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Evaluation of resultant pellet quality and low temperature closed-cycle grain drying system

by

Mingjun Ma

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Program of Study Committee:
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DEDICATION

This thesis is dedicated to my mother Xia Li and my father Cong Ma for their love and support. Thank you for the unconditional moral and financial support.

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NOMENCLATURE

db	Dry basis
DDGS	Distillers Dried Grains with Solubles
L/D	Length to diameter
EIA	Energy Information Administration
LCA	Life Cycle Assessment
TEA	Techno-Economic Analysis

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ABSTRACT

Along with the increasing population, the lack of food and energy have become major global issues in 21 century. Bioethanol is now one of the most popular renewable energy sources and is mostly produced by corn in the US. The corn-based ethanol production has grown rapidly over the past two decades. The increasing of corn ethanol production also created a huge amount of by-product like DDGS, which commonly used as animal feed and make the whole industry even more profitable. However, the low bulk density and poor flowability inhibit the value of DDGS. The DDGS low bulk density and low flowability could be improved by pelleting process. Pellet quality is the key aspect of this project. To obtain a high yield of corn ethanol and high quality DDGS the quality of the ingredients is very important. There are many things can affect the overall corn quality from planting to storage. The drying process is a vital step to maintaining corn quality and extent the corn storage life. Our study was conducted to analysis the resultant DDGS pellet quality and evaluate a prototype low-temperature grain drying system.

The pelleting studies in this thesis were focused on analysis the resultant pellet quality by using 100% corn-based DDGS. The pelleting process was operated with three different DDGS moisture content and three different dies. The results showed that by using pilot-scale pellet mill, the bulk density can be increased and the flowability of DDGS could be improved by pelleting process.

The grain drying project talks about an experiment of measure the power consumption and moisture removal efficiency of a prototype low temperature grain drying system. The data were collected through two replications of the drying process. The drying results indicated that the system had high efficiency and had no negative effect on germination performance.

The TEA and LCA study were conducted to understand both environmental and economic impacts of an on-farm low-temperature grain drying system. Three scales of this drying system were analyzed in this study. The result showed that the unit drying cost decreased as the drying capacity expanded and the lowest unit drying cost was 0.46 USD per bushel of corn.

In conclusion, the pelleting process could be a valid way to improve the low bulk density and poor flowability of DDGS. The low temperature closed-cycle grain drying system was more efficient than other commonly used high temperature grain dryer and maintain the grain quality.

CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

General Introduction

The world population has reached more than 7.3 billion today and projected to increase to 9.6 billion or more by 2050 (Population Institute, 2015). Practically all the population growth will be happened in the developing world, where has an enormous demand for food. Drought, war, or food loss due to disease or insects all could make the food shortage become more severe and less predictable (Campbell and Trechter, 1982). In 2012-2014, around 805 million people suffered chronically undernourished all over the world (FAO, 2014). Energy is essential for daily life since it is almost required in all aspects (Sayigh, 2004). Along with the increasing population, urbanization, and modernization, the demand for energy has increased rapidly (Asif and Muneer, 2007). The energy shortage has become one of the world biggest issues due to the increasing demand for energy. The fast-growing population and energy consumption brings an enormous pressure to the environment. Human activities have produced a 40% increase in atmospheric carbon dioxide concentration than preindustrial level, by the end of the twentieth century (Schlesinger, 2013). Human activities also consumed 60% of freshwater run-off (Postel et al. 1996).

The optimization of agricultural processing could be an effective way to produce enough food to meet the demand for increasing population and reduce the environment pressure brought by human activity. Optimized agricultural processing could contribute to reducing the input energy and water usage while maintain the output product quality or even add extra value to the final product. As a result, the food and energy shortage circumstances could be improved. Meanwhile, the environment issue, such as greenhouse gas emission, land usage, water pollution, habitat destruction, ect., could be enhanced.

To optimize the agricultural process, it is vital to understand and analysis the different processing by modeling. Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stage of a product's life from the cradle to the grave. Techno-Economic Analysis (TEA) is a systematic analysis used to evaluate the economic feasibility aimed to recognize opportunities and threats of projects. Both models are extensively used for research or commercial purpose and could help decide in new technology implication and improve the on-going operation.

DDGS (Distillers dried grains with solubles) is well known as the by-product of modern dry grind ethanol production. DDGS has been extensively used as animal feed for decades since DDGS has a high concentrate of protein. Though the DDGS wild used today, the problems associated with DDGS has become significant. The first problem of DDGS is because of the low bulk density; typically the bulk density has been found at range from 365 to 630 kg/m3 (U.S. Grains, 2008). The DDGS may fill a truck or trailer to the maximum volume, before reach the maximum weight capacity and this will cause the shipping costs increase, therefore, reduce the value of DDGS. The second problem of utilizing DDGS was the low flowability; this will cause extra labor when loading and unloading DDGS from site to site and result in increasing cost.

Pelleting could be one of the valid ways to improve the problem associated with DDGS when handling the material. Wilson and McKinney, (2008) has conducted an experiment about pelleting 100% DDGS. They found that the bulk density has been improved after the pelleting process, and along with the increase of L/D ratio the pellets durability was increased.

Grain drying is a vital process in grain handling. It can move the internal grain moisture out of grain and maintain the grain quality. Grain drying is a very energy intensive process (Gunasekaran and Thompson, 1986). A well-designed drying system is critical to saving energy during the drying process.

This thesis focused on evaluating the quality of DDGS pellet and assessment of a prototype low temperature closed-cycle grain drying system. Both TEA and LCA has been done on the low temperature closed-cycle grain drying system to discuss the possibility of large scale implementation. The following literature review provides the background for better understanding DDGS, pelleting processing, and grain drying process.

Fuel ethanol and DDGS production

The interest of using bio-based alcohol as transportation fuels could be traced back to Henry Ford's time. Then the whole fuel ethanol and beverage industries start to grow up after the prohibition ended. However, the main motive of growing fuel ethanol industry was because of the oil crisis at the mid-1970's. Since that time, the fuel ethanol industry started to grown rapidly. The fuel ethanol production has changed from 0.75 billion gallons at 1990 to 14.34 billion gallons at 2014 (EIA, 2015). For corn ethanol plant there are mainly three different commercial production process, known as wet milling, drying milling, and dry grind ethanol processing (Raush and Belyea, 2006). In recent years, the dry grind ethanol processing has become a predominant fuel ethanol production processing in U.S., just in 2009 RFA (Renewable Fuel Association, 2009c) reported that more than 80% of fuel ethanol production plant was using dry grind ethanol processing. The main reason dry grind ethanol processing became more popular was because it is a simpler process with lower capital cost and high ethanol yield than other ethanol production process.

Like many other production processes, dry grind ethanol process also generates waste or co-products, in this case, distiller grains and carbon dioxide. Typically, the distiller grains were consumed in the form of DDGS, which has an actively interest in animal feed industry. Back in the early stage, the DDGS was only seen as the by-product of the fuel ethanol production process, with a little or no value. The situation was changed due to the dramatic expanded in fuel ethanol production result in an enormous amount of DDGS been produced. Just in 2014 about 44.28 million short tons, DDGS has been produced (Wisner, 2015). The DDGS started to take the place of corn and soybean meal since it is a relatively low-cost ingredient and high nutrition level.

The component of DDGS could be varied from plant to plant. Spiehs et al. (2002), showed that most of the nutrient variation of DDGS were due to the crop used, the amount of dried solubles added back to DDGS and the fermentation process duration or the completion of the fermentation process. Typically speaking DDGS contains around 29% protein, 10% oil, 9% crude fiber and 5% ash (Lim and Yildirim-Aksoy, 2008). Plenty of research has been done in respect of using DDGS to feed poultry, swine, dairy cattle and beef cattle. Dicostanzo and Wright. (2011) conducted an experiment to use DDGS to feed beef cattle. The DDGS was applied at 0.29%, 0.49%, 0.69%, 0.88%, 1.08% and 1.27% of body weight (BW). As the amount of DDGS increased a linearly average daily gain (ADG) from 0.9 to 1.81 lb per day was observed. For dairy cattle, Owen and Larson (1991) reported that when DDGS has applied at 18.8% of diet DM, the milk production increased most likely due to increased dietary RUP. However, the milk yield was decreased when DDGS was applied at 35.8% of the diet DM. The author pointed out that the decreased milk production was due to lower protein digestibility and low lysine concentration.

Pelleting Process

Pelleting is the process of by using moisture and heat compressing the finely divided feed material into a pellet shape. Pelletized feed materials could increase the raw materials bulk density, therefore increasing the capacities of storage and transportation. Pelleting also could help improve the flowability of the raw materials to obtain better handling characteristics without compromised nutritional properties or adding high costs.

The physical quality of final pellets products is critical. The good flowability is important at feed mill especially when moving ingredients from site to site. If the material has good flowability it will keep the load times as short as possible and decrease clean-up times since less material will accumulate in low-flow areas. Flowability is also of particular importance in automated feed lines where low flowability material can cause damage to equipment and may leave feeders unfilled (Fahrenholz, 2008). Durability and hardness are also the critical basic physical quality of pellets. The proper durability pellets could withstand the strict transportation process and reduce the fine material generate. Hardness and durability could also become a parameter to evaluate the effects of ingredients formulation, pelleting condition, expander treatment and pellet mill die selection. (Pfost, 1963).

The factors that influence pellet quality can be divided into several categories. The most important factor is the ingredients formulation. The grain used and the percentage of each component can have a significant influence on final pellets quality. The pellet quality could be significantly reduced by the content of fats or oils. The ingredient grind fineness could have many effects on pellet quality. In general, the finer the grind, either pre- or post-grind, the better the pellet quality. Regarding pellet mill operations, the die selection has a significant influence on the final pellets quality. The L/D ratio is the parameter that helps decided the die used in the pelleting process. Typically speaking, the larger the L/D value, the higher the pellets quality. However, the pelleting condition was more critical than die selection. A large amount of attention must be paid to pelleting condition control such as moisture content, steam quality, mixing action in the conditioner and retention time.

Grain drying

Grain is the majority resources of carbohydrates and proteins worldwide and the primary source of food for the people in the world. (Warchalewski et al., 2000). Grain can hold moisture like any other hygroscopic material (Shove and Oliver, 1967). Although the grain moisture content is important for grain quality, high moisture level inside the grain could increase the mold and fungi infection risk (Brooker et al., 1992). The situation could be improved by grain drying process which can reduce the internal grain moisture content level. The substance of grain drying is to remove the excess moisture level inside the grain and allow the grain store in a certain period without compromise the grain quality.

There are a lot of conventional grain drying system that available in the market. All the conventional drying system could be classified based on their working temperature into low and high temperature dryers.

From energy usage perspective, grian drying is a energy intensive process (Gunasekaran and Thompson, 1986). It has been estimated that the energy use for on-farm grain drying operation is almost 50% of the overall energy used in on-farm grain processing and handling (FEA, 1974). The key to achieving good drying result and high drying efficiency is a well-designed drying system. Beedie (1995), showed that by only improve 1% of drying system energy efficiency, the profits of drying could increase as much as 10%. For this reason, many researches have been done to analyze the efficiency of different drying system. Kenyon and Shove (1969) and Shove (1973) showed the intermittent blowing hot air and cold air into grain could improve the overall drying efficiency. Foster (1964) introduced the dryeration process, which