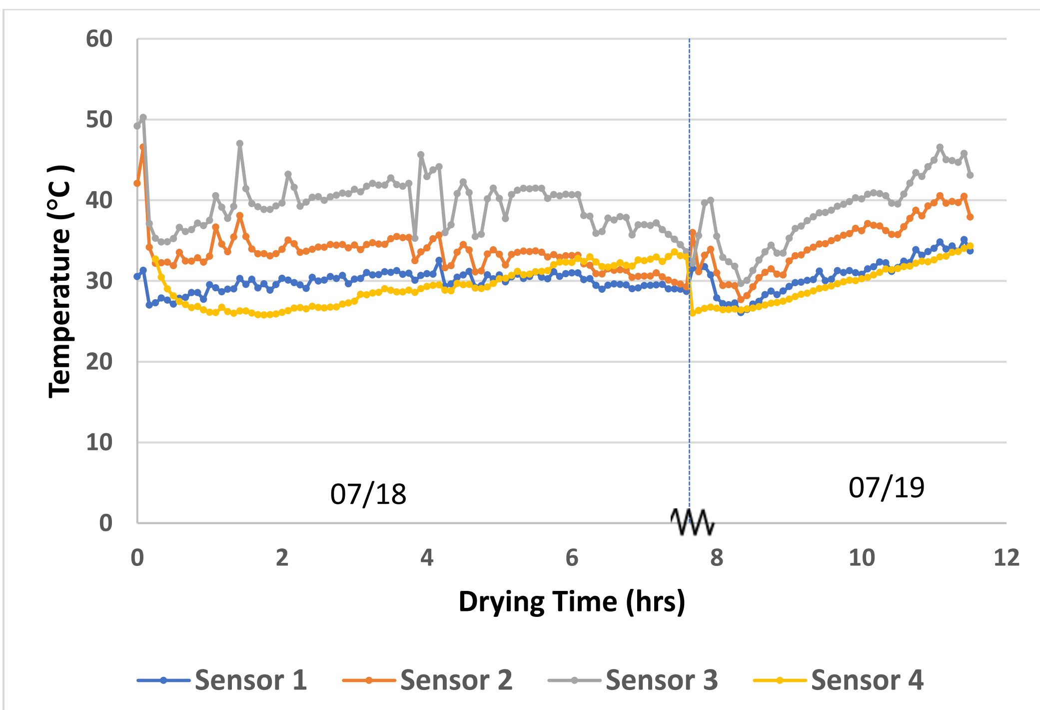

Figure 4.20 Graph of temperatures (Hobo sensors) versus drying time for test 20180718

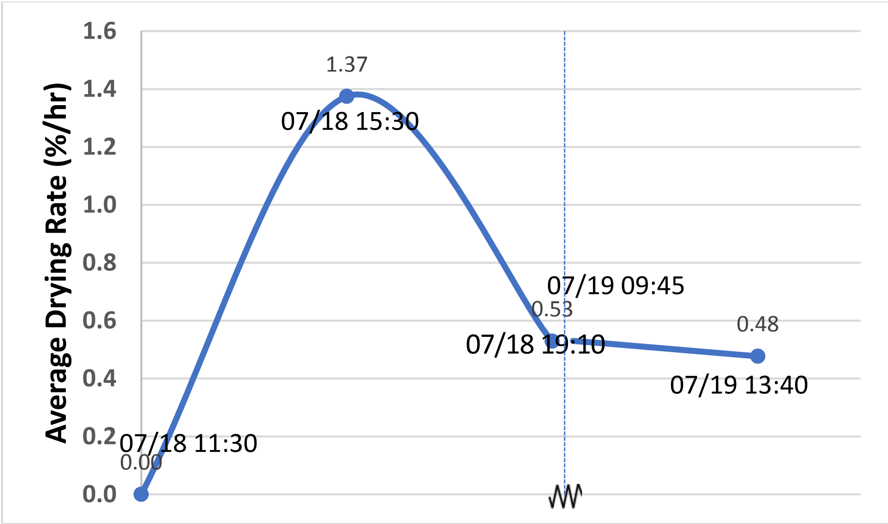

Figure 4.21 Average drying rate for intervals between samplings for Test 20180718

4.2.4 Test conducted on August 9th 2018 at Purdue

4.2.4.1 Introduction

The major objective of this test was to evaluate the performance of the dryer when there was wire mesh added to the bottom of two of the trays, beneath the maize. The mesh was the screen wire sold at hardware stores for replacing window screens. The addition of the wire mesh, which has small holes, would make it possible to use the POD for drying vegetable or fruit seeds that are small and would fall through the holes in the bottoms of the plastic trays. Also, it was anticipated that the mesh could increase the resistance to airflow in the two end trays, bringing their moisture contents closer to those of tray 3. In addition, it was reasoned that if the air is in contact with the maize for a longer period of time, it could also absorb more moisture.

For this test, the wood frame used in previous tests was replaced with a fan frame constructed from a sheet of aluminum and aluminum angle. Figure 4.22 shows pictures of the modified POD. The new fan frame had thinner edges which made it easier to attach it to the trays and to secure the plastic sheets to the frame. In addition, it could easily be disassembled by removing the small bolts holding in place the two vertical pieces of angle iron that elevate the fan frame above the ground. Disassembling the frame makes it more compact so that it can be transported more easily.

Figure 4.22 Modified POD that uses an aluminum fan frame

4.2.4.2 Results and discussion

The test was started at 11:45 on August 9th, 2018 and stopped at 19:20 on that day after 7.58 hours of drying. The test was resumed at 9:45 on the next day and stopped at 14:25 after another 4.67 hours of drying. The 90 kg of maize had been rewetted to 21.0% initially and the final moisture content achieved was on the average 13.4% moisture content. The total drying time was 12.25 hours and the average drying rate was 0.62 percentage points of moisture content reduction per hour. There was a heavy rain starting at 11:30 on August 10th which lasted about 20 minutes. The dryer protected the maize from picking up moisture from the rain, although water had collected in pools at several locations on the plastic covering the top of the dryer. The plastic was pinched between thumb and forefinger and lifted up to allow the water to run off the plastic. Afterwards, the plastic inflated as usual when the fans were started.

Figure 4.23 shows the moisture contents of the shelled maize in each of the trays at the sampling times. The performance was similar to that observed in previous tests. The additional airflow resistance did not have a noticeable effect on uniformity of moisture among the trays. In this test, the final moisture content of the maize in tray 3 was 13.82%. Tray 5 (light blue line), had the lowest final moisture content, 12.76%. The standard deviation of the final moisture contents of the five trays was 0.44. The tray moistures still varied, but the corn moisture contents in the five trays were more consistent than in 2017 when the fans were located at one end of the POD.

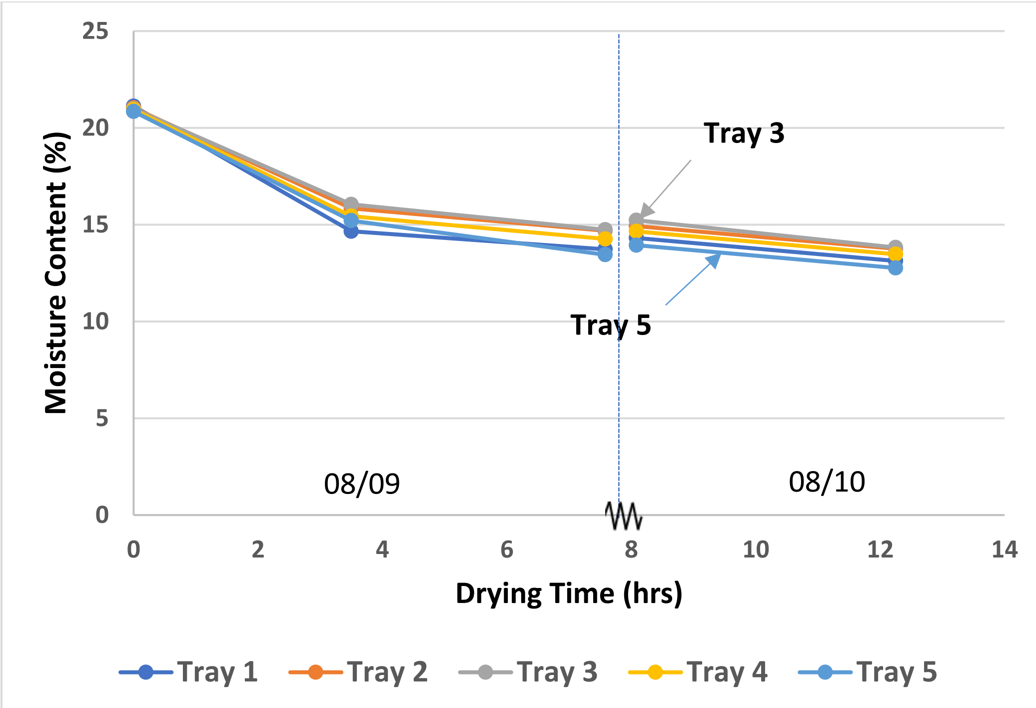

Figure 4.23 Moisture contents for Test 20180809

Figure 4.24 and Figure 4.25 are, respectively, plots of relative humidity (in percent) and temperature (in °C) obtained from the Hobo sensors. The placement of the sensors was identical to the placement used in test 20180718 (Table 4.2). During most of the test the relative humidity of air exiting from Tray 1 (yellow line) was higher than the relative humidity of the inlet air (gray line), with differences as high as 31 percentage points during the first day of drying. However, on the second day the ambient relative humidity approached 100% between hours 9 and 10 of drying (from 11:24 to 12:10). This was the time when the rainstorm occurred. Within the hour after the beginning of the rainstorm project personnel arrived at the sight and drained the water from the plastic. Afterwards the relative humidity of the air exiting Tray 1 was once again higher than the relative humidity of the inlet air.

The plot of the temperatures shown in Figure 4.24 shows that the air above maize in Tray 1 (gray line) was heated up to 21°C warmer than the inlet air. During the afternoon of the first day when the sun was lower on the western horizon and there was less solar radiation incident on the east end of the dryer, the air above Tray 1 was cooler than the inlet air by up to 3°C. The air above

Tray 3 (orange line) was heated up to 12°C warmer than the inlet air. In the late afternoon when there was less solar radiation, the air above Tray 3 was as much as 3°C cooler than the inlet air. The ambient air temperature dropped during the rainstorm and then gradually increased until drying was finished.

Figure 4.26 gives the average drying rates for the intervals between the times when samples were collected. The average drying rate was the slowest in the late afternoon on August 9th and the early morning on August 10th and also towards the end of the drying test when the maize was approaching its target moisture content. These trends are similar to those shown in Figure 4.21 and are consistent with the temperature trends shown in Figure 4.25.

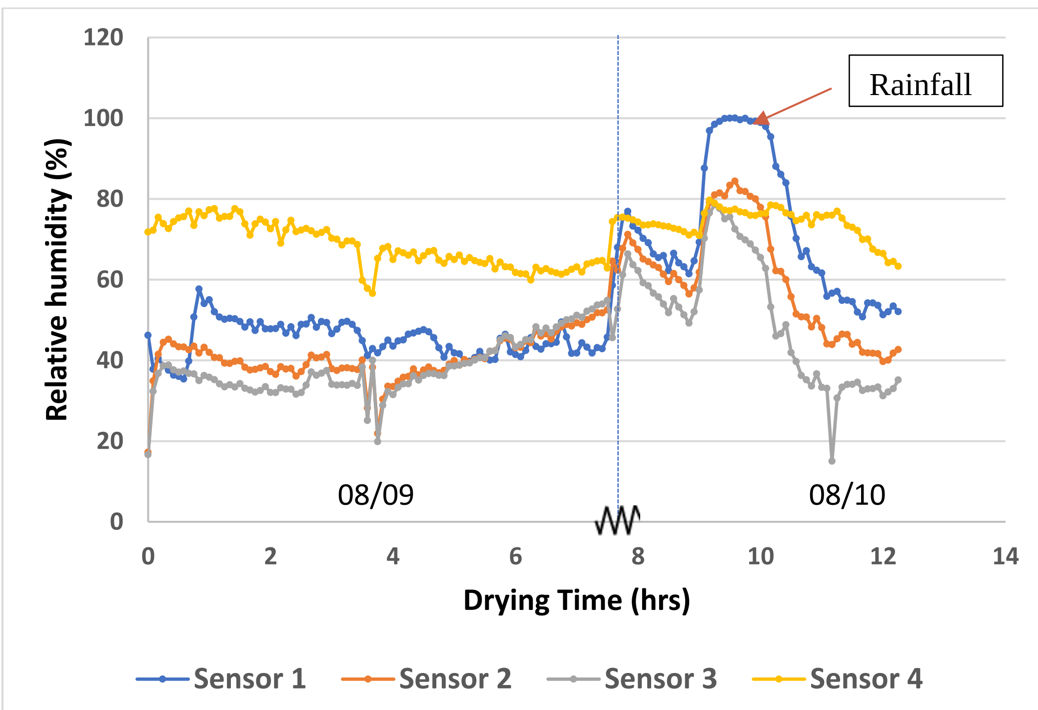

Figure 4.24 Graph of relative humidity data (Hobo sensors) versus drying time for test 201809

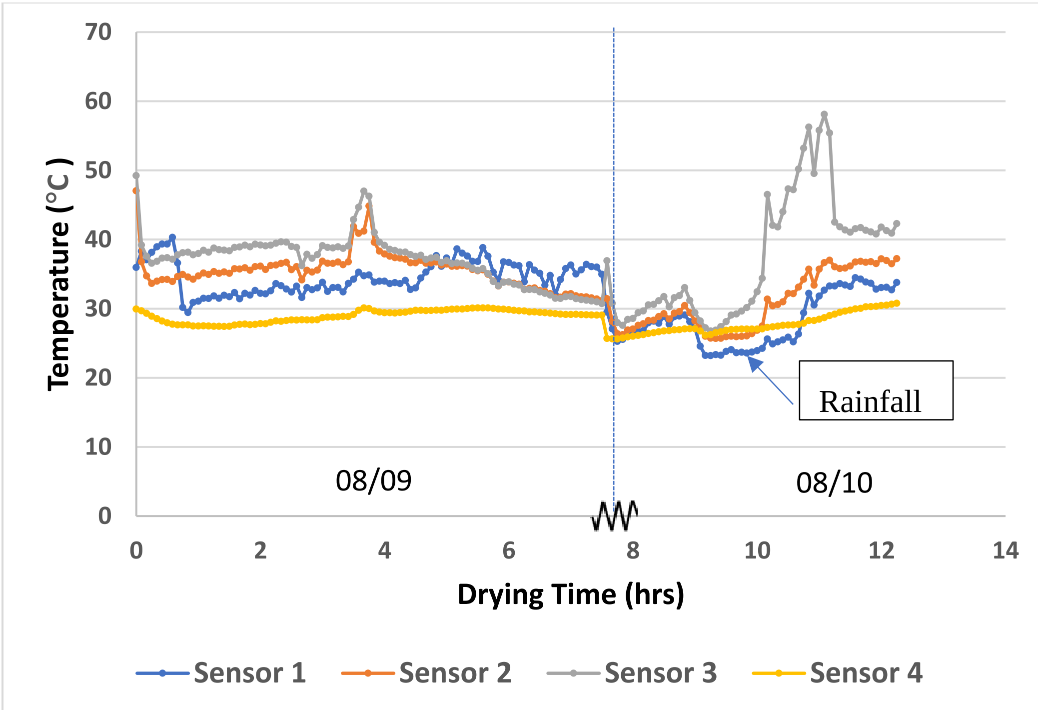

Figure 4.25 Graph of temperature data (Hobo sensors) versus drying time for test 20180809

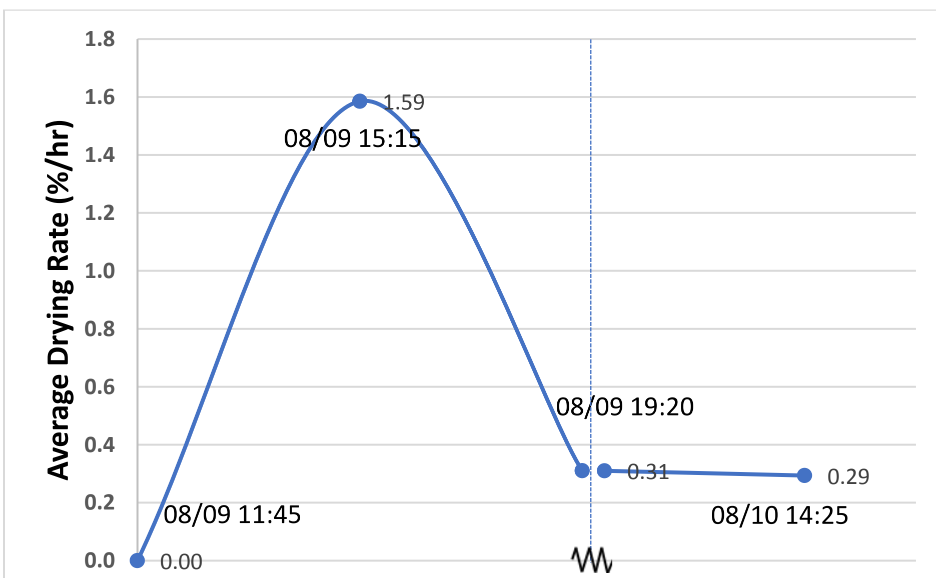

Figure 4.26 Average drying rate between times when samples were taken for Test 20180809

4.2.5 Test conducted on September 12th 2018 at Purdue

4.2.5.1 Introduction

The objective of the Test 20180912 was to evaluate the performance of the POD, after modifications made during the summer of 2018, with freshly harvested maize and compare it with tarp drying. The maize was harvested by hand from a field at Purdue's Agronomy Center for Research and Extension (ACRE) on September 10th, 2018. Maize was shelled the next day using the rubber roller sheller at Purdue's Plant Phenotyping Facility located at ACRE (see section 4.1.2). After shelling was completed, the samples were transported to the ADM Agricultural Innovation Center, where the drying test was conducted. The total weight of maize was 281 kg. It was placed in a pile on the concrete floor of the ADM building and mixed with a shovel by scooping corn with the shovel and dumping it on the of the pile. After the sample was mixed, 139 kgs of maize were placed on a plastic tarp for natural sun drying. The remaining 142 kgs were placed in the 5 plastic trays of the POD.

The POD was started at 16:40 on September 12th, 2018 and stopped at 19:40 on the same day after 3 hours of drying. The test was resumed at 09:50 on the next day and stopped at 19:00, which added another 9.25 hours of drying. On the third day, the test was resumed at 09:50 and stopped at 19:20. On the last day of drying which was September 15th, the test was resumed at 09:45 and finished at 12:40. The initial moisture content of the maize dried in the POD was 30.07% and the average final moisture content of the samples taken from the five trays was 13.29%. The total drying time was 24.5 hours spread over four calendar days and the average drying rate was 0.68 percentage points of moisture reduction per hour.

The tarp test was started at 15:00 on September 12th, which was one and a half hours before the POD was started. The initial moisture content was 30.28 %. Drying was stopped at 19:00 on the first day at which time maize on the tarp was collected and placed in two plastic trash containers that were moved inside the ADM building. The maize in the POD remained in the drying trays overnight. Drying on the tarp was resumed on September 13th at 09:45 and stopped at 18:15 that day. On the third day, the test was resumed at 09:50 and stopped at 18:50. On the last day of drying, which was September 15th, the test was resumed at 09:50 and stopped at 17:15. The maize on the tarp had an average moisture content of 13.53% when the test was finished. The total drying time was 29.0 hours over four calendar days and the average drying rate was 0.58 percentage points of moisture content reduction per hour.

4.2.5.2 Results and discussion

Figure 4.27 shows the moisture contents of the shelled maize in each of the trays and the tarp at the times when samples were taken. The vertical lines show the approximate time when the test was stopped overnight. Since the samples were taken at different times, there were differences in the number of hours of drying. The ratio of the average drying rate of the POD to the average drying rate of the tarp was 1.17. The initial moisture content of the maize on the tarp was 0.21 percentage points higher than the initial moisture content of the maize placed in the POD and the final moisture content of the maize on the tarp was 0.24 percentage points higher. The drying rate of Tray 5, which is plotted with a light blue line in Figure 4.27, was 0.72 percentage points per hour This was 1.24 times the drying rate for the tarp. The drying rate of Tray 3 (gray line) was 0.63, which is 1.09 times the drying rate for the tarp. Figure 4.27 also reveals the differences in moisture content among the trays. The standard deviation of the final moisture content of the maize in the five trays was 1.02. As shown in Figure 4.28, the standard deviation increased for the first four or five samplings but decreased after that. It seems possible that the wetter maize began to catch up with the lower moisture maize because the wetter maize could be dried more easily.

Throughout most of the drying period, the maize in Trays 1, 4 and 5 was lower in moisture than the maize in Trays 2 and 3. At the end of drying the moisture content of the maize in Tray 3 was 2.43 percentage points greater than the moisture content of the maize in Tray 1 and 2.26 percentage points greater than the maize in Tray 5. The standard deviation of the final moisture content of the five trays for this test was higher than the standard deviation for Test 20170915. However, in this test, the initial moisture content was much higher (30.1 % versus 26.8 %). The higher initial moisture means that more points of moisture were removed and this may have magnified differences. Furthermore, in test 20170915 the maize was moved from the POD into a plastic trash container and stored in the container for almost a week. When the maize was returned to the POD it had equilibrated and had been mixed. Therefore, there was only one day for variations in moisture content among the trays to develop.

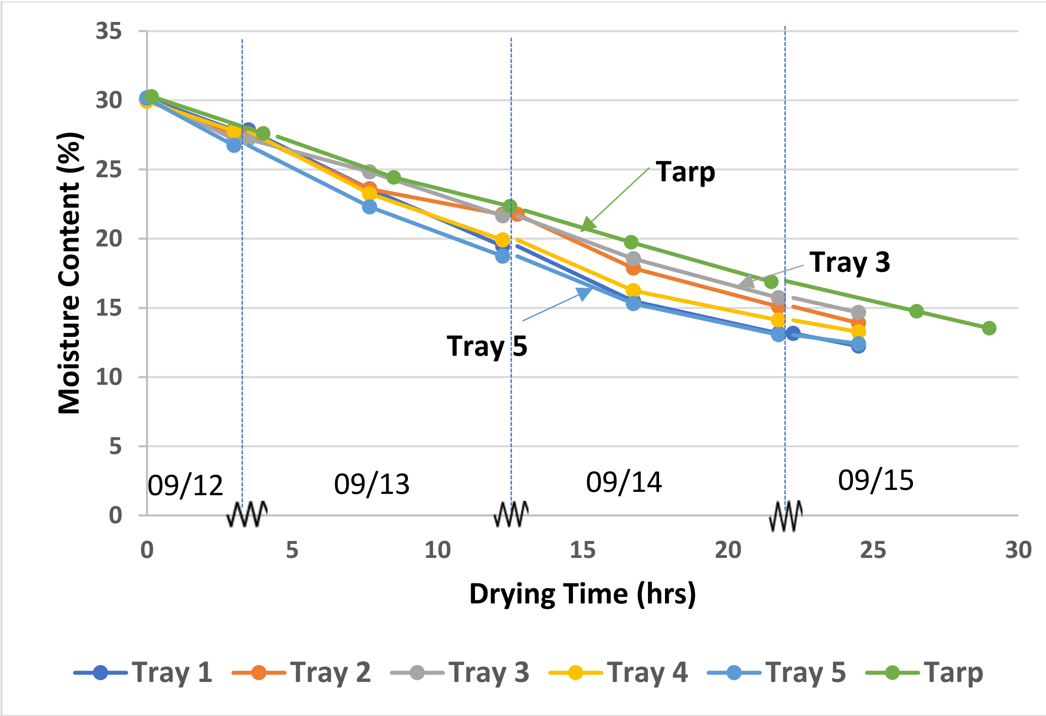

Figure 4.27 Moisture contents for Test 20180912 at Purdue

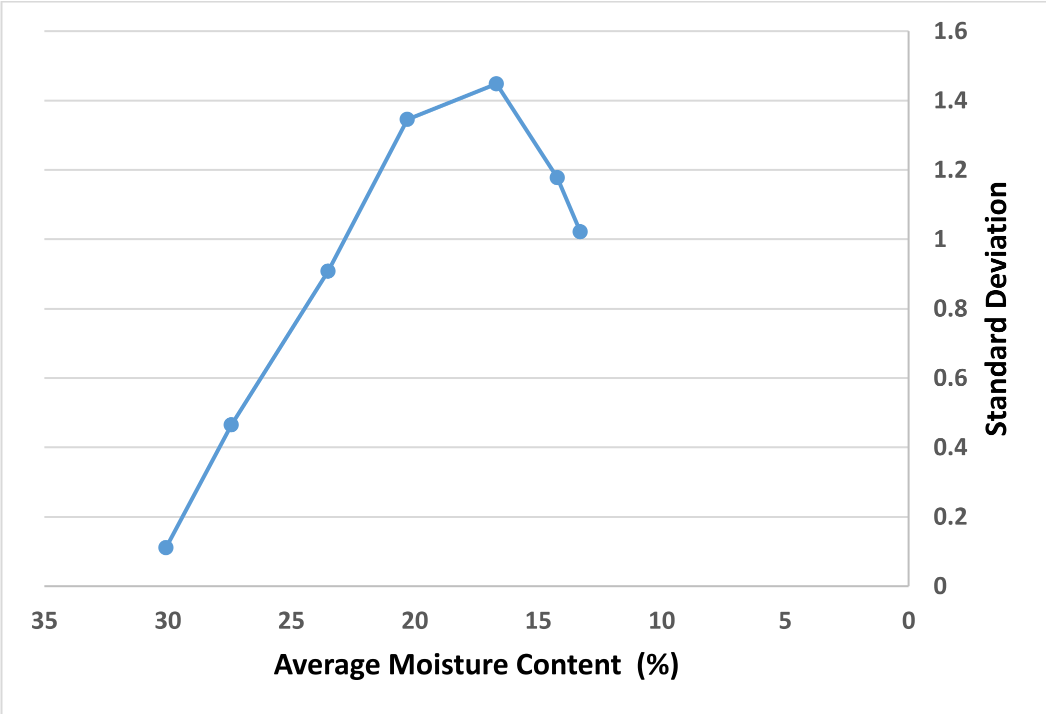

Figure 4.28 Standard deviations of tray moistures for Test 20180912 at Purdue

Figures 4.28 and 4.29 show, respectively, plots of relative humidity and temperature versus drying time for the data obtained from the Hobo sensors. The sensors were placed at the same locations used in the previous tests (Table 4.2). According to Figure 4.28, the relative humidity of air exiting from Tray 1 (yellow line) was 13 to 45 percentage points higher than the relative humidity of the air entering the inlet (gray line). For much of the second day the relative humidity of the air exiting Tray 1 was about 40 to 45 percentage points higher. This large rise in relative humidity occurred when the solar radiation was strong and the maize was wet. As is shown in Figure 4.29, the air above the maize in Tray 1 (gray line) was heated from 1°C to 10°C above the temperature of the inlet air. However, the data obtained by Sensor 2 (orange line) revealed that the temperature on the surface of maize in Tray 3 continued to be close to the ambient air temperature and sometimes it was slightly below ambient temperature. The two times when the temperatures on Tray 3 tended to be lower than the inlet air temperatures were during the morning (9:00 to 13:00) or evening (16:00 to 18:00). A possible explanation is there was evaporative cooling of the air on Tray 3 and there was less solar radiation. . There would be less heating of the air, bringing it closer to the ambient temperature.

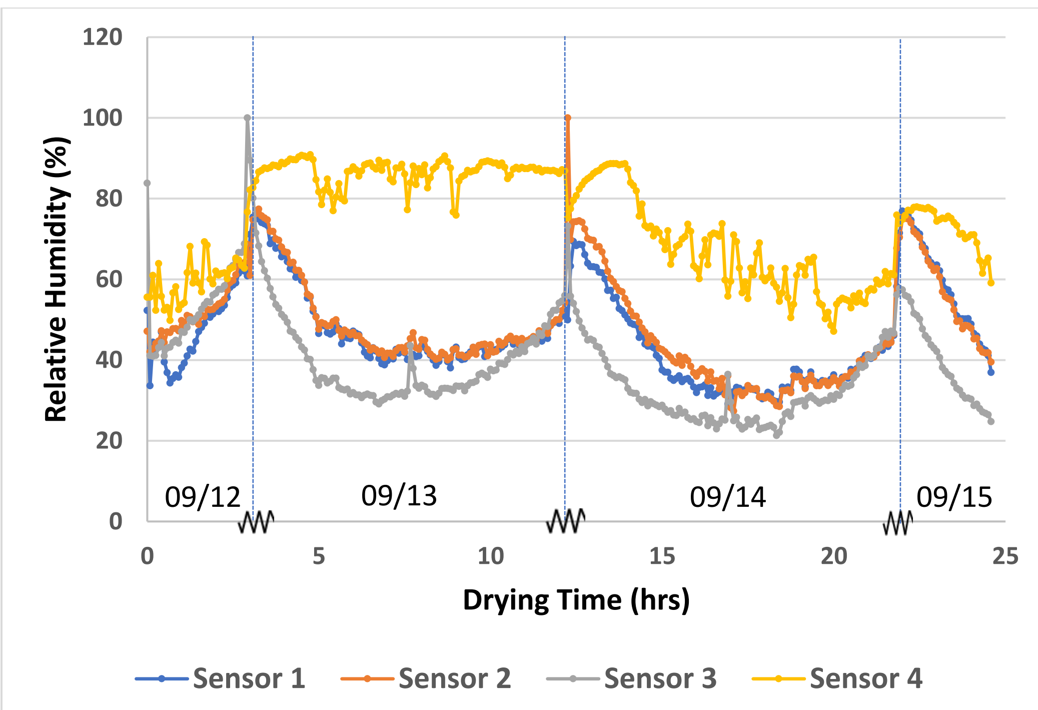

Figure 4.29 Graph of relative humidity (Hobo sensors) versus drying time for test 20180912

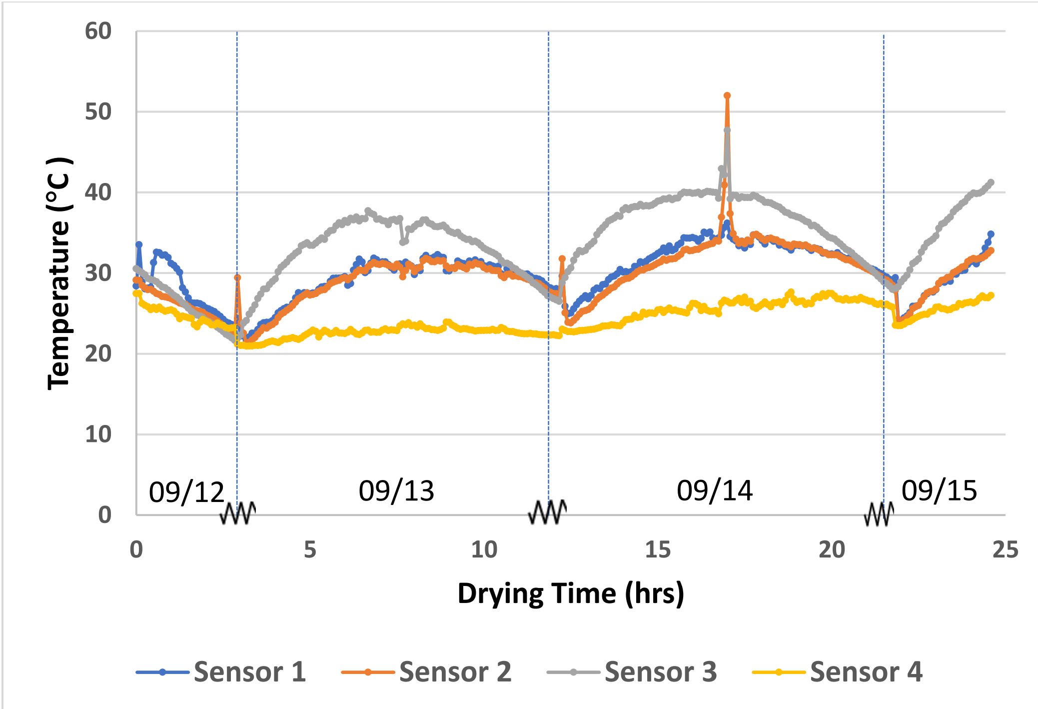

Figure 4.30 Graph of temperatures (Hobo sensors) versus drying time for test 20180912

Figure 4.30 shows the average drying rate for the 5 POD trays and for the tarp at each of the time periods between the times when samples were taken. The fastest drying occurred for both the POD dryer and the tarp when maize moistures were high and air conditions were excellent for drying (low RH and elevated temperatures). The drying rate slowed considerably after the third day of drying when moistures were around 16%. The drying rate of the POD was between 1.1 and 1.23 times the drying rate of the tarp except for near the end of drying when the maize in the POD was approaching 13%. On the fourth day of drying, the maize on the tarp was drying faster than the maize in the POD since the moisture content of maize in POD had already fallen below 14 percent while the moisture content of the maize on the tarp began the day at around 16.9 %.

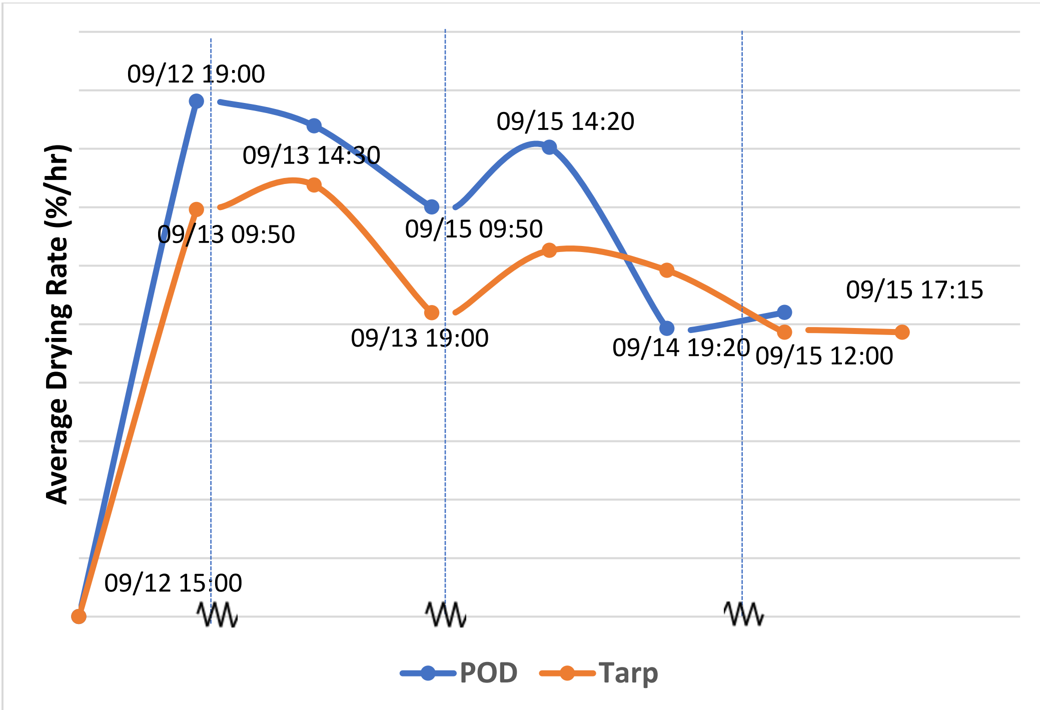

Figure 4.31 Average drying rate of Test 20180912

The solar radiation data obtained from Purdue's Applied Energy Laboratory for September 12th to 15th, when the drying test was conducted, is shown in Figure 4.31. Only hours when the drying test was being conducted are included in the plot. The solar irradiance was over 800 W/m^2 from 11:30 to 15:30, which is favorable for drying. In test 20170915 (Figure 4.14), the irradiance frequently dropped below 800 W/m^2 when clouds disrupted the solar radiation. In this test, the irradiance dropped below 450 W/m^2 after 17:40. The trends in the temperatures shown in Figure 4.29 were consistent with the solar irradiance shown in Figure 4.31. It appears that the temperature increase of the air above the maize inside the plastic covering over the trays was influenced by the intensity of the solar radiation.

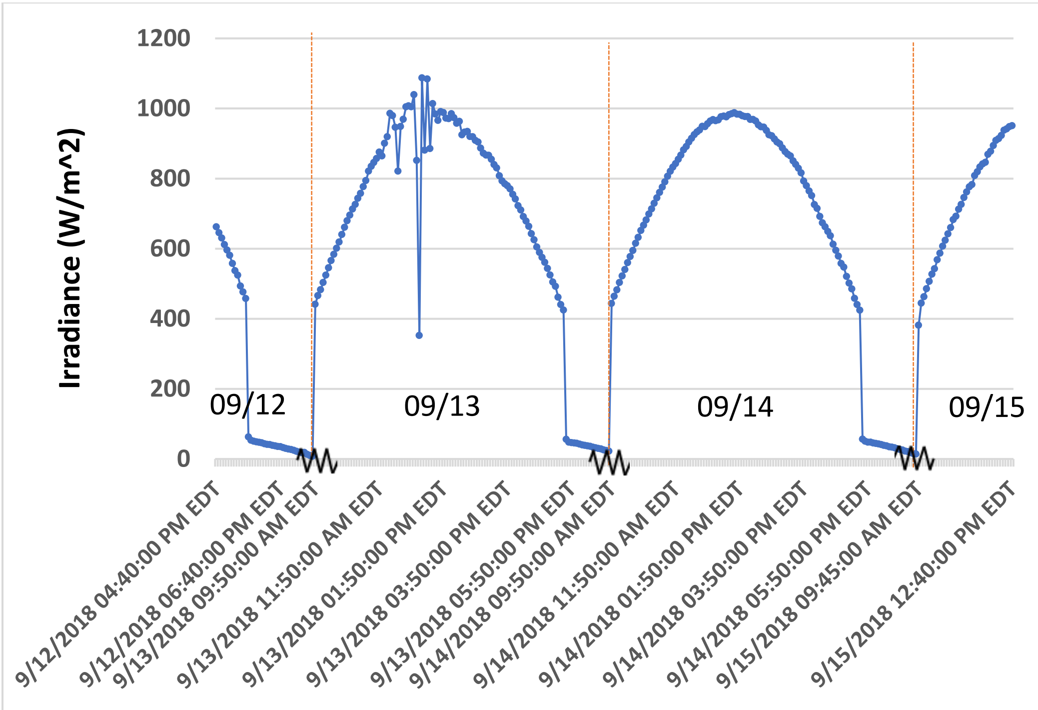

Figure 4.32 Graph of solar irradiance versus time of drying for Test 20180912

4.3 Conclusions

Data from a total of 5 POD performance tests conducted at Purdue University are included in this thesis. Two were conducted in 2017, and the remaining 3 were conducted in 2018. Two tests of drying in the sun on a tarp were also conducted, one each year in September. This provided a comparison between drying on a tarp and drying in the POD. The advantages of drying with the POD compared to drying on the tarp can be summarized as follows:

1. The drying rate in the POD was higher. In 2017, the total drying time for the POD was 0.75 times the time required to dry the maize on the tarp (24.9 hours compared to 33.2 hours). The final moisture content of the maize in the POD was 0.3 percentage points lower than the moisture on the tarp (12.2 % versus 12.5 %). In Test 20180912, the total drying time for the POD was 0.844 times the drying time on the tarp (24.5 hours compared to 29 hours). The initial average moisture content of maize in the POD trays was 0.21 percentage points lower than the moisture content of the maize on the tarp and the final moisture content of the maize dried in the POD was 0.24 percentage points lower than the moisture of the maize on the tarp. (13.29% versus 13.53%).

2. Drying with the POD required less labor than drying on the tarp. When tests were being conducted, the maize on the tarp was mixed every two to four hours including before the samples were taken. When the tests were stopped overnight, maize on the tarp was collected and stored inside the building while the maize in the POD was left outside. It was also more convenient to collect maize from the POD than from the tarp when the drying test was completed. If two people were available, the duct tape connecting a tray to the adjacent tray could be removed and the tray could be picked up and dumped into the plastic trash container.
3. When there was an unexpected rain during Test 20180809, the POD was able to protect the maize from being re-wetted. Because the rain was not expected or predicted, if there had been maize drying on a tarp nearby the rain would have fallen on it and it would have increased in moisture content.
4. Maize being dried in the POD was enclosed in the dryer without exposing it to dirt and animals, while insects (a few weevils and spiders) were observed in the maize being dried on the tarp.

Two tests were conducted using recently harvested maize, Test 20170915 and Test 20180912. These two tests can be compared to each other. The POD dried the maize in 24.9 hours in 2017 and in 24.5 hours in 2018 even though the starting moisture was 4 % higher in 2018. The drying rate for Test 20180912 was 1.17 times the drying rate for Test 20170915. The weather conditions for these tests are compared in Figure 4.32 and Figure 4.33. Since the fans were located differently in the two tests, the temperatures of the air above the shelled maize in Tray 1 in Test 20180912 were compared to the temperatures of the air above Tray 3 in Test 20170915 (Figure 4.32). This assumes there is a linear relationship between the distance the air travels before it goes through the maize and the °C heating of the air. Both the ambient air temperature and the temperature of the air inside the POD for the test in 2018 were slightly higher than in the 2017 test. Figure 4.33 shows the ambient relative humidities for the two tests. The average ambient relative humidity for Test 20170915 was 11 percentage points higher than the average ambient relative humidity for Test 20180912 (53% versus 42%). As shown in Figure 4.14, clouds apparently blocked a significant portion of the solar radiation causing sharp drops in solar irradiance during Test 20170915. This leads to the assessment that solar heating was generally better in Test 20180912 than in test 20170715. In addition, Test 20180912 started with a higher initial moisture content (30% versus 26.8%). The lower the moisture of the maize, the slower the drying rate of the maize.

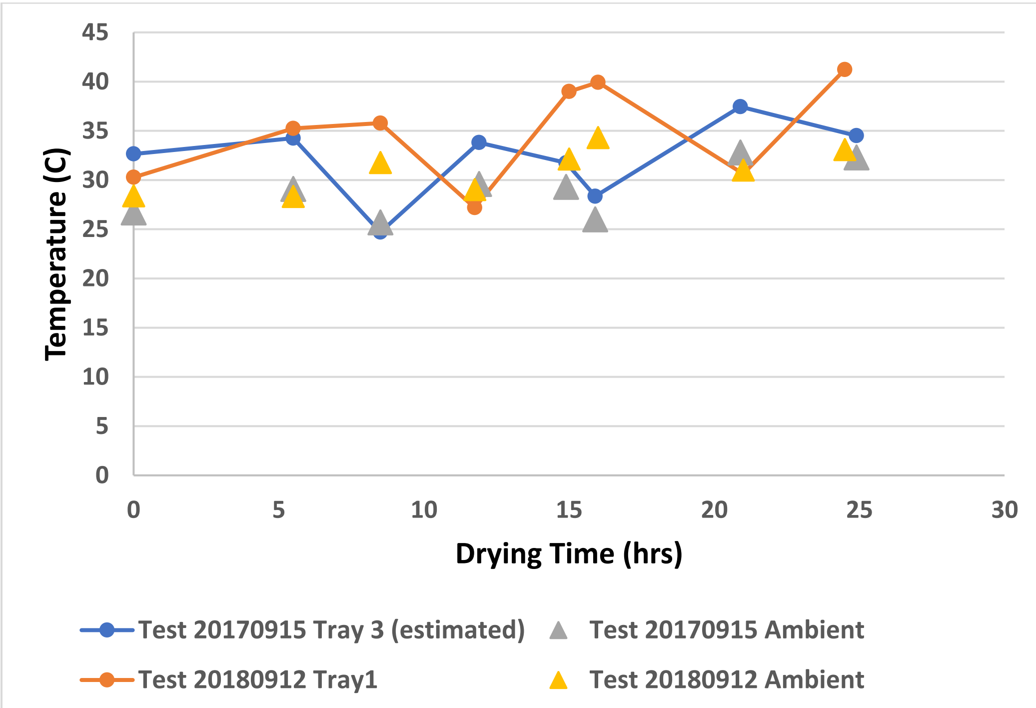

Figure 4.33 Comparison of temperature for Test 20170915 and Test 20180912

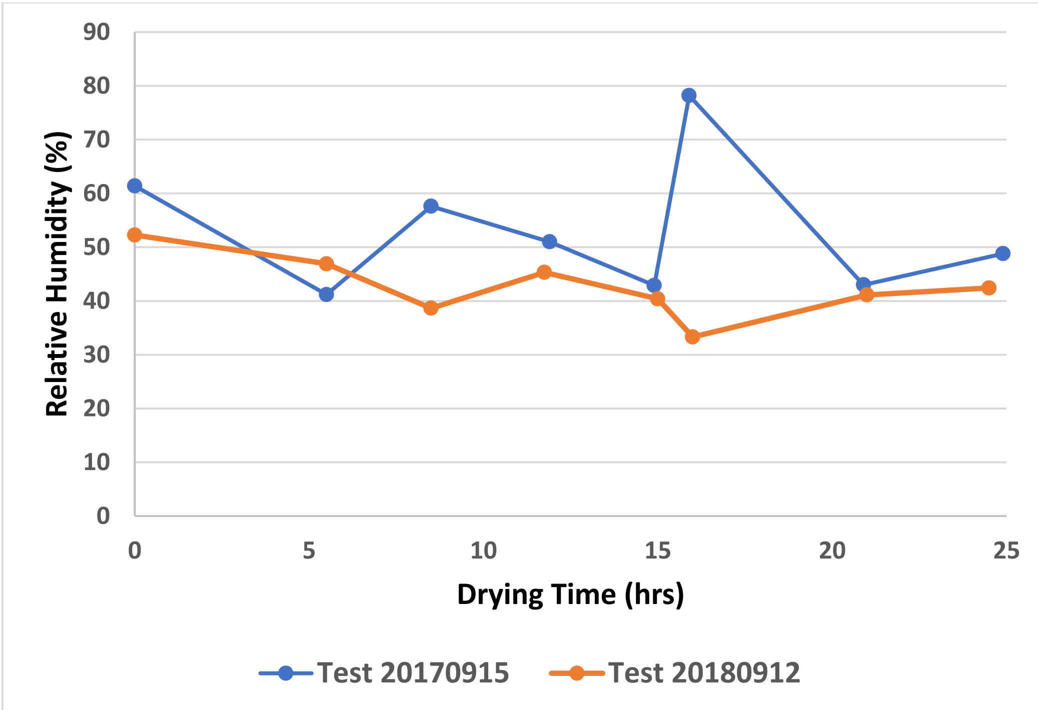

Figure 4.34 Comparison of ambient relative humidity for Test 20170915 and Test 20180912

In 2017, the fans that forced air through the maize were located at one end of the trays. This apparently caused a difference in moisture content among the trays during drying. The maize in the tray that was closest to the fans had the highest moisture content at the end of the test. In 2018, the fans were moved to the middle of the trays. In this configuration, maize in the middle trays had the highest moisture content. The standard deviations of the moisture contents of the samples taken from the five trays at each of the sampling times are plotted and compared in Figure 4.34. The horizontal axis shows the average moisture content of maize during drying. It goes from high on the left to low on the right. As shown in Figure 4.34, the tests that started with a higher initial moisture tended to have larger standard deviations in the measured moisture content among the samples towards the end of drying test.

In Test 20180809, which is plotted in dark blue, wire mesh was put in two end trays. The idea was that increasing the airflow resistance in the trays that have had faster drying rates to even the moisture content. The variation decreased slightly during this test but the final moistures had about the same standard deviation as the other tests. It was also notable that the standard deviation went down when drying from 15% to 13%. The wetter maize began to catch up with the lower moisture maize. This observation is consistent with the observation that drying rate is higher when moisture content is higher. The wetter maize was easier to dry.

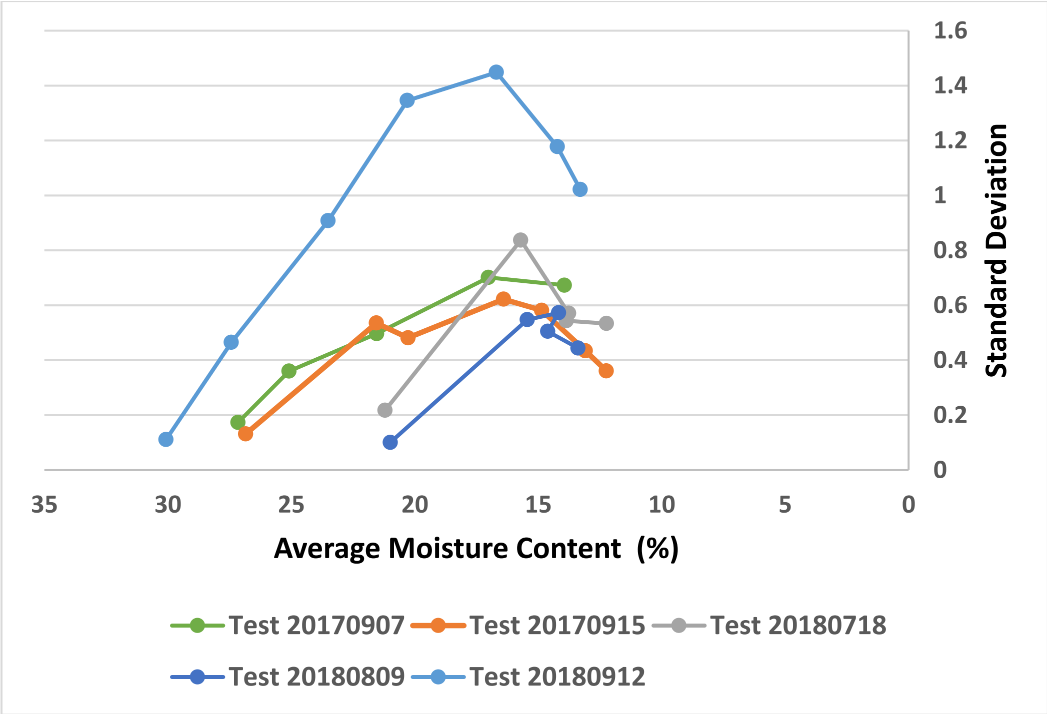

Figure 4.35 Comparison of standard deviations of the tray moisture contents for the POD tests

One last observation from the tests conducted at Purdue relates to the performance of the solar panel used as a source of electricity to run the fans. In all 5 tests, which were conducted outdoors, the power generated by the solar panel during the tests satisfied most of the energy needs. The battery voltage was relatively stable throughout the test, so there was no need to charge the battery or to change batteries. The POD used renewable energy only so that the operating expense is very low.

4.4 References

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[2] Psychrometric Calculations, The sugar Engineers, achieved from http://www.sugartech.co.za/psychro/index.php

[3] Purdue Applied Energy Laboratory, Purdue Knoy Technology Department, http://technrg1.ecn.purdue.edu (Accessed May 20 2019).

[4] C. W. Hall, "Chapter 1: History and importance of drying," *Drying and Storage of Agricultural Crops*, edited by C. W. Hall , 1980.

[5] R. Shrestha, "Development And Testing Of A Multipurpose Solar Dryer For Smallholder Farmers – Corn (Zea Mays) Drying", Master Thesis, Purdue University, 2017.

CHAPTER 5. EVALUATION OF THE PERFORMANCE OF THE PICO SOLAR CROP DRYER IN WESTERN KENYA

5.1 Introduction

The study funded by Food Processing Innovation Lab (FPL) aims to increase access to safe and nutritious foods in sub-Saharan Africa. The drying and storage component of the project seeks to increase the drying and storage capacity of smallholder farmers. The main objective of the POD trials in Kenya was to determine the POD's performance in different agro-ecological zones in order to provide recommendations for dissemination and adoption. The POD offers a low cost opportunity for smallholder farmers to dry their maize to a safe storage moisture thereby preventing development of harmful mycotoxins. This helps to ensure that the maize they use as food for themselves will be safe to consume. It also gives them flexibility in marketing their maize so that they can secure a good selling price. End results of wide spread use of the POD would be improved food security and increased household incomes.

After the initial testing of the first version of POD was completed at Purdue in February of 2017, the POD was sent to KALRO in Kakamega, Kenya where tests were conducted by Dr. Patrick Ketiem, Senior Research Officer at KALRO. The dryer was delivered by Mr. Ron Ellis from the Purdue Research Foundation who was traveling to Kenya for another purpose. Dr. Ketiem conducted tests from March 21st to 25th, 2017 using both 22.5 and 45 kg of maize. In the last test he conducted, he also dried maize on an open tarp so that the performance of the POD could be compared to the method that some African farmers are currently using. According to the results that Dr. Ketiem reported [1, 2], for the 22.5 kg test the initial moisture contents for the maize placed in the POD and placed on the tarp were 34.2% and the final moisture contents for the maize, after 21 hours of drying, were 17.9% for the maize dried in the POD and 18.0% for the maize dried on the tarp. For the 45 kg test, the shelled maize placed on the tarp was initially at 30.6% mc while the maize placed in the POD had an initial moisture content of 26.1%. The moisture contents after 18 hours, when the test was ended, were 13.9% for the POD and 15.8% for the tarp. The slopes of the drying curves, which are an indication of the drying rates, were similar if not the same. That indicates that the POD was drying the maize at approximately the same rate as it dried on the tarp. Dr. Ketiem also reported that the POD dryer heated the air approximately 5°C above ambient temperature thereby lowering its relative humidity to the point where it could continue to dry the grain even when ambient relative humidities are higher.

Based on the performance of the POD during tests conducted in September 2017 at Purdue University, it was determined that it was ready for testing in Kenya. After the plastic trays were successfully adapted for use with the POD, a dryer was prepared for testing by Dr. Ketiem at KALRO. The dryer components, including a set of five trays, a wooden fan frame, plastic sheeting, wood lath pieces cut to the proper lengths, clamps, and binder clips, were placed in two packages that were transported to Nairobi, Kenya by Dr. Jacob Ricker-Gilbert, the FPL Team Leader for Drying and Storage. Dr. Patrick Ketiem tested the dryer at the KALRO in May of 2018 using maize from the off season crop.

In the summer of 2018, the components for assembling another 5 POD's were prepared and sent for additional tests in 5 counties of Kenya (Figure 5.1). The 25 plastic trays required to assemble the 5 dryers were purchased from Linqi Shunda Plastic, in Shandong, China and shipped to Mr. Hugo DeGroot, Principle Scientist, Agricultural Economics, who is located at the CIMMYT office in Nairobi, Kenya. The fans were mounted in the newly implemented aluminum fan frames .The fans in their frames, pieces of wood lath cut to the proper length, wiring, binder clips and related items were prepared at Purdue. Then they were placed in two packages that were taken to Nairobi Kenya in September of 2018 by Dr. Jennifer DeBoer, Assistant Professor of Engineering Education who was attending a meeting in Nairobi. (Dr. DeBoer is not associated with the FPL project but is very involved in Purdue's Global Engineering Program.). The multi-location POD trials were conducted in 4 counties in western Kenya. Those counties were Nakuru, Trans-Nzoia, Uasin Gishu and Nandi. A test in Bungoma was planned but had to be canceled due to the onset of the heavy rains that mark the beginning of the rainy season. The location of the counties is shown in Figure 5.1.

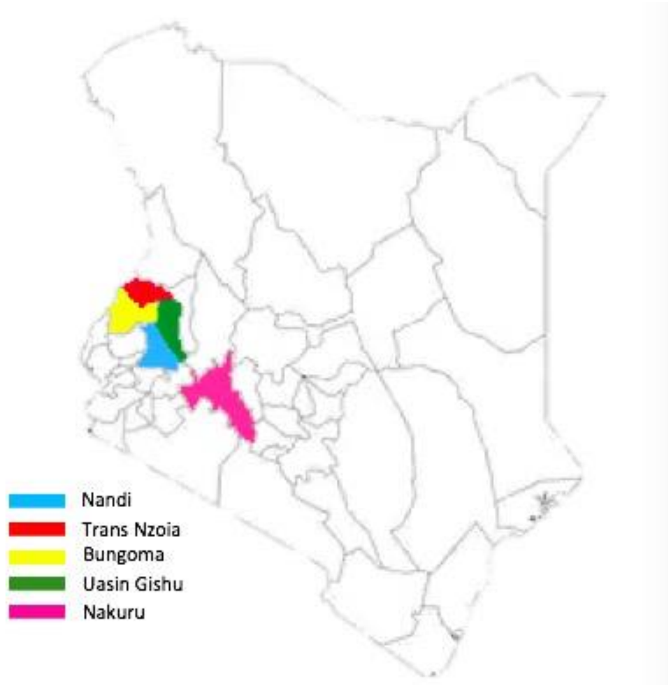


Figure 5.1 Map showing the counties for the POD trials in Kenya

Dr. Stroshine provided written instructions for assembling and using the POD's and Mr. Patrick Ketiem and his team conducted the tests. The first of this series of tests was conducted in November of 2018 in Nakuru County. Difficulties encountered with transferring funds to support the remaining tests delayed the additional tests. Tests in three additional counties were conducted in March of 2019. Data recorded included moisture contents of samples from each tray before and at two-hour intervals during drying. Moisture contents were measured using a hand held electronic moisture meter. In addition, the ambient temperature and the temperature inside the plastic covering of the dryer were measured using indoor-outdoor thermometers. Weather data were also obtained including cloud cover, relative humidity, light intensity and wind speed.

5.2 Result and Discussion

The first performance test of the POD in Kenya (Test 20180515 Kenya) was conducted on May 15th and 16th of 2018 at the Kenya Agricultural and Livestock Research Organization (KALRO) facility located in Njoro near Kakamega, Kenya (Kakamega County). The test was started at 09:00 on the first day of drying and stopped at 17:00. It resumed at 09:00 on the second day and again stopped at 17:00. The total drying time was 16 hours with an average drying rate of 0.39 percentage points of moisture content reduction per hour. The initial moisture content of maize was 21 %. At the point when the test was stopped, the maize reached 14.74 % on average.

Results of the drying tests are shown in Figure 5.2. The uniformity of the moisture contents of the individual drying trays was better (moistures were more uniform) than in the tests conducted at Purdue. The standard deviation of the final moisture content was 0.18. The middle tray (Tray 3) had the highest final moisture content of 15 % while the tray furthest to the left when facing the fans from the side opposite the fans (Tray 1) had the lowest final moisture content of 14.5 %, only 0.5 percentage points lower than the moisture content of Tray 3.

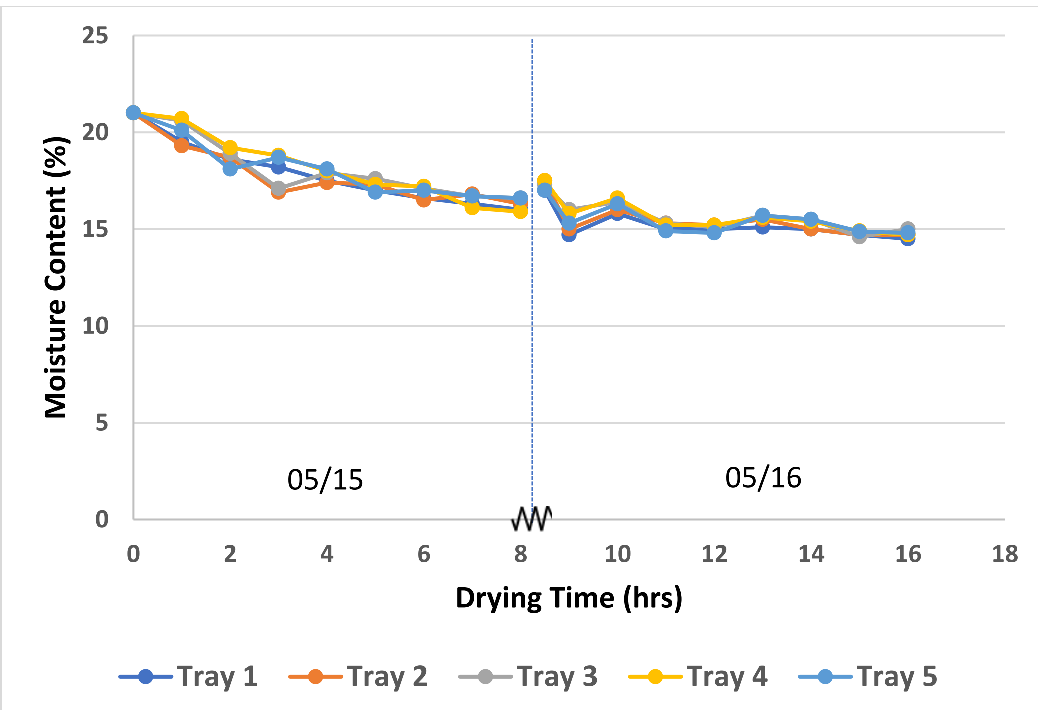


Figure 5.2 Moisture contents of individual trays for Test 20180515 conducted at KALRO

Weather data for the test are shown in Table 5.1. The ambient temperature varied between 11°C and 26°C for the two drying days. Drying was conducted during the day, and therefore the low temperature (11°C) probably does not reflect the ambient temperature during most of the drying test. The relative humidities, calculated from the wet bulb and dry bulb temperatures measured at the KALRO weather station, were 69 % and 77 % for days one and two, respectively. There was partial cloud cover and the Okta measurements for the two days when drying was conducted were 3 and 5 (see footnote to Table 5.1). On the first drying day, there was less than 0.5 mm rainfall (a trace), while on the second day, there was 31.7 mm of rainfall.

The weather data and observations explain why the drying rate of 0.38 percentage points of moisture per hour was much lower than the rates observed in tests conducted at Purdue. Considering the partly cloudy conditions and rain events that occurred late in the day during both days of the test, the POD performed well.

Table 5.1 Weather conditions for Test 20180515 at KALRO, Kenya

Date	Maximum Temperature (°C)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity	Cloud Cover (Okta*)	Rainfall (mm)
5/15/2018	26	18.5	15	69 %	3	TR**
5/16/2018	24	17.5	15	77 %	5	31.7

*Okta = Meteorological measure of cloud cover in any given location. The scale has a range of 0 to 8; where a scale reading of 0 indicates a completely clear sky while a reading of 8 indicates a completely overcast sky;

**TR = Trace (Rainfall less than 0.5mm)

In November of 2018 one of the POD's was tested in Nakuru County near Njoro. Njoro is a town located in an agricultural district on the western edge of the Rift Valley about 18 km west south west of Nakuru. KALRO is located near Njoro. After the first test was completed, further testing was suspended while Dr. Ketiem waited for additional funds to be transferred to CIMMYT. In February 2019 the transfer of funds was completed. Three additional tests were conducted in March of 2019 in Trans-Nzoia, Uasin Gishu, and Nandi counties.

The November 2018 test was conducted at the end of Kenya's major maize harvest season using 75 kg of maize. Figure 5.3 shows the results for the drying test. The initial moisture content of the maize was 30 %. Seventy five kg of wet maize were dried in the test. Drying lasted for 20 hours over three calendar days, and at the end of the test, the moisture content was 13.3%. This gave an average drying rate of 0.835 percentage points of moisture reduction per hour. The ambient relative humidities are shown in Figure 5.4. The relative humidity was 64% at 08:30 on the first day of the test, which was the highest value recorded during the test. On the second day the relative humidity was 46% when drying began at 10:30. During the mornings the relative humidity gradually decreased reaching a low of 34% at 13:30 on day 1 of drying and 30% at 14:30 on day 2. When drying was stopped in the late afternoon or early evening relative humidity had increased by 6 to 9 percentage points above its minimum for the day.

The temperatures and wind speeds are plotted in Figures 5.5 and 5.6. The greatest temperature increases inside the POD compared to the ambient temperature were 20°C at 12:30 on the first day and 21°C at 12:30 on day 2. These roughly corresponded to the times when the ambient air reached its minimum relative humidity. Wind speed was lowest in the morning when drying began and tended to gradually increase throughout the day. The lowest wind speed was 6 Kph (3.7 Mph) at 10:30 on day 2 when drying had just begun, and the highest wind speed, 15 Kph (9.3 Mph), was recorded at 16:30 on the first day of drying.

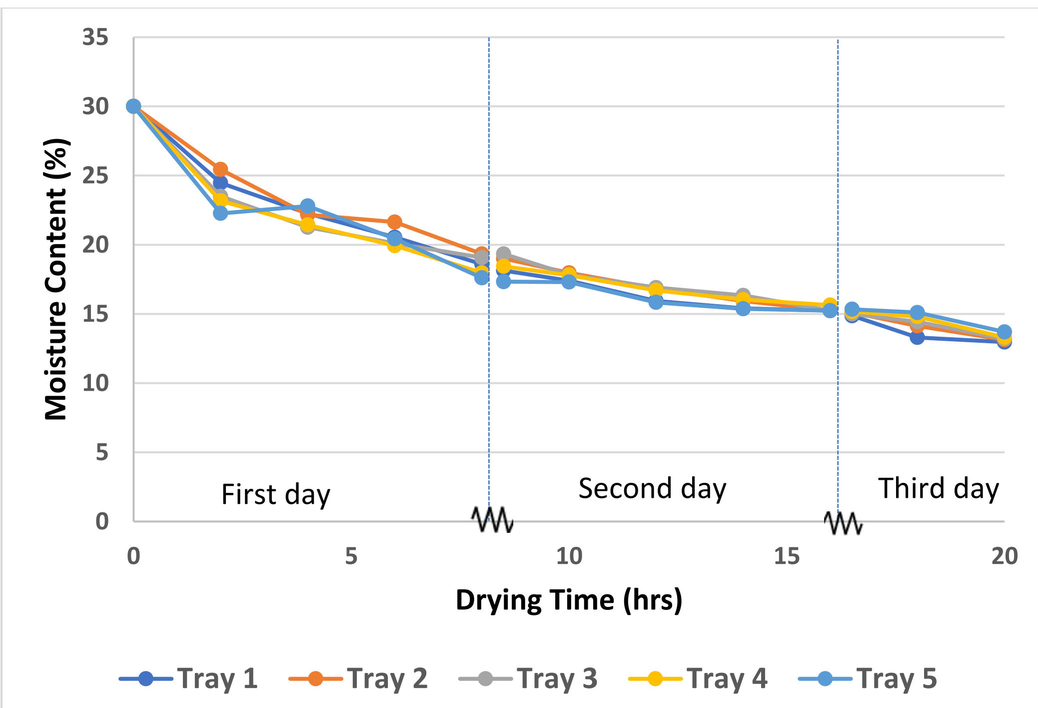


Figure 5.3 Moisture contents of the individual trays for the Nakuru county test

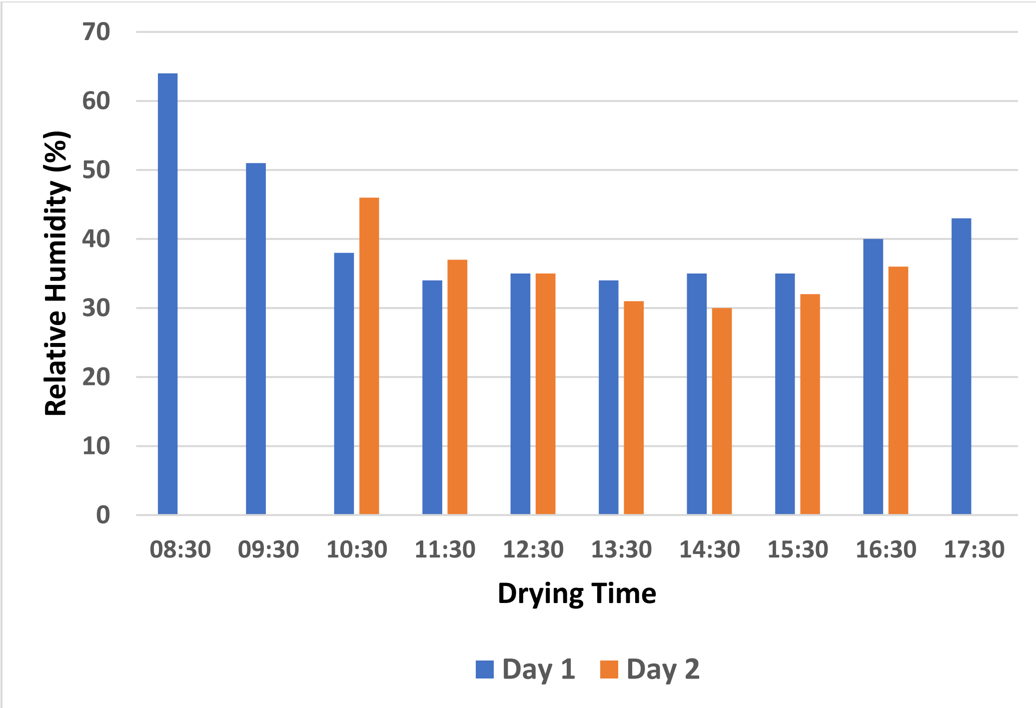


Figure 5.4 Ambient air relative humidities for the Nakuru County test

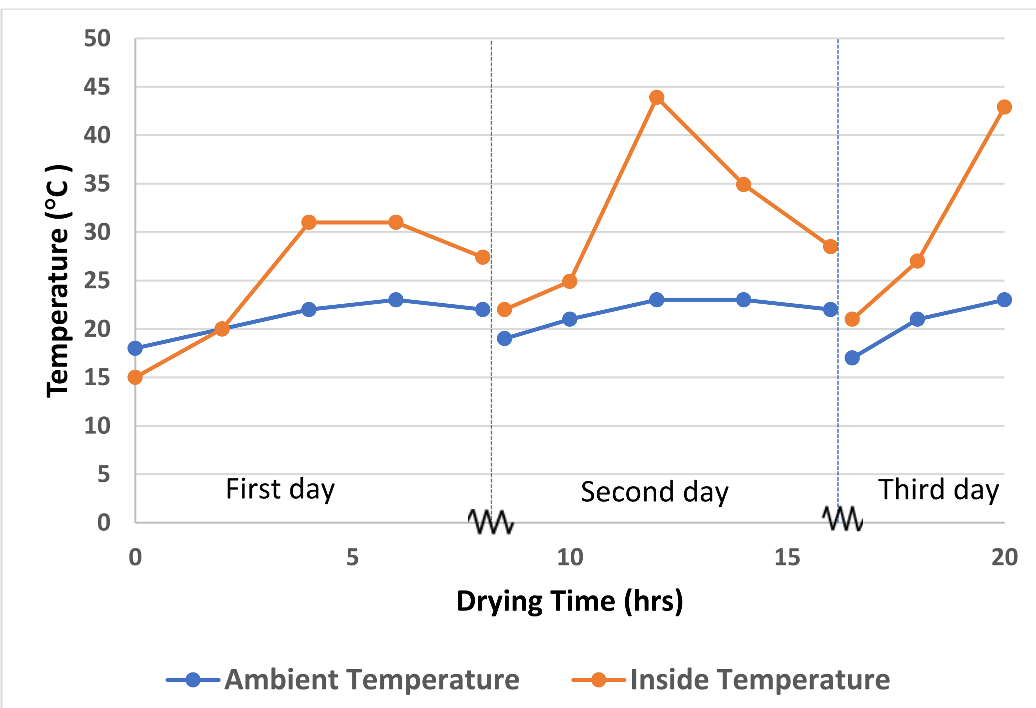


Figure 5.5 Temperatures measured during the test in Nakuru County

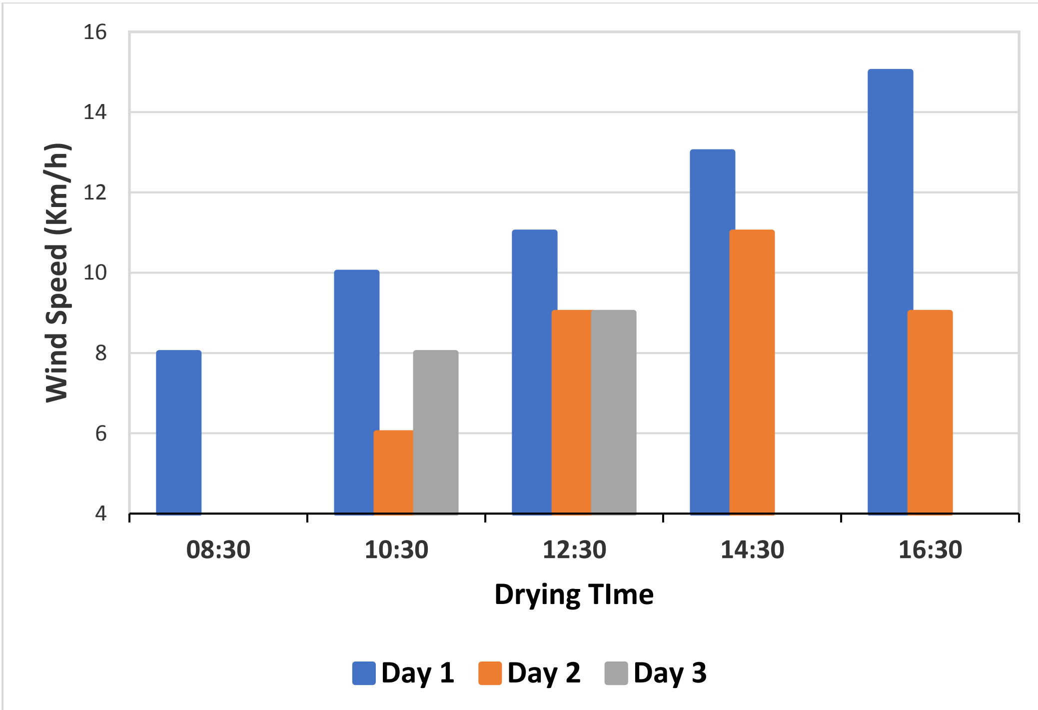


Figure 5.6 Wind speeds measured during the Nakuru County test

Figure 5.7 shows the results for the drying test conducted in Trans-Nzoia county. Sixty kg of wet maize were dried in this test. The initial moisture content of the maize was 29%. After 20 hours of drying over three calendar days, the moisture content reached 13.9% giving an average drying rate of 0.755 percentage points of moisture reduction per hour. The average moisture content decreased by 12.5 percentage points during the first day of drying giving a drying rate of 1.25 percentage points moisture reduction per hour for that first day when maize moisture was high.

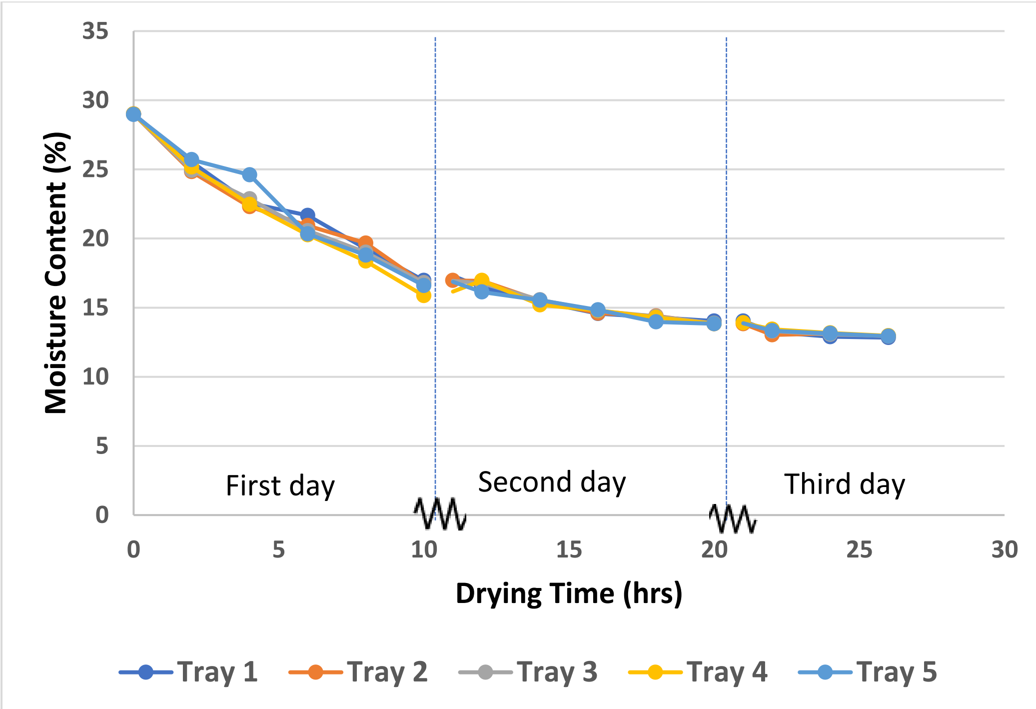


Figure 5.7 Moisture contents of individual trays for the test in Trans Nzoia County

The ambient relative humidities, measured at 2 hour intervals on the days when the Trans Nzoia county test was conducted, are shown in Figure 5.8. The relative humidity at 08:00 varied from 30% to 65% and, with the exception of the first day, continued to decrease until about 14:00. On the first day, the relative humidity first increased and then decreased. For all three days, the relative humidity gradually increased towards the end of the day. The temperatures and wind speeds are plotted in Figures 5.9 and 5.10. During the first day of drying, the temperature inside the POD was 1 to 3°C lower than ambient temperature before 16:00. After 16:00 on the first day the temperature inside the dryer was higher than the ambient temperature. . One possible explanation of why the temperature inside the dryer was lower than the temperature inside the plastic covering of the POD is that there was evaporative cooling. The maize moisture content was high, leading to a high rate of moisture evaporation. More heat may have been given up by the air to evaporate the moisture from the maize than the heat the air gained from solar radiation. On Day 2 before 10:00 the temperature inside the dryer was below the ambient temperature. This may have been the result of the rapid ambient temperature increase, from 23.5°C to 30.3°, between 10:00 and 12:00. At 18:00 the temperature inside the dryer again fell below the ambient temperature. Weather records indicated that it was partly cloudy at 14:00, mostly cloudy at 16:00 and partly cloudy at 18:00. The ambient temperatures at 14:00 and 16:00 were 31.8°C and 29.9°C, respectively. The reduced solar radiation could explain the drop in air temperature inside the dryer. For most of the time during the third day, the temperature inside the dryer was higher than ambient. Although there were clouds in the sky, the relative humidity remained low (Figure 5.7).

Wind speeds were lowest in the morning (4 to 6 Kph or 2.5 to 3.8 Mph) and tended to increase during the day until they were 18 to 19 Kph (11.2 to 11.8 Mph) by 18:00. This means that the POD is able to operate on days when there is a significant wind velocity.

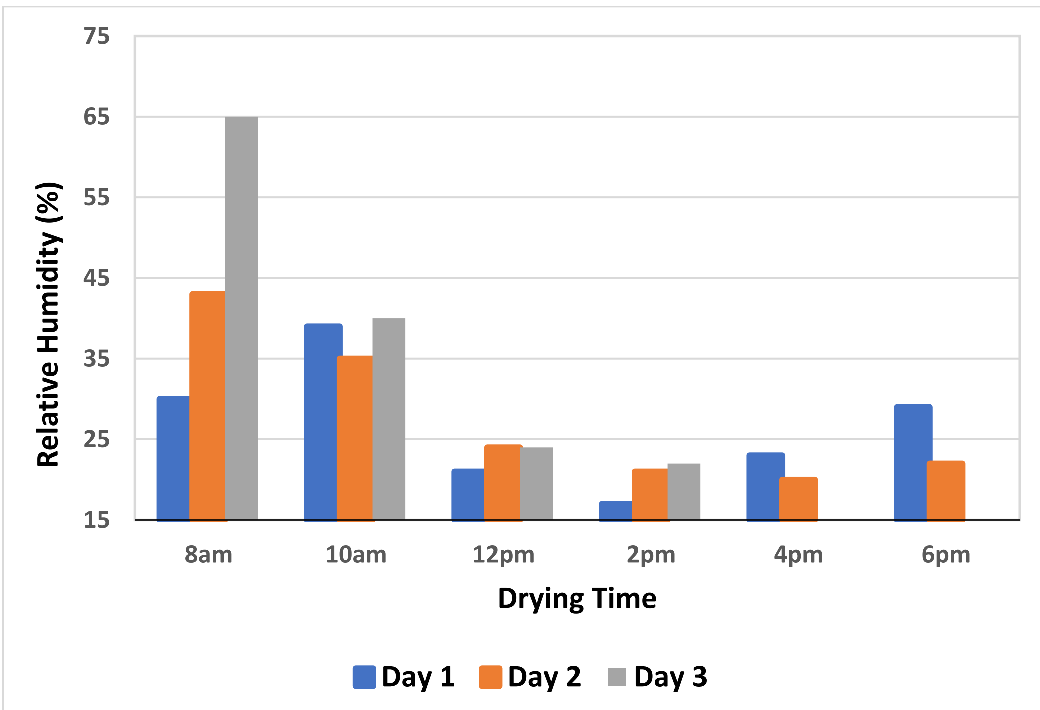


Figure 5.8 Relative humidities measured during the Trans Nzoia County test

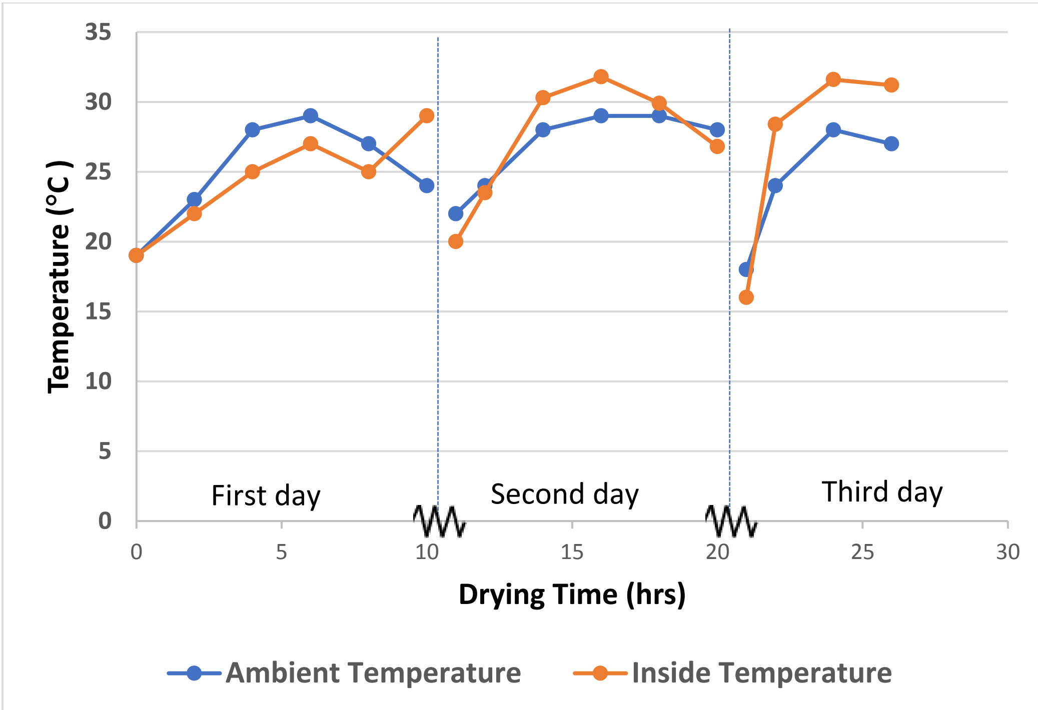


Figure 5.9 Temperatures measured during the Trans Nzoia County test

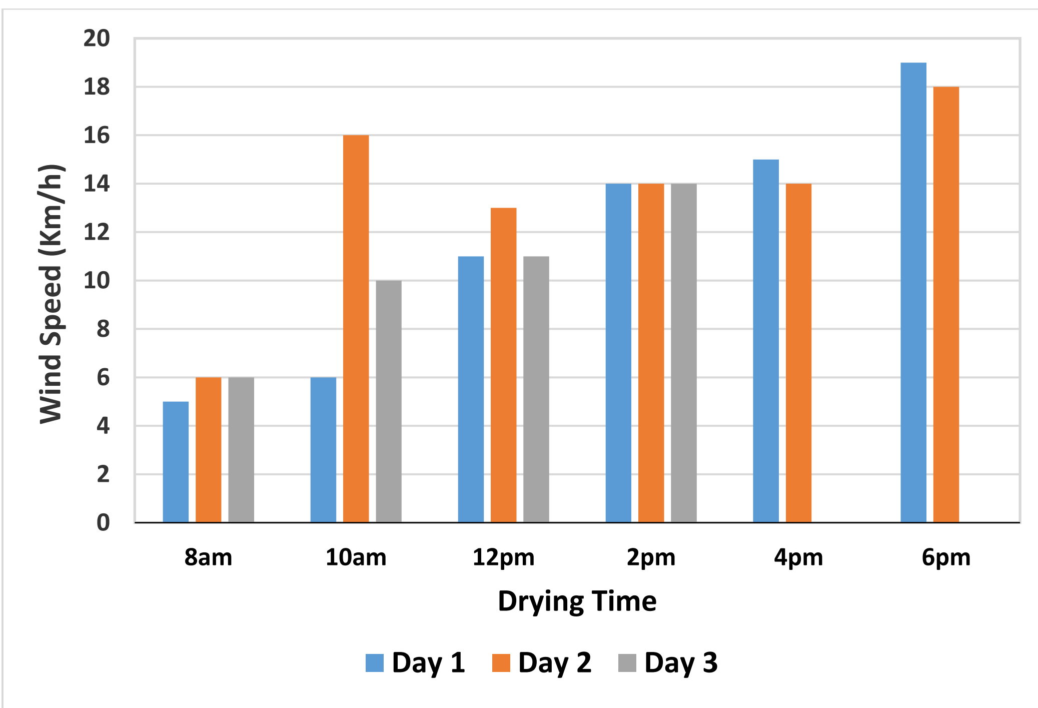


Figure 5.10 Wind speeds measured during the Trans Nzoia County test

The results for the drying test conducted at Uasin Gishu are shown in Figure 5.11. Sixty kgs of wet maize were dried in the test. The initial moisture content of the maize was 26% and the final moisture content was 12.6%. The total drying time was 16 hours over two calendar days and the average drying rate was 0.838 percentage points of moisture reduction per hour. The moisture content dropped rapidly during the first 2 hours of drying. Tray 1 (dark blue line) lost 9.8 percentage points of moisture in those 2 hours giving that interval the highest drying rate observed in POD testing, 4.9 percentage points of moisture reduction per hour.

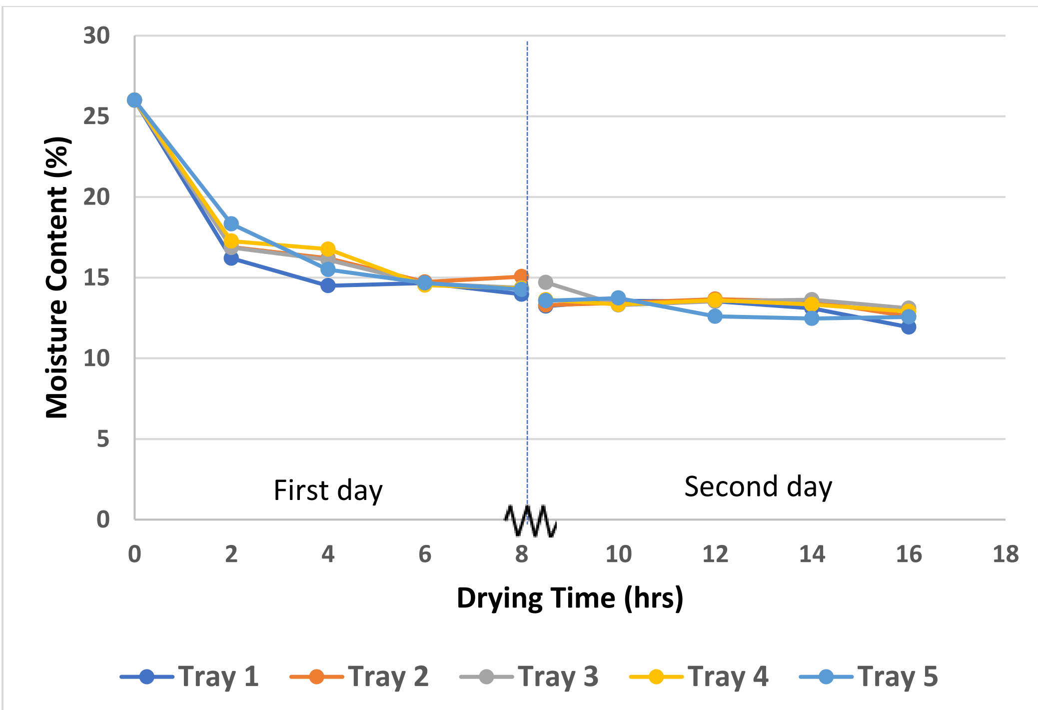


Figure 5.11 Moisture contents of the individual trays for the test in Uasin Gishu County

The ambient relative humidities measured during the test in Uasin Gishu county are shown in Figure 5.12. During the 2 days of drying, the lowest relative humidity was 19 % and the highest was 57 %. The relative humidities for the second day of drying were higher than those of the first day with the highest value, 57 %, occurring when the test was begun at 10:00 on the second day. Temperatures and wind speeds are graphed in Figures 5.13 and 5.14. The temperature inside the POD was 1°C to 11.8°C higher than the ambient temperature with greater differences occurring in the afternoons, as expected. Wind speed varied from 5 to 32 km per hour (3 to 20 Mph). The lowest recorded wind speed occurred at 8 am on the second day, but testing did not start until 10 am on both days.

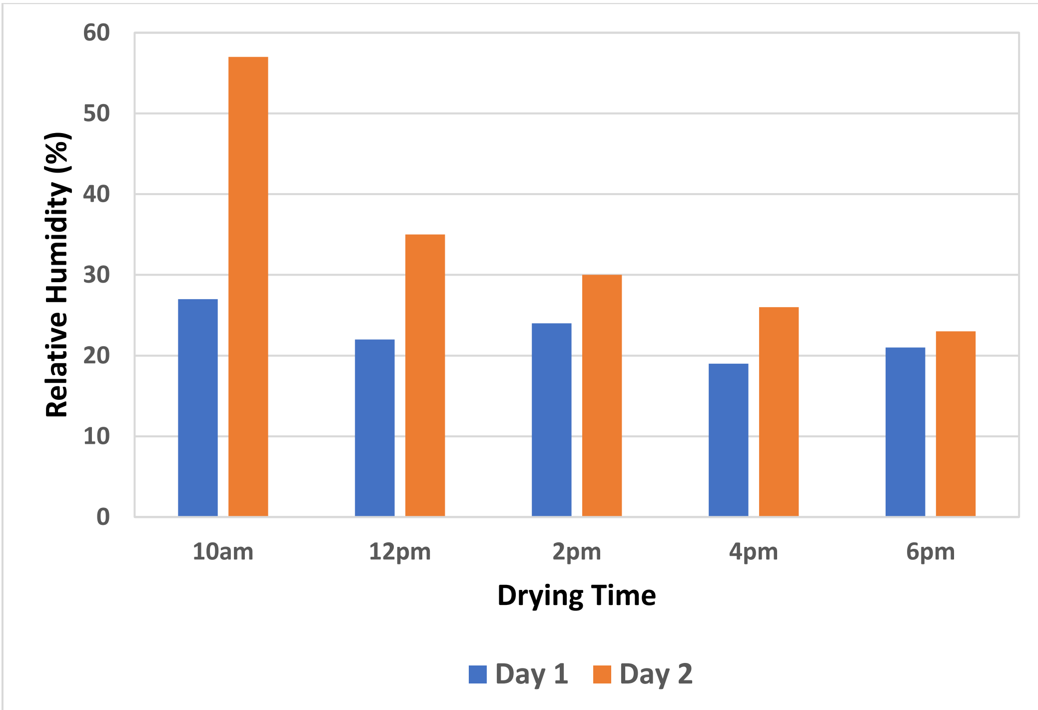


Figure 5.12 Relative humidities measured during the test in Uasin Gishu County

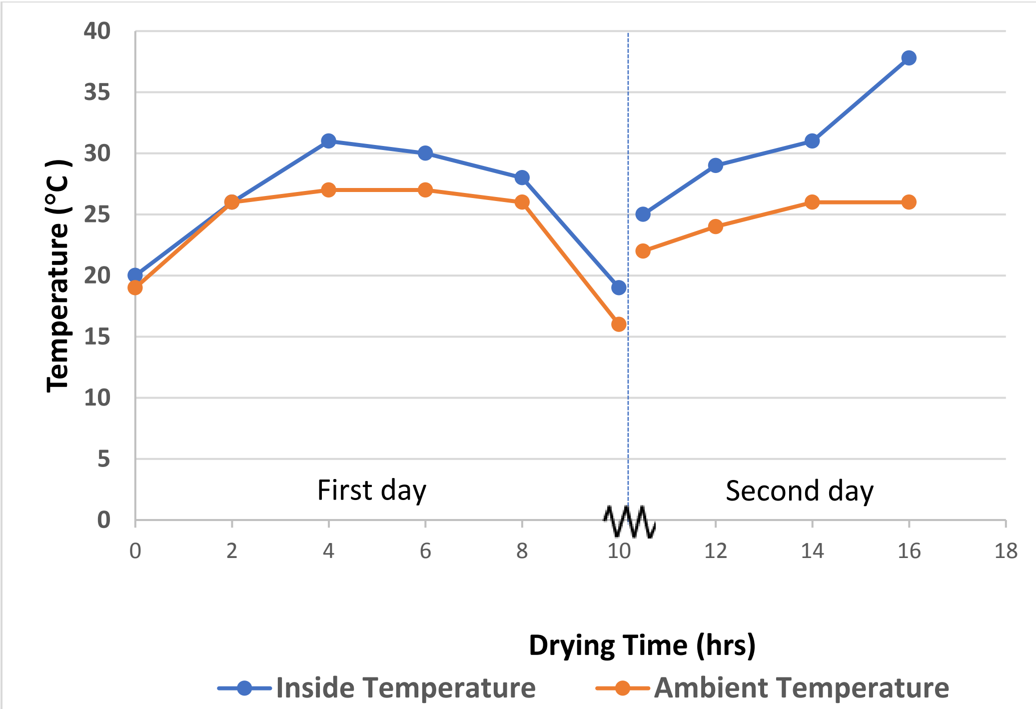


Figure 5.13 Temperatures measured during the test in Uasin Gishu County

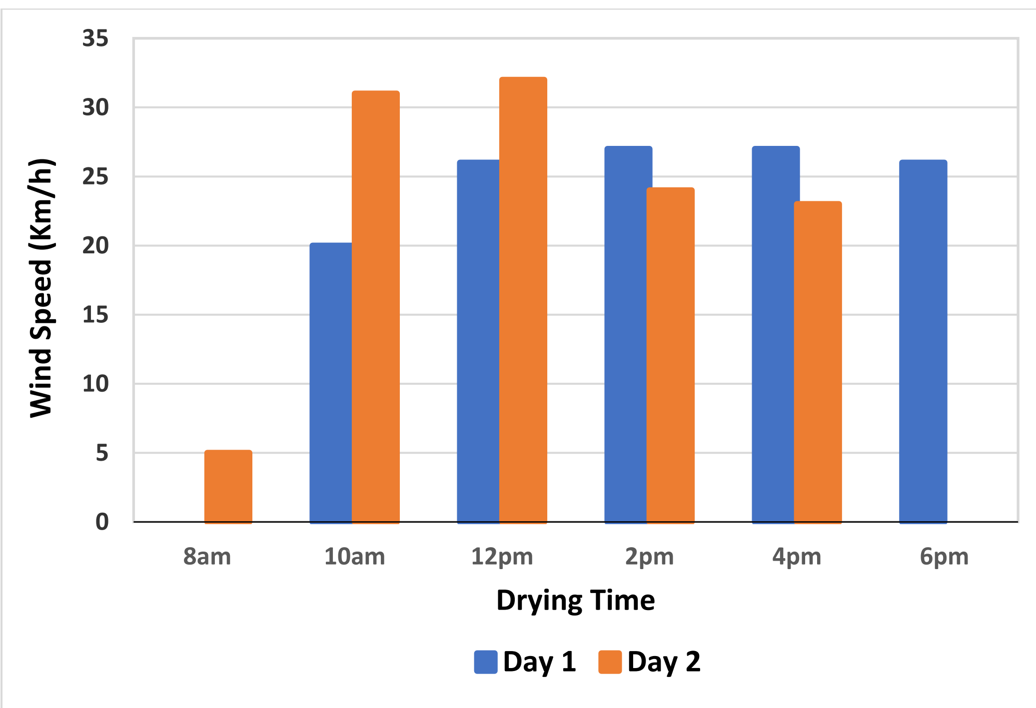


Figure 5.14 Wind speeds measured during the test in Uasin Gishu County

The last of the three tests conducted in March was conducted in Nandi County using 50 kg of maize. The initial moisture content of the maize in the POD was 36.4%, and the final moisture content was 13.0%. The drying results are shown in Figure 5.15. It took 24 hours of drying, spread over 3 calendar days, to complete the test. The average drying rate was 0.975 percentage points per hour, which is the highest overall drying rate that has been achieved to date by the POD. The fastest drying occurred during the first two hours of the test. A total of 17.3 percentage points of moisture content were removed during the 24 hours of drying. At the end of the first day of drying, the maize was collected and stored overnight. The moisture content decreased by around 1.5 percentage points during that overnight period. There is no apparent explanation for this decrease. It is possible that when the moisture meter measurements were taken, uneven moisture distribution in the maize led to a reading that was higher than the actual moisture. The maize may have equilibrated overnight resulting in a better moisture meter reading the next morning before the resumption of drying.

This is the only POD test of the four conducted in November 2018 and March 2019 in which 50 kg of maize was also dried on a tarp. The initial moisture content of the maize on the tarp was 36.8 %, which is 0.4 percentage points higher than the initial moisture content of the maize dried in the POD. A total of 100 kg of wet maize were dried in POD (50 kg) and on the tarp (50 kg). The drying curves for the maize are included in Figure 5.15. Drying on the tarp was stopped when the maize being dried in the POD reached its target moisture. At that time, the maize that was dried on the tarp had a moisture content of 16.3%. The average drying rate was 0.85 percentage points per hour. This is one of the fastest drying rates observed for drying on a tarp, reflecting the excellent weather conditions for drying. As can be seen in Figure 5.15, the good drying conditions also helped the POD perform well and it dried the maize more rapidly than the tarp.

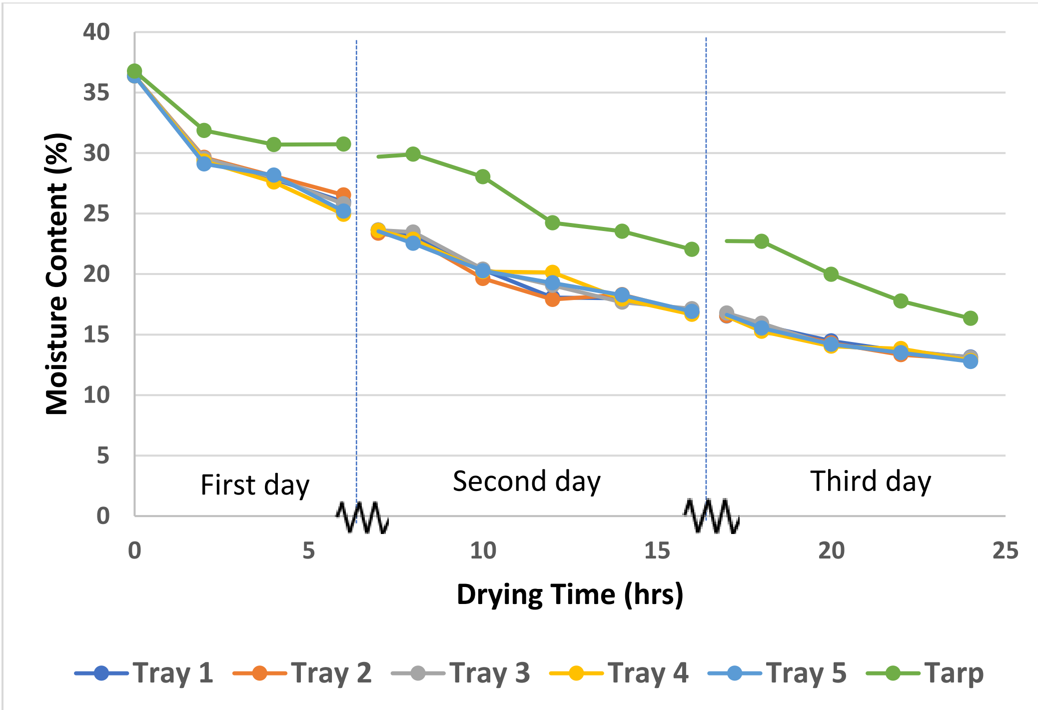


Figure 5.15 Moisture contents for individual trays for the March 2019 POD test in Nandi County

The temperature and wind speed data recorded for the Nandi County test are shown in Figures 5.16 and 5.17. The temperature inside the POD was 3°C to 15°C higher than the ambient temperature during the test. A closer examination of Figure 5.16 reveals that the peak temperature rise was attained during the middle of the day for each of the three calendar days of the drying test.

The wind speeds, shown in Figure 5.17, varied from 10 to 24 km per hour (6.2 to 15. Mph). The highest wind speed of 24 km per hour (15 Mph) was recorded at 14:00 on the third day of drying. The wind speeds observed in the tests conducted in Kenya in March of 2018 were greater than the wind speeds typically encountered in tests conducted at Purdue.

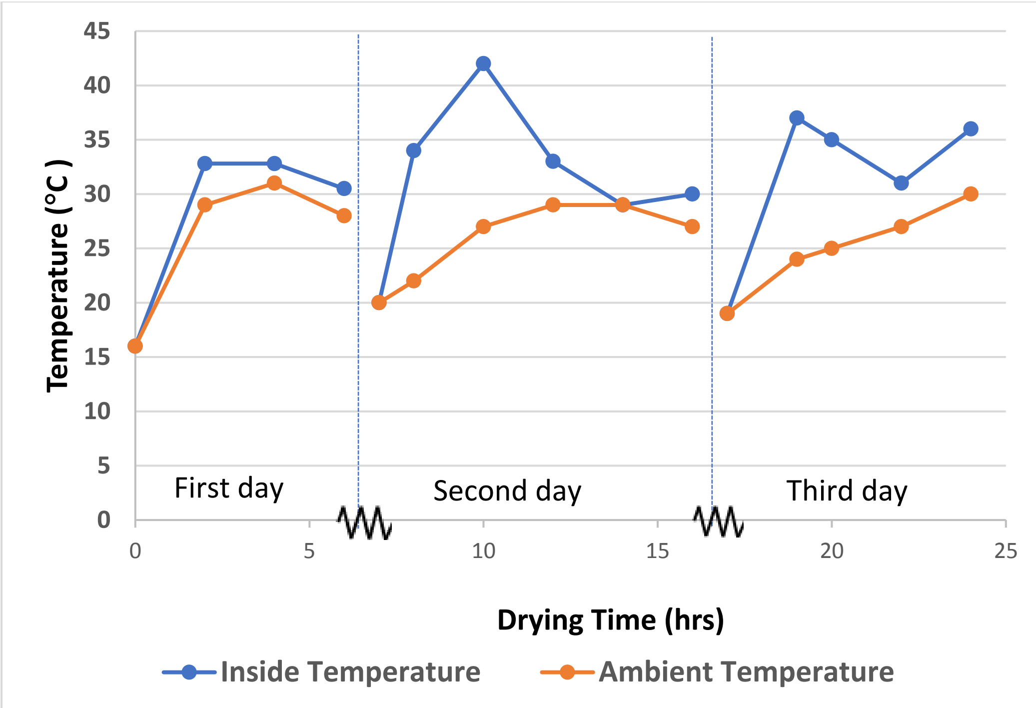


Figure 5.16 Temperatures measured during the Nandi County test

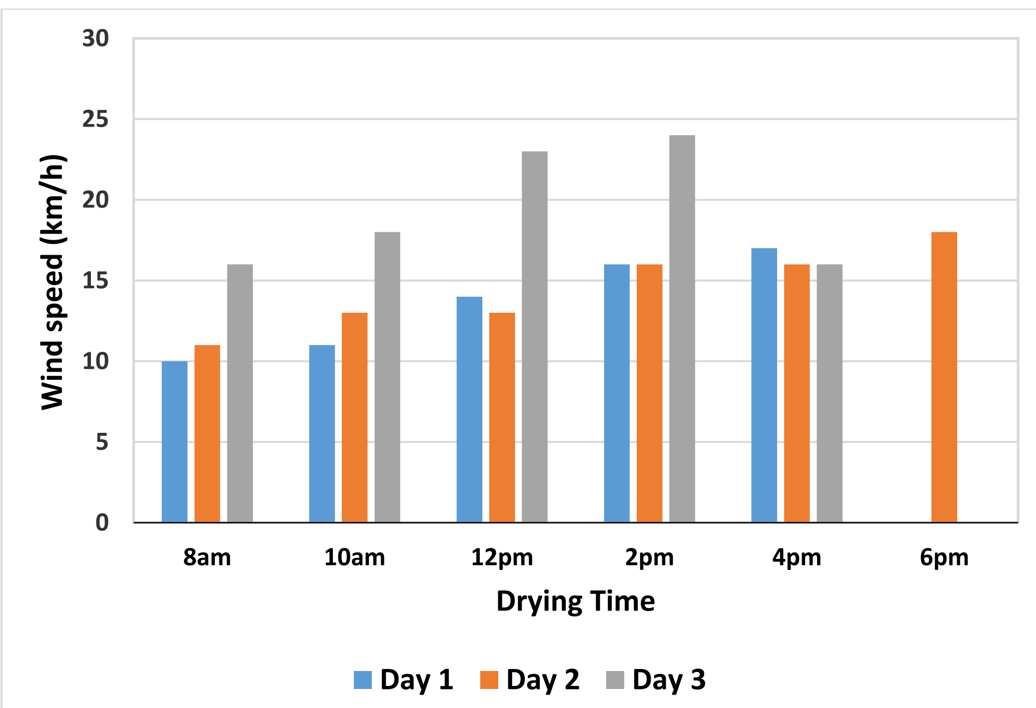


Figure 5.17 Wind speed measurements made during the Nandi County test

5.3 Conclusion

The tests that evaluated the performance of the POD in Kenya provided important insights on the performance of the POD in that country compared to performance in West Lafayette, Indiana. Table 5.2 summarizes the results of tests conducted in Kenya.

Table 5.2 Summary of all Kenya tests

Location	Date	Drying Hours	Begin MC	End MC	Pts/hr
Nakuru County (KALRO)	5/15/2018	8	21	16.3	0.6
	5/16	8	17.3	14.7	0.3
	overall	16	21	14.7	0.4
Nakuru County Njoro	11/7 /2018	8	30	18.5	1.44
	11/8	8	18.4	15.3	0.39
	11/9	4	15.1	13.3	0.45
	overall	20	30	13.3	0.84
Uasin Gishu	March '19 - Day 1	8	26	14.4	1.45
	March '19 - Day 2	8	13.7	12.6	0.14
	overall	16	26	12.6	0.84
Trans-Nzoia	March '19 – Day 1	10	29	16.6	1.24
	March '19 - Day 2	10	16.7	13.9	0.28
	March ’19 – Day 3	6	13.9	12.9	0.17
	overall	26	29	13.0	0.62
Nandi County	March '19 - Day 1	6	36.4	25.7	1.78
	March '19 - Day 2	10	23.6	16.9	0.67
	March '19 - Day 3	8	16.6	13	0.45
	overall	24	36.4	13	0.98
Nandi County outside tray	March '19 - Day 1	6	36.4	30.7	0.95
	March '19 - Day 2	10	29.7	22	0.77
	March '19 - Day 3	8	22.7	16.3	0.80
	overall	24	36.4	16.3	0.84

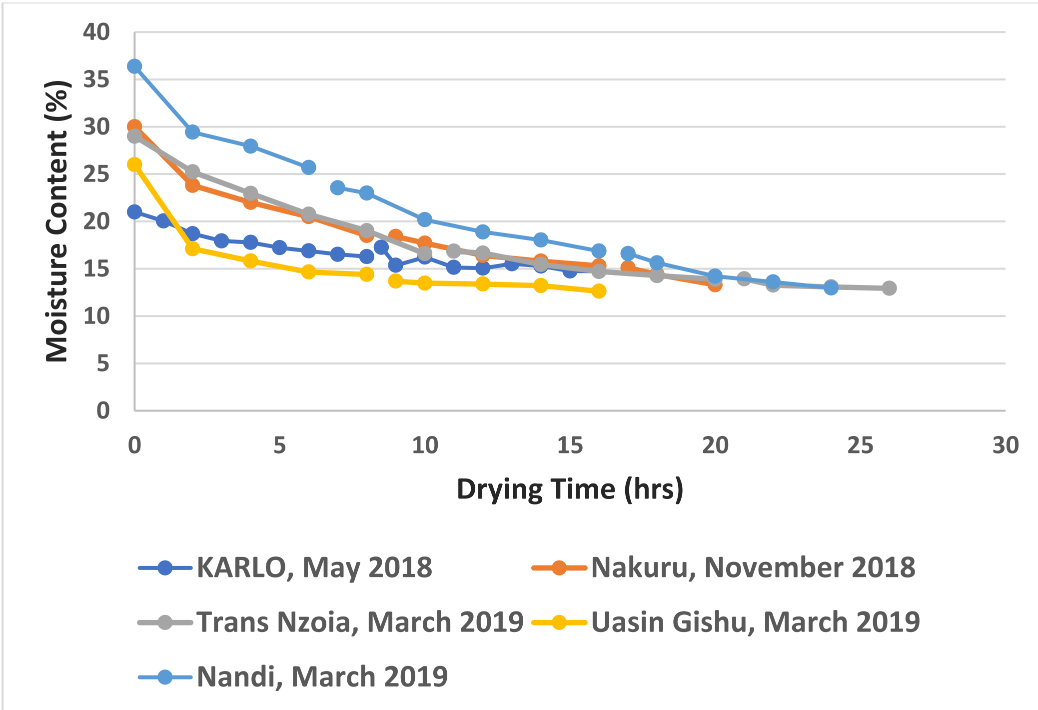


Figure 5.18 Comparison of all Kenya tests

The following comments were made by Dr. Ketiem in his report of the drying tests he conducted in November of 2018 and March of 2019 [3]:

1. The POD achieved a higher drying rate and lower moisture content values at any given time compared to the open sun drying method.
2. The POD adequately protected the grains from birds, animals, and any air borne contaminants, which enhanced the phytosanitary conditions [during drying] of the [maize].

The following are conclusions drawn from this study:

1. The average drying rate of the POD test conducted in May 2018 in Kenya was 0.391 percentage points of moisture reduction per hour. The drying rates of the tests conducted in November 2018 and March 2019 were faster, varying from 0.581 to 0.975 percentage points of moisture reduction per hour. The fastest drying occurred in Nandi County which was the fastest average drying rate that the POD has achieved to date. The slowest drying rate occurred in the test conducted in Trans-Nzoia County.

2. The differences in drying rate could have been caused by differences in weather conditions. For example, for the three tests conducted in March, the Nandi County test had the fastest drying rate while the Trans Nzoia test had the slowest drying rate. The average ambient temperature and relative humidity during the hours when the Nandi county test was being conducted were 31°C and 28%, respectively while those same averages were 25.7°C and 31% for the Trans Nzoia County test.
3. The average drying rate for the test conducted in Nakuru County in May of 2018 was 0.39 percentage points of moisture per hour. The average maximum temperature for the two days when the test was conducted was 25°C and the average of the relative humidities calculated from the dry bulb temperatures recorded by the KALRO weather station for those days, was 73%. In addition, the Okta cloud cover rating was 4 where a rating of 8 means the sky is completely overcast. Therefore, the weather conditions during the May test were very poor for drying. This is a second illustration of the effect of weather conditions on the performance of the POD. The final moisture content of the maize was 14.8%. Using the Chung equation and the dry bulb and wet bulb measurements made at the KALRO weather station for the second day of drying (Table 5.1, a temperature of 17.5°C and a relative humidity of 77%), the predicted equilibrium moisture content is 16.0%. The Chung equation can be used to calculate the relative humidity of air at 17.5°C that would be in equilibrium with maize at 14.8% moisture content. The air would have to have been heated enough to reduce its relative humidity to 71% or below.
4. The fastest observed reduction in maize moisture content was a decrease of 9.8 percentage points during the first 2 hours of drying in Uasin Gishu County when the maize moisture content was drying from 26% to 15% moisture. This is a drying rate of 4.9 percentage points of moisture content reduction per hour.
5. Considering the drying rates for the individual trays of the POD, faster drying was observed in the trays at the opposite ends of the drying bed (trays 1 and 5) as compared to the tray in the center (tray 3). However, in the Kenya tests the moisture contents of the 5 trays were more nearly uniform compared to the variations in moisture contents among the trays in the tests conducted at Purdue. The standard deviation of the test conducted in

Trans Nzoia was 0.05 which was the lowest standard deviation of the final moisture contents of the trays that the POD has achieved to date.

5.4 References

[1] A. Raman, R. Stroshine, “Annual report Solar Pico Crop Dryer (POD) low cost on farm solar grain dryer for small holder farmers in Africa,” Unpublished research report provided to Purdue’s Food Processing Laboratory, Purdue University, 2017.

[2] R. Stroshine, Personal communication, Purdue University, May 2019.

[3] P. Ketiem, “Multi-location solar POD trials in western Kenya: technical report,” Unpublished research report provided to Purdue’s Food Processing Laboratory, Kenya Agricultural Livestock Research Organization, 2019.

CHAPTER 6. INVESTIGATION OF SEVERAL FACTORS THAT AFFECT THE POD DRYING RATE BASED ON THIN LAYER DRYING EQUATION

6.1 Introduction

When grain is harvested at moisture contents that are high enough to allow the growth of xerophytic fungi, drying is a crucial factor in maintaining the good quality of the grain during storage. The main objective of drying is to reduce the water activity of the seeds in order to extend the storage life of the product. In general, the so called "storage fungi", the xerophytic organisms that grow on grain, cannot grow at water activities of 0.65 or below [1]. However, optimizing performance of a dryer by conducting tests can be difficult and time consuming because it would require many tests to be conducted [2]. Dryer performance is affected by many factors including weather conditions, initial moisture content of the grain, air flow rate, and air temperature and relative humidity. An alternative to physical trials is to use appropriate mathematical equations that describe drying behavior of the grain and airflow through the grain to gain insight into factors that affect the performance of a drying system [3].

A thin layer drying equation was adapted for use in predicting the drying rate in the POD. The adaptation allows investigation of some of the factors that affect the POD's performance such as ambient air conditions and airflow rate. It was assumed that after the equation was adjusted by replacing the relative humidity with an effective relative humidity and the temperature with an effective temperature, it would give at least an approximate prediction of the rate at which maize will dry in the POD. The physical basis for the adjustments are explained below. The maize depth in the trays does not change (the geometry is constant) and the corn is thoroughly mixed approximately every four hours prior to taking samples for moisture content. The mixing of the maize eliminates the gradient in moisture content that develops. The thin layer drying equation does not account for gradients in moisture content. These are reasons why it is worthwhile to try this approach. No articles were found in the literature that indicate this approach has been taken by other investigators.

A number of researchers have developed thin-layer drying equations for shelled maize using experimental data obtained from laboratory tests conducted in specific ranges of maize moisture content and air conditions. Table 6.1 summarizes several of the thin-layer drying equations found in the literature [4, 5, 6, 7, 8].

Table 6.1 Thin-layer drying equations.

Model	Equation	Reference
Newton	$MR = \exp(-kt)$	O'Callaghan et al. [4]
Page	$MR = \exp(-kt^n)$	Page [5]
Henderson and Pabis	$MR = a*\exp(-kt)$	Henderson and Pabis [6]
Logarithmic	$MR = a*\exp(-kt)+c$	Yagcıoglu et al. [7]
Tow term	$MR = a*\exp(-k_1t)+ b*\exp(-k_2t)$	Henderson [8]

The approach taken to simulating drying in the POD was to choose an appropriate equation from the list above and then use temperature and relative humidity data collected by the Hobo sensors from several of the POD tests to identify the values of multipliers for temperature and relative humidity that allow the equation to make reasonable predictions of drying curves for those same tests. Airflow data for the tests were obtained by conducting tests to develop a fan curve for the fans that are used in the dryer.

The objective of the modeling study was to:

1. Develop an approach to using a thin layer drying equation to predict the drying rate of the POD given weather conditions (air temperature and relative humidity, solar heating of the air in the POD)) and airflow rate.
2. To validate the approach by comparing its predictions with data from previous experiments.
3. To use the adapted equation to investigate how ambient air temperature and relative humidity, heating of the ambient air by solar radiation, and airflow rate affect the drying rate of the POD and to reveal what approaches could be taken to increase the drying rate or reduce the energy requirements.

6.2 Approach

6.2.1 Determine the drying airflow

The airflow rate through the product being dried is one of the essential pieces of information used by mathematical models of drying. Equations are available for predicting the airflow through shelled maize and other seeds if a fan curve is available. The fan curve describes the relationship between resistance to airflow (operating pressure) and the airflow that is delivered by the fan. As resistance increases, pressure increases and airflow decreases. Fan curves are available from the manufacturers of fans that are used to dry seeds such as maize. However, the fans used in the POD were 120 mm Ultra Silent Case Fans (Apevia Corporation, Neihu, Taipei, Taiwan) manufactured for providing cooling to computers and related equipment. No fan curves were available. Therefore, it was necessary to conduct a test to determine the fan curve for these fans.

The fan curve was determined by mounting the fan in a test fixture that was designed to follow as closely as possible the specifications (Figure 6.1) found in AMCA 210: Laboratory Methods of Testing Fans for Aerodynamic Performance Ratings [10]. The first test setup used, which was assembled on a laboratory bench top, is shown in Figure 6.2. Two 12.7 cm (5-inch) diameter galvanized take off start collars, purchased from Home Depot, were mounted on each side of the fan. Weather stripping was applied to both faces of the fans before the collars were brought into position. Four iron C-Clamps were used to secure the collars to the fans. As the clamps were tightened the weather stripping was compressed, forming a tight seal. A piece of 12.7 cm (5 inch) diameter plastic tube that was 91.4 cm (36 inches) in length was attached to the end of one of the collars using duct tape. Four equally spaced holes were drilled around the circumference of the plastic tube and plastic male hose barb adapters were threaded into those holes. Flexible polyethylene tubing was connected to the adapters and the flexible tubing from two adapters on opposite sides of the plastic tube were connected to a barbed plastic T connector. Those two sets of two connecters were in turn connected to a single T connector with the flexible tubing. The flexible tubing was used to connect the last T connector to the handheld digital manometer UEI EM201 (UEI Test Instruments, Beaverton, OR). The digital manometer was used to obtain precise values of pressure. A 12.7 cm (5 inch) diameter W1008 Blast Gate (Woodstock International, Inc., Bellingham, Washington, USA) was attached to the end of the plastic tube with duct tape to allow the airflow to be throttled. Using duct tape, a Testo 417 portable digital vane anemometer (Testo North America, West Chester, PA) was affixed to the takeoff collar opposite to the plastic tube and blast gate.

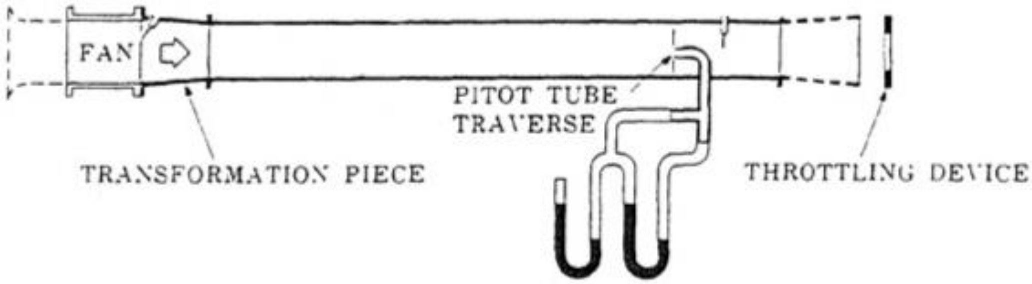


Figure 6.1 Configuration used for testing fan performance (airflow versus pressure head) [10]

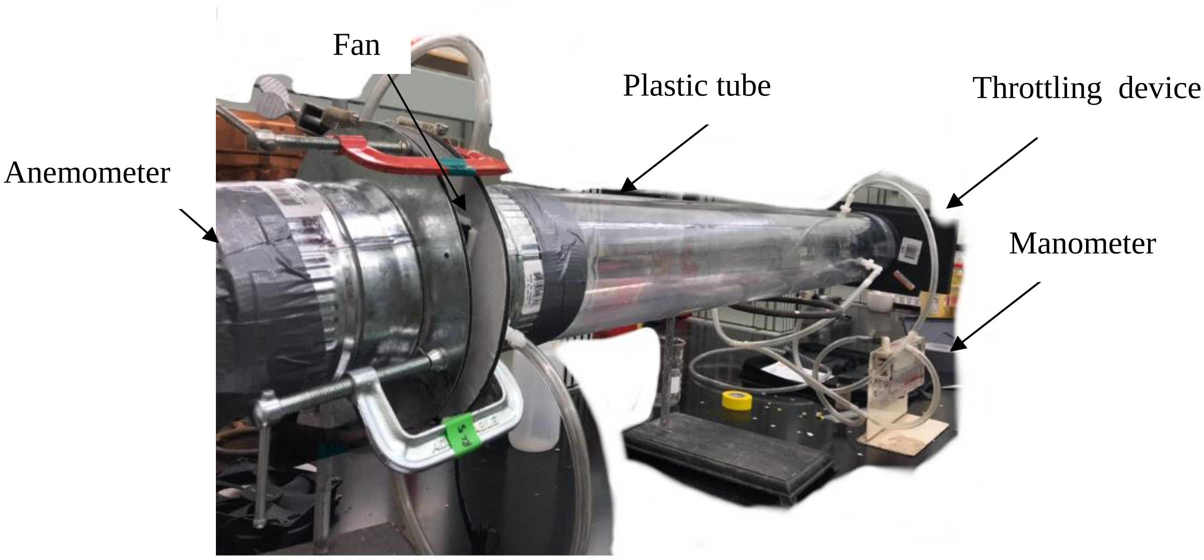


Figure 6.2 Configuration of the fan testing device (with plastic tube)

The following is the procedure used when conducting the fan tests. The blast gate was fully opened, the fan was connected to a battery so that the blade began rotating, the air velocity was measured using the anemometer and recorded, and the pressure reading from the digital manometer was recorded. Airflow was calculated by multiplying the area of the collar by the velocity measured with the anemometer. The blast gate was closed in increments to give a series of measurements.

After two preliminary tests with the plastic tube, the tube was removed and the blast gate was connected directly to the collar. This was done because of concern that with the low airflows generated by the fan, there would be a significant pressure drop down the length of the plastic tube that would make the pressure appear to be smaller than it actually was. Holes were drilled in the metal collar to allow the male hose barb connectors to be fitted directly into the collar. The connectors were affixed to the collar with plastic cement. When this configuration (shown in Figure 6.3) was used the air began to flow in the opposite direction when the blast gate was approximately three quarters of the way closed. The anemometer began to register a negative velocity and therefore the measurements were stopped.

Figure 6.3 Configuration of fan testing device (without plastic tube)

Figure 6.4 shows the plot of data for pressure drop versus airflow data generated during the fan test. Two tests were conducted with two different fans with identical specifications. The two fans are labeled as “fan 1” and “fan 2” in Figure 6.4. The X-axis is the pressure increase, ΔP, which was calculated using Equation 6.1. The anemometer was set to take an average value for airflow rate in one-minute intervals. The flow rate was taken twice and the values on the Y-axis of the graph are the averages of the two readings. A statistical ANOVA test was conducted to compare the data from the two fans using SAS (SAS Institute Inc, Cary, NC) and the results are shown in

Table 6.2. The comparison indicated, there was no significant difference in the data obtained from the two fans.

$$\Delta P = P_{static} - \frac{P_{static}}{Q_{max}^2} Q^2 \qquad (6.1)$$

Where, ΔP is the pressure drop in Pa, P_{static} is the fan static pressure in Pa, which is the difference between the velocity pressure at the fan outlet and the pressure at the fan inlet, Q is the airflow rate in m^3/hr, Q_{max} is the maximum value of airflow when the blast gate is wide open.

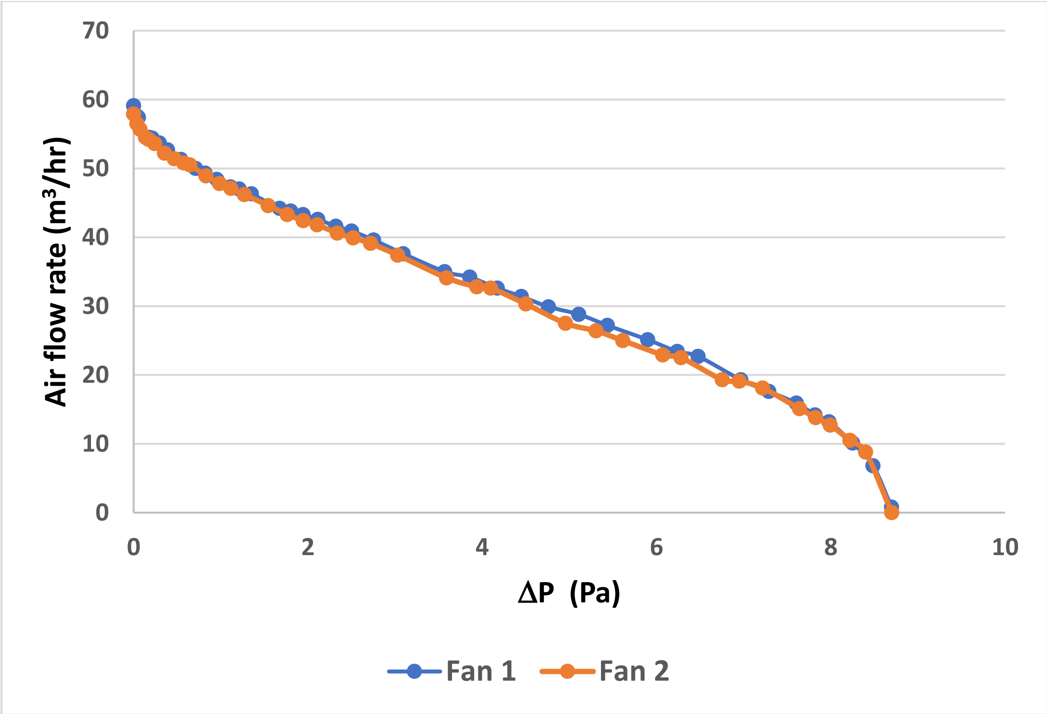


Figure 6.4 Relationship between pressure and airflow rate of the fans

Table 6.2 ANOVA test for comparison of fan 1 and fan 2 test results

Source	DF	Type I SS	Mean Square	F Value	Pr > F
pressure	1	14510.39032	14510.39032	1584.04	<.0001
fan	1	3.12500	3.12500	0.34	0.5611

6.2.2 Airflow resistance of the shelled maize

The resistance to airflow through agricultural materials has been studied for many years. Several theoretical models have been developed relating pressure drop to airflow. Three models for drying at low airflow rates were evaluated in this study.

The most frequently used empirical model is the one proposed by Shedd [11] who proposed that the following equation could be used to describe the relationship between the pressure drop in the bed of grain, ΔP, and the air velocity:

$$Q = a(\Delta P)^b \qquad (6.2)$$

where, Q is airflow in $m^3/(m^2*s)$, and a and b are product-dependent constants obtained from experiments. According to Shedd [11], the constants for shelled maize are a=62, b=0.68.

Shedd [11] suggested that the range of airflow over which equation 6.3 is valid is 0.005 to 0.3 $m^3/(m^2*s)$. The Shedd equation is easy to incorporate into mathematical models and has been used by many engineers and scientists to estimate the pressure drop in bulk grain [12].

Due to the narrow range in which the Shedd equation applies, Hukill and Ives [13] proposed the following equation that they said was valid for the range in airflow of 0.01 to 2.0 $m^3/(m^2*s)$. ASABE Standard D272.3 [14] recommends the use of their equation for predicting pressure drop for several types of grain, including maize:

$$\frac{\Delta P}{L} = \frac{aQ^2}{log_e(1+bQ)} \qquad (6.3)$$

Where, L is the bed depth in m, Q is airflow in $m^3/(m^2*s)$, and, for shelled maize, $a = 9.77 * 10^3, and\ b = 8.55$.

Chuma et al. [15] used the Ramsin equation to determine the effect of the depth of the grain bed and the airflow rate on statistic pressure [16]:

$$\Delta P = aQ^n H^m \qquad (6.4)$$

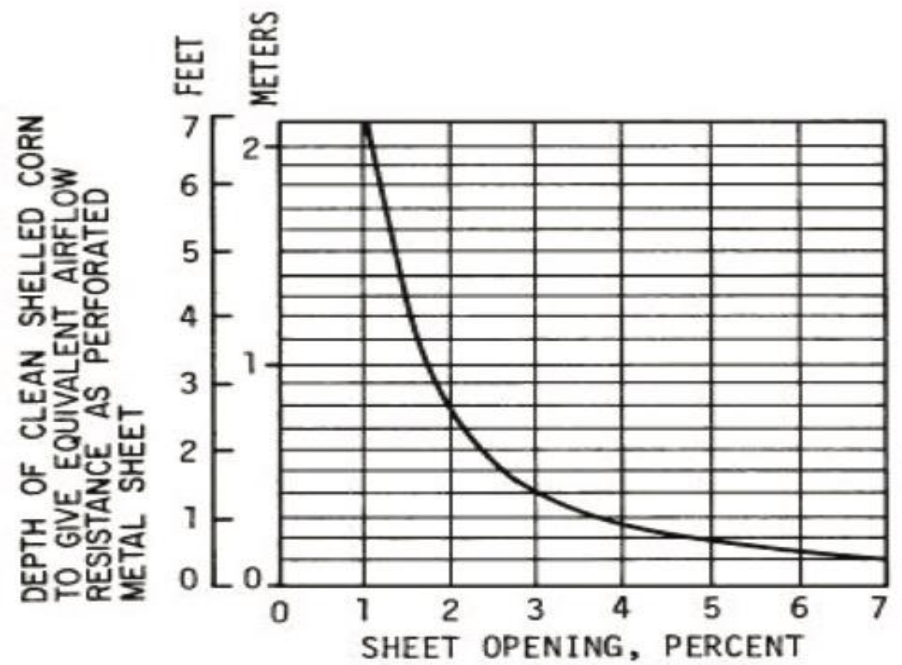
Where, ΔP is the pressure drop in mm of water (mmAq where 1 Pa = 9.77 mmAq), a, n, m are constants, Q is the airflow in $m^3/(m^2*s)$, and H is the depth of grain in meters. Chuma et al.[15] stated that constants a, n, and m depend on the type of grain and its moisture content. Table 6.3 is a table of constants that can be used in the equation when the air is passing through shelled maize at different moisture contents.

Table 6.3 Constants for shelled maize derived for the equation $\Delta P = aQ^n H^m$ at different moisture contents [15]

Material	Moisture content (% w.b.)	a	n	m
Shelled maize	33.3	90	1.69	1.03
	23.2	62	1.66	1.09
	16.8	42	1.53	1.05
	15.3	31	1.59	1.17
	12.9	18	1.72	1.29

As stated in Chapter 3, the bottoms of the trays used for the POD have holes in them. This means that the bottom of the trays would behave like a perforated sheet. If the proportion of the sheet area that is holes is too small, then a perforated sheet can offer a significant resistance to airflow. The size of the holes and number of holes were measured and this information was used to calculate the porosity of the bottom of the tray. The size of each hole is around 0.355 cm^2, and there are around 0.83 holes per cm^2 tray area. Therefore, the area of all the holes was about 30 % of the total area of the bottom of the tray. According to information given in ASABE Standard D272.3 [14] (Figure 6.5), "when sheet openings amount to 20 %, no additional resistance to airflow is produced." Therefore, the airflow resistance of the bottoms of the trays was assumed to be negligible.

The pressure drop for a 0.1 m depth of shelled maize at 13% moisture content was calculated for a range of airflow rates using the three equations. The results are plotted in Figure 6.6. The points where the fan curve and the airflow resistance curves intersect is where the fan will operate. This is the pressure and airflow rate used in modeling the POD. The points of intersection for the Chuma Equation, the Shedd Equation, and the Hukill and Ives Equation are (0.06 Pa, 56.55 m^3/hr), (0.7 Pa, 48.65 m^3/hr), and (4.12 Pa, 32.16 m^3/hr), respectively.



NOTES: When sheet openings amount to 20 percent, no additional resistance to airflow is produced.
A large number of small perforations is preferred to a smaller number of large perforations for the same amount of opening.
The curve shown is based on tests of sheets having width of perforations from 1 to 3.3 mm (0.04 to 0.13 in.).

Figure 6.5 Resistance to airflow of perforated metal sheets when supporting grain (Henderson) [14]

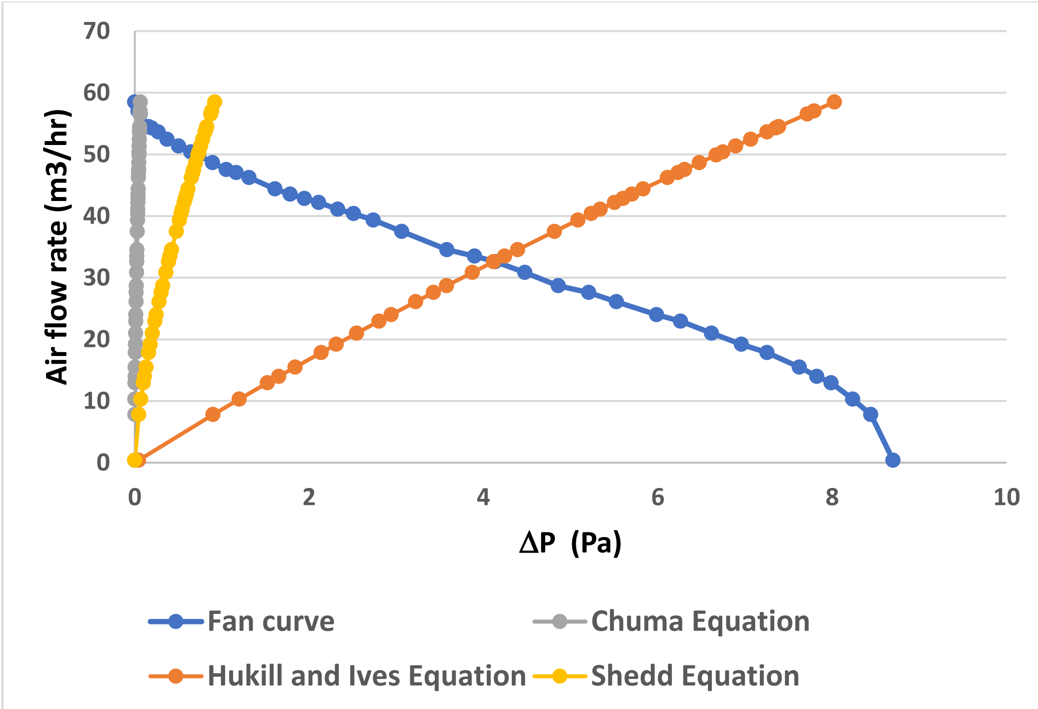


Figure 6.6 Comparison of Chuma, Hukill and Ives, and Shedd Equation [11, 13, 15]

The UEI handheld digital manometer was used to measure the pressure inside the plastic covering of the POD when the trays were filled to a depth of 0.1 meter with 13 % moisture content shelled maize. The sensor, which was at the end of a long section of flexible plastic tubing, was placed on the surface of the maize in the middle tray and then on the surface in both end trays. The pressure oscillated between 3.8 Pa and 4.3 Pa, so the average of 4.05 Pa was assumed to be the measured value. The pressure drop predicted by the Hukill and Ives Equation was the closest to the measured. It was 1.72 % lower than the observed value, and therefore their equation was used in the model for estimating airflow. The corresponding airflow rate is 32.16 m^3/hr (0.00893 m^3/s) for 1 fan. Since the fans were in parallel, the total airflow rate was assumed to be 7 times the airflow of a single fan, which is 225.12 m^3/hr or 0.0625 m^3/s. With the surface area of 1.989 m^2, the air velocity for the fan was calculated using the following equation:

$$v = Q/A \qquad (6.5)$$

According to the calculation, the velocity for a single fan would be 0.0045 m/s and therefore the velocity for 7 fans would be seven times this value, 0.0314 m/s.

6.2.3 Governing Equations

In 1980, Misra and Brooker [9] examined thin layer drying data for shelled maize obtained from all available sources and used the data to develop a thin-layer drying equation using the air temperature, air humidity, air velocity, and initial moisture content of the maize as independent variables. According to the preliminary test conducted by Misra and Brooker [9], the most promising model was the model developed by Page [5] and shown below, which had an R^2 value of 0.967, the highest value among the models tested. The Page Model was used in this study because the range of airflows and other variables had previously been validated.

$$MR = \exp(-kt^n) \qquad (6.6)$$

where n and k are constants specific to the type of grain, and "t" is the elapsed time since the beginning of the thin layer drying test. They defined moisture ratio, MR as the ratio of ($M – M_e$) to $M_0 – M_e$) where M_0 is the initial moisture content (dry basis) of the grain when drying begins, M_e is the moisture content (dry basis) of the grain when it is in equilibrium with the air being used to dry the grain, and M is the moisture content (dry basis) of the grain at time "t." This gave them the following thin-layer drying equation:

$$M = (M_o - M_e)\exp(-kt^n) + M_e, \qquad (6.7)$$

$$Where, k = exp(-7.1735 + 1.2793 * \ln(1.8T + 32) + 0.1378V), SI\ Unit$$

$$n = 0.0811 \ln(H) + 0.0078M_o$$

and V is the drying air velocity in m/s, T is the drying air temperature in °C, and H is the drying air relative humidity in percent. The equilibrium moisture content in percent (dry basis) can be determined using Equation 6.8,

$$M_e = E - F * \ln[-(T + C) * \ln(RH)] \qquad (6.8)$$

where RH is the relative humidity (decimal value), T is the temperature in °C and E, F, and C are constants depending on the type of grain. For shelled maize, E=0.33872, F=0.05897, and C=30.205 [17].

The ranges of the variables used in the tests from which data were taken when determining the constants for the equations were reported by Misra and Brooker and they are summarized in

Table 6.4 along with the values of the variables encountered in the POD tests. All of the values of the variables in the POD tests were within the ranges reported by Misra and Brooker.

Table 6.4 Ranges of the variables used to develop Equation 6.8

Variable	Range	Range for POD tests*
Drying air temperature	2.2 to 71 °C	21 to 52 °C
Drying air relative humidity	3 to 83 %	15 to 84 %
Drying air velocity	0.025 to 2.33 m/s	0.0314 m/s
Maize initial moisture content	18 to 60 % (d.b.)	24.7 to 43.2 % (d.b.)

*POD Test 20180718, Test 20180809 and Test 20180912

6.3 Validation of the approach

The use of the thin layer drying equation for predicting POD drying rate was studied using the data from Test 20180718, Test 20180809 and Test 20180912 in which Hobo sensors were used to measure the air conditions at several locations in the POD during the test. Data for the drying air temperature as well as drying air relative humidities were obtained from Hobo sensors and recorded in 5-minute intervals. The use of the sensors for this test and the placement of these sensors are described in Chapter 4. Two sensors were used to measure the temperature and relative humidity of air on the surface of maize. One was in Tray 3 and the other in Tray 1. One sensor was placed at the fan inlet. The fourth sensor was placed under Tray 1 to measure the relative humidity and temperature of the air exiting Tray 1.

Misra and Brooker's Equation predicted the drying rate for a single thin layer. However, the layer of maize dried in the POD was much thicker and cannot be considered a thin layer. The more realistic model is to assume the POD is a series of thin layers. For example, the POD drying bed could be divided into 10 layers. The air coming out of the first layer would be the air going into the next layer. Because the air has evaporated some of the moisture from the maize, it will have a higher relative humidity and a lower temperature. This will continue from one layer to the next until the air emerges from the 10th layer. The air emerging from that layer will be noticeably higher in relative humidity and lower in temperature. As relative humidity increases and temperature decreases, the drying rate will decrease. Therefore, if the top layer drying air relative humidity and temperature are applied to all 10 of the thin layers, the model will overestimate the drying rate of the POD.

In order to improve the simulation results, drying air relative humidity and temperature were replaced with an effective relative humidity and effective temperature, which were defined as follows:

$$RH_{eff} = A * \frac{1}{2} * (RH_{in} + RH_{out}) \quad (6.9)$$

$$T_{eff} = B * \frac{1}{2} * (T_{in} + T_{out}) \quad (6.10)$$

In Equation 6.9 and 6.10, effective relative humidity and effective temperature are assumed to be the average values of the air above the surface of the maize and the air exiting the POD. This assumes there is a linear relationship between distance traveled through the maize and the change in both RH and temperature. In actuality, it is unlikely that the relationships are linear. For that reason the correction factors A and B were applied to the equations.

When the model is used to simulate POD drying, the exiting air conditions are usually unavailable, so that Equations 6.9 and 6.10 were replaced with Equations 6.11 and 6.12.

$$RH_{eff} = A' * RH_{in} \quad (6.11)$$

$$T_{eff} = B' * T_{in} \quad (6.12)$$

Data for Test 20180912 were used to determine the values of A’ and B’. Only the data for Tray 1 were used since that was the only tray for which the exiting air data were measured. Table 6.5 summarizes the simulation results and the R-square values.

R-Square is calculated using the following equation:

$$R^2 = 1 - \frac{\sum_{i=0}^{n}(y_{1i}-y_{2i})^2}{\sum_{i=0}^{n}(y_{1i}-\overline{y_1})^2} \quad (6.13)$$

Where y_1 is the observed data, y_2 is the simulated data and $\overline{y_1}$ is the average of y_1.

Table 6.5 Determination of parameters A′ and B′ for the revised model using data from Test 20180718, Test 20180809 and Test 20180912. Values in parentheses in the last line of the table are percent differences between the predicted and observed moisture content.

		Observed Data	A’=1 B’=1	A’=2.17 B’=0.51
Test 20180718 Tray 1	R^2	-	<0	0.77
	Final moisture content(%)	11.7	5.17 (-55.8%)	11.7 (<1%)
		Observed Data	A’=1 B’=1	A’=1.57 B’=0.62
Test 20180809 Tray 1	R^2	-	0.35	0.91
	Final moisture content(%)	12.8	7.34 (-40.8%)	12.8 (<1%)
		Observed Data	A’=1 B’=1	A’=1.7 B’=0.7
Test 20180912 Tray 1	R^2	-	0.35	0.95
	Final moisture content(%)	12.4	7.34 (-40.8%)	12.34 (<1%)

Figures 6.7 compares the model predictions for Tray 1 in POD Test 20180912. The predictions of the simulation when using the drying air relative humidity measured by the sensors (A’=1, B’=1) is in green. It is obvious that it predicts that the moisture content of the maize being dried in the POD will be lower than the observed moisture content over almost the entire drying period. The predictions of the simulation are much closer to the measurements made during the test. The revised model slightly underestimated the moisture content of the maize in Tray 1 at the beginning of the test and slightly overestimated the moisture content of the maize during the middle period of drying. One possible explanation is that the model is more sensitive to the air conditions than the dryer and it responds faster than the maize in the dryer when there are changes in the inlet air properties.

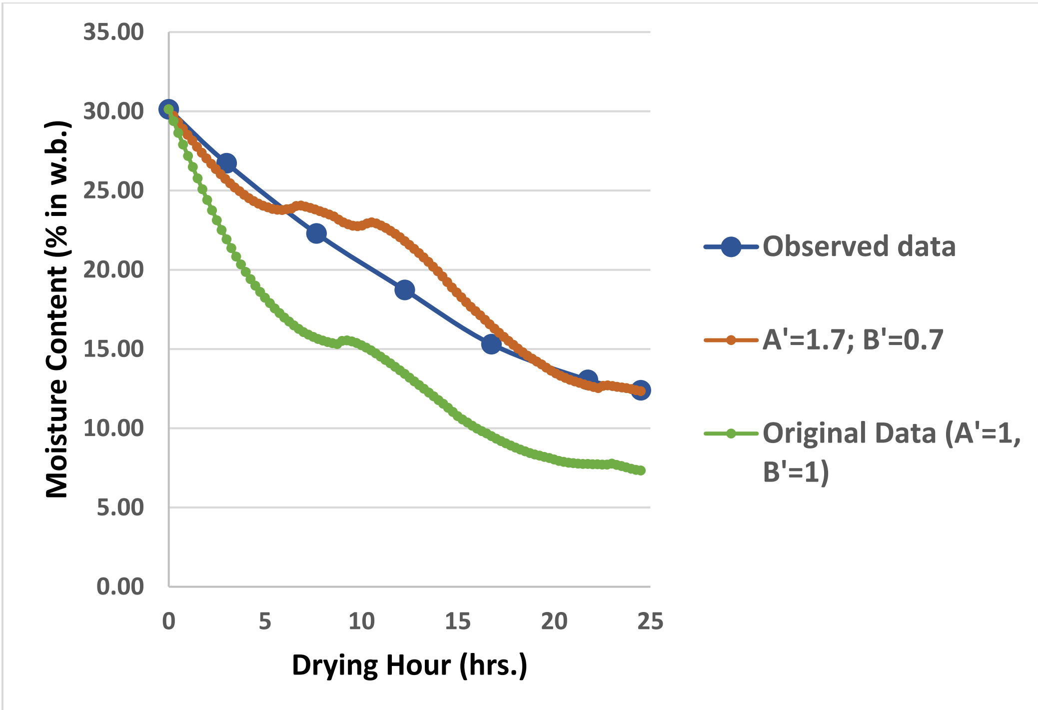


Figure 6.7 Model evaluation for Tray 1 in Test 20180912

The model predictions were also compared with drying data from Test 20170915. Table 6.6 summarizes the predicted final moisture content and the R-square value. Since data for the relative humidity of the air above the surface of maize were unavailable, it was estimated based on the relative humidity of the ambient air and the temperature differences between ambient air and the air above the maize. The value was determined using the psychrometric chart. The average values of A′ and B′ calculated from the three tests in Table 6.5 were used in the numerical prediction, which are 1.79 and 0.61 respectively.

Table 6.6 Validation of model with Test 20170915

		Observed Data	A'=1.79,B'=0.61
Test 20170915 Tray 5	R^2	-	0.79
	Final moisture content (%)	11.81	9.91 (-16%)

6.4 Application of the approach

After the model was evaluated as described above, it was used to investigate the effect of changes in input values on the performance of the POD. Plots were made to show the effects of relative humidity (Figure 6.8), air temperature (Figure 6.9) and airflow rate (Figure 6.10) on the POD drying rate. To calculate the drying time, the initial moisture content and the target moisture content were assumed to be 28% and 15% (d.b.) (21.9% and 13% w.b.), respectively. Figure 6.8 shows that if the temperature is greater than 30°C, for relative humidities below 60%, the relative humidity of the drying air has very little effect on drying rate. Figure 6.9 shows that, if the drying temperature increases by 10 °C, the drying time will be shortened by approximately 50 %. In other words, the drying rate at the higher temperature will be approximately twice the rate at the lower temperature. This means that if the number of degrees of temperature added to the air by solar heating can be increased, drying will be faster.

Figure 6.10 shows the effects of airflow rate on the POD drying rate. The relative humidity was set to be 40% when the data for the plot were generated. The plot indicates that if the airflow rate is doubled, the reduction in the required drying time would be less than 2 %. This means that significantly faster drying will not be achieved by adding more fans. In fact, it should be possible to reduce the number of fans. As explained in Chapter 3, section 3.4, the two additional fans were added because with 5 fans the plastic would not always fully inflate. If a method of supporting the plastic other than by airflow could be devised, the 5 fans should give almost the same drying rate as the 7 fans and less solar energy would be required.

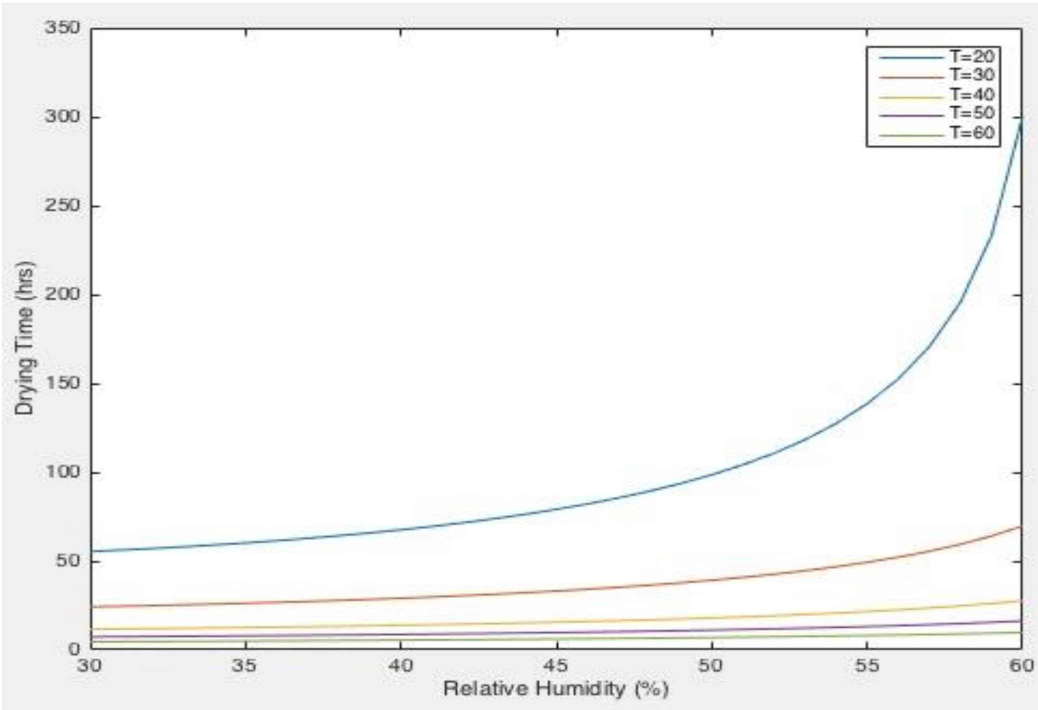


Figure 6.8 Effects of relative humidity on the POD drying time

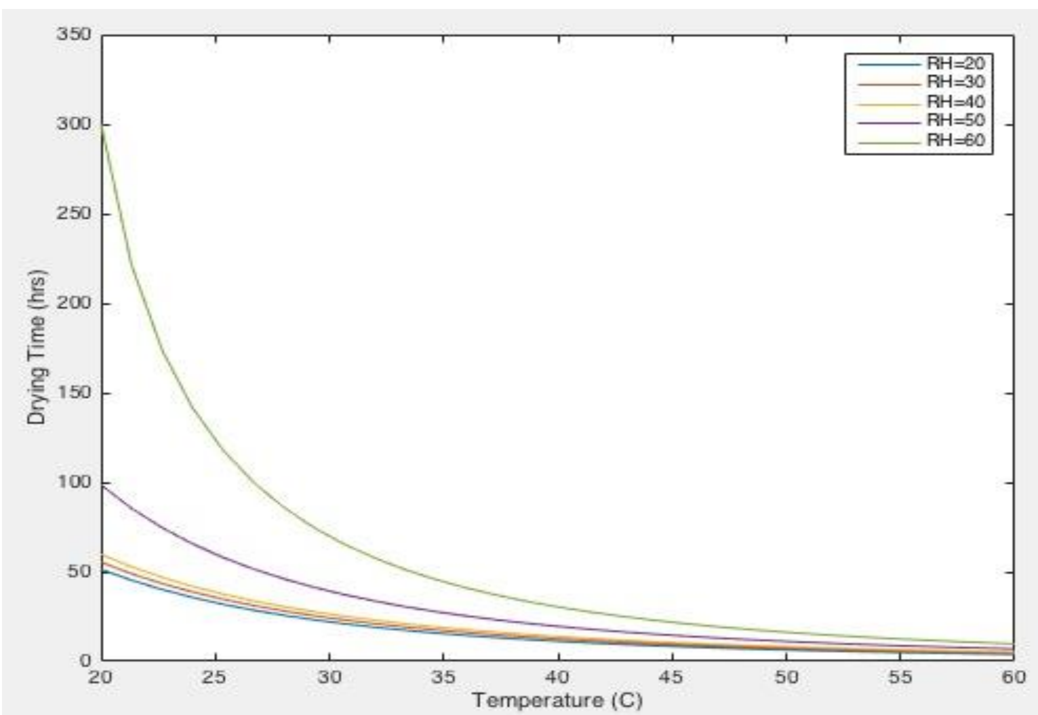


Figure 6.9 Effects of temperature on the POD drying time

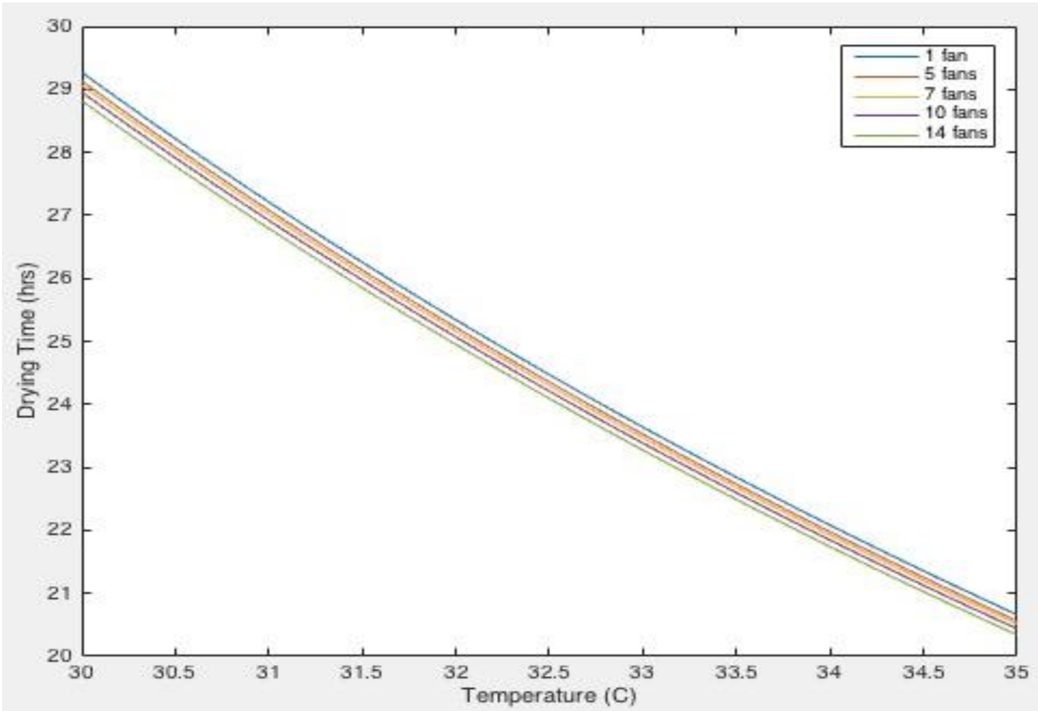


Figure 6.10 Effect of airflow rate on the POD drying time

6.5 Conclusions

A thin layer drying equation was adapted for simulating the performance of the POD. The equation developed by Page [5] and subsequently further evaluated and adapted for use with maize by Misra and Brooker [9] was used. It takes into account the effects of air properties and airflow. The adaption was validated using data from three POD tests conducted at Purdue. The equation used by Misra and Brooker predicted drying of a single thin layer of maize. However, the better representation of drying of the maize in the POD is that the maize is a series of thin layers. Therefore, drying air relative humidity and temperature were replaced with an effective relative humidity and temperature, defined by Equations 6.11 and 6.12. As shown in section 6.3, the adjustment greatly improved the agreement between the model predictions and the drying rate observed in the three POD tests conducted at Purdue. Due to the lack of measurements of exhaust air temperature and relative humidity for other trays in the dryer only the drying in Tray 1 was used to determine the constants A′ and B′ in the revised model. These parameters were then used to predict the performance of the POD for POD test 20180915. The predictions were assumed to be acceptable and the adaptation of the thin layer drying equation was used for evaluating the effects of air relative humidity and temperature and airflow on the performance of the POD.

According to the adapted thin layer drying equation, both the temperature and relative humidity of the drying air have significant effects on the drying rate of the POD, while airflow rate does not. Increasing the temperature of the drying air, which will correspondingly decrease its relative humidity, should improve the POD's performance. However, increasing the airflow by adding more fans should have very little effect.

6.6 References

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CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Project overview

The primary goal of this project was to further develop and test the Pico Solar Crop Dryer (POD), making changes that improved its performance or reduced the cost of the dryer. The overall goal of the project described in this thesis is to develop the POD to the point that it performs well and is acceptable to small holder farmers in Kenya and other developing countries. A total of 7 tests were conducted at Purdue's ADM Agricultural Innovation Center between September 2017 and May 2019 for the purpose of testing the performance of the POD and making improvements. The POD was also tested at several locations in Kenya. One test was conducted in May 2018, another was conducted in November 2018 and three more tests were conducted in March 2019. The procedures used in the tests and the results of the tests were documented, analyzed, and discussed in this thesis. In addition, between September of 2017 and March of 2019, the performance of the POD was compared with drying on a tarp in two tests conducted at Purdue and one test conducted in Kenya. A thin layer drying equation was adapted to investigate the effects of air temperature and relative humidity, and also airflow rate on the POD's drying rate.

7.2 Major findings

1. There were a total of 7 POD performance tests conducted at Purdue and 5 more were conducted in Kenya. The approach to testing was to conduct several tests during the summer to improve the performance of the POD and then conduct a final test for the season in September using recently harvested maize. In these last tests of the season the performance of the POD was compared to drying on a tarp. Results are summarized below.
2. For the 2 tests conducted in 2017, the average drying rate of POD was from 0.46 and 0.59 percentage points of moisture content reduction per hour. After several changes were made to the POD, the drying performance improved. For the 3 tests conducted in 2018, the average drying rate of the POD was from 0.62 to 0.78 percentage points of moisture

content reduction per hour. The uniformity of the moisture content of the samples taken from individual trays was also improved after the location of the fans was changed.

3. There were a total of 5 POD performance tests conducted in various locations in Kenya. The drying rate of the POD for the test conducted in May of 2018 was 0.39 percentage points of moisture reduction per hour. The drying rate increased from 0.39 to between 0.581 and 0.975 percentage points moisture reduction per hour for the 4 tests conducted from November 2018 to March 2019 in Kenya. The highest drying rate, 0.975 percentage points per hour, occurred during the Nandi county test. It was the highest overall drying rate that the POD has achieved.
4. The POD performed well in comparison to drying maize on a tarp. In the drying tests conducted at Purdue in September 2017, the POD was able to dry 123 kg of recently harvested maize from 26.2% moisture content to 12.2% moisture content in 24.9 hours which was 0.75 of the time required to dry the maize using the tarp. In the Purdue tests conducted in September of 2018 the POD was able to dry 142 kgs of recently harvested maize from 30.1% moisture content to 13.3% moisture content in 24.5 hours. The maize placed on the tarp dried from 30.3% moisture content to 13.5% moisture content in 29.0 hours. The POD dried the maize in 0.84 of the time required to dry the maize on the tarp. For the test conducted in Nandi County, Kenya the POD dried the maize from 36.4% moisture content to 13.0% moisture content in 24 drying hours over 3 calendar days. At the same time, the maize dried on the tarp dried from 36.4% moisture content to 16.3% moisture content.
5. A thin layer drying equation was adapted to investigate the effects of weather conditions and the airflow rate on the POD’s drying rate. An adaption of Page’s thin layer drying equation was able to predict the final moisture content of the maize that was dried in the POD (test 20170915) to within 16% of the observed value. According to the results, both the drying air temperature and its relative humidity can have significant effects on drying rate, while airflow rate has only a small effect.

7.3 Recommendations for future work

7.3.1 Design of a new POD prototype

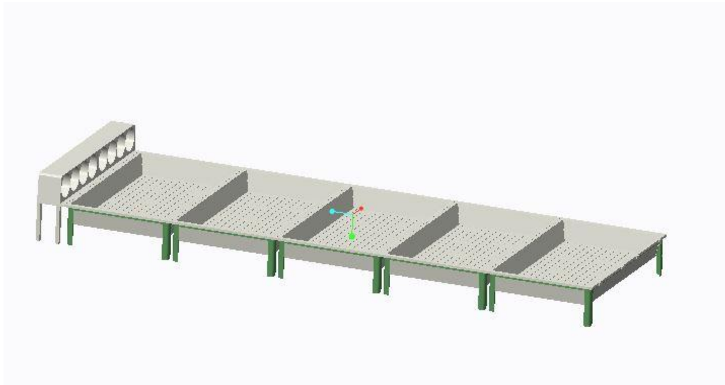
If the POD is commercialized it would be advantageous to produce the needed components using extrusion molding. Although the injection mold needed to produce the components would be expensive to make, costing approximately $6,000, once an injection mold is available the components can be produced economically. This should lower the cost of the POD. In October of 2017 two POD designs were developed that could be mass produced using extrusion molding. The objectives of the design were to reduce the number of components, to make the dryer easier to assemble and transport, and to reduce the requirement for using other materials such as duct tape and clamps when assembling the POD.

The prototypes, which were designed using CAD, are shown in Figure 3.4. Both types of trays were designed to be nestable, with each tray fitting partway inside the tray beneath it so that a stack of five trays would be smaller in size and more easily transported on the back of motorcycles. The trays would be interlocking with each other to form the drying bed and the fan frame would interlock with the trays so that duct tape would not be required to seal gaps between trays or between the trays and the fan frame. The prototype in the upper half of Figure 7.1 has three components: the standard tray, two end trays, and the fan frame. The second prototype, shown in the lower half of Figure 7.1, also has three components: 5 identical trays, legs that support the trays, and a fan frame.

A)

Figure 7.1 Injection molding prototypes of a fully plastic version of the POD

Figure 7.1 Continued



Once the injection molds have been manufactured, the cost of making one tray should be approximately 2.5 US dollars and the cost for the fan frame and other plastic components will be similar. This should significantly lower the cost of making the POD. If 5 trays similar in size to the trays currently purchased from China were used to form the bed of the dryer the cost of the dryer and fan frame should be no more than 20 dollars. The retail cost of the fan, solar panel, battery, charge controller, plastic sheet and other components including binder clips which are used to fasten the plastic sheets to the trays, will be around 100 US dollars. If the dryer were mass produced, the cost of the trays could be slightly less than $1.00 US dollar. If hundreds of the dryers were built, the cost of the solar panel ($45) and battery ($18) would probably drop by about 25%.

7.3.2 Drying other agricultural products with POD

Although the performance tests with the POD mainly focused on drying maize, it can be adapted for drying other products. A test was conducted by drying sliced potatoes in April 2019 at Purdue. Six of the black plastic DEHYTRAY^{TM}'s made by JUA Technologies International (Indianapolis, Indiana), without their covers, were used in the assembly of the POD used to dry potatoes. They replaced the trays made in China that were used in previous tests.

The slots in the sides of the trays were covered with blue painter's tape (Figure 7.2 left). There was rainy weather predicted and the POD was set up inside the ADM building. The potatoes were sliced into circular pieces with a thickness of 3 to 8 mm and were spread over the bottoms of 5 of the trays so as to completely cover the bottom surface. Black plastic was placed in the sixth tray to prevent air from escaping through it. The POD dried 30 pounds of sliced potatoes from 81 % moisture content to 58 moisture content in 18.35 hours. Drying was slow because the air temperature inside the building was 20 to 22°C and the air relative humidity was high, particularly during rain storms.

As, the potatoes were drying they shrank exposing some of the holes in the bottoms of the trays (Figure 7.2 right). This decreased the airflow resistance which meant that the plastic would no longer remain “inflated” above the dryer. Therefore, four small frames were made using strips of wooden lath to hold the plastic about 20 cm (8 inches) above the tops of the trays. This allowed the drying to proceed unhindered. The exposure of the holes in the bottoms of the trays had no apparent effect on the airflow through the dryer. The test was stopped because it had demonstrated the ability of the POD to be adapted to drying fruit and vegetables.

Figure 7.2 Drying sliced potatoes with POD (left: before drying; right: after drying)

7.3.3 New prototype – The folding bed dryer

Efforts continue to look for locally available components that are suitable for building the POD. The cost of shipping plastic trays from China to the United States and the difficulties and expenses encountered when shipping plastic trays from China to Kenya for the Kenyan drying tests served as motivation for looking for an alternative source of trays or another approach to forming the drying bed. In January of 2019, Dr. Raman proposed that a folding bed (sometimes called a cot) be used to support the material being dried. Dr. Raman was familiar with the widespread availability and low cost of this type of bed in developing countries and knew that

they could be easily purchased in those countries for a reasonable price. The prototype of the folding bed dryer was developed during the spring of 2019 and tested at Purdue in June.
The outer frame of the bed was 178 cm long and 99 cm wide (70 in by 39 in). The sides that formed a box-like reservoir in which the maize could be placed were made from vinyl siding of the type used for the exterior of houses. A single piece of siding was cut into several pieces of the proper length. The pieces were connected together with duct tape so that the siding could be folded into a more compact configuration for transport. The siding was attached around the outer frame of the bed using a dozen clamps that clamped the bottom of the siding to the metal frame (Figure 7.3, left). This formed a drying bed with a height of 23.8 cm (9.375 in). A flexible plastic netting or mesh was placed inside the bed. The holes in the netting were small so that maize kernels would not pass through the net.

The investigations with the mathematical model described in Chapter 6 indicated that changes in airflow rate, within the normal operating range, have a relatively small effect on the POD's drying rate. Therefore, only two 120 mm solid case fans (Apevia corporation) were used in the dryer. The fans were glued to a 15 cm (6 inch) long piece of PVC piping that had an inside diameter of approximately 12 cm (4.75 in). Initially, the fans were placed on opposite sides of the bed and at one end of the dryer (Figure 7.3, left). However, in order to achieve a more uniform air distribution within the bed, they were moved towards the centers of the two sides of the bed and offset slightly in opposite directions from the middle (see Figure 7.3, right). The bed frame was covered with a "double" plastic sheet (black plastic beneath a layer of clear plastic) that extended down outside of the vinyl side and could be clamped in place using the same clamps used to hold the vinyl siding to the frame.

The first tests on the dryer were conducted with dry corn. "Tel Tru" smoke sticks (E. Vernon Hill Corporation, Benicia, California) were used to produce smoke that was introduced into the fan inlet. The smoke emerged from the dryer with the exiting air and was visible to observers. This led to the discovery that, when the netting was put in place, there was a small gap between it and the siding, even when the drying bed was filled with maize. Air was emerging from this space instead of moving through the maize. Therefore strips of clear plastic sheet slightly wider than the vinyl siding were placed on the sides of the bed to prevent the air from escaping through those sides (right picture in Figure 7.3). Subsequent tests with the smoke stick indicated that the smoke was emerging underneath the bed, as desired.

Figure 7.3 The folding bed dryer (left) prepared to receive the maize and (right) filled with maize

A maize drying test was conducted both inside (day 1) and near but outside adjacent to the north side (day 2) the ADM building beginning on June 13th. About 90 kgs of maize at 13% moisture content were re-wetted to 21% moisture and placed in the folding bed dryer, which was located inside the ADM building because of rainy weather. Drying began at 15:30 and continued until 18:30. At the beginning of the test and the end of the day samples were taken from 9 locations evenly spaced around the drying bed (3 across the width of the bed at each end and 3 across the middle) with the intent of determining how evenly the maize was drying. After the samples were placed in bags, they were immediately tested in the Steinlite moisture meter and the results were recorded. According to moisture meter tests, only 0.3 percentage points of moisture were removed during the 3 hours of drying.

On the 14th the weather was clear and sunny so the dryer was moved outside the ADM Building to the stone covered parking area and driveway immediately north of the building. Using the charge controller, the solar panel was connected to the fans and a battery. This provided power for the fans (Figure 7.4). This outside portion of the test began at 08:55 on June 14th and continued until 17:20 with a one-hour interruption at 12:55 pm for taking maize samples and then testing the maize moisture. After 8.42 hours of drying, the average moisture content of the samples was 16.1%. Approximately 4.1 percentage points of moisture had been lost giving a drying rate of 0.49 percentage points per hour.

The final moisture content of the samples varied among the 9 sampling locations from 14.8% moisture content to 17.1% moisture content. The locations with lower moisture contents were along the side of the bed adjacent to the solar panel (the west side of the bed). The highest moisture was in the southeast corner of the bed. The drying was slower than desired, perhaps because of the low airflow. Additional tests can be conducted to increase the airflow and improve the uniformity of the drying.

Figure 7.4 Drying test with the folding bed dryer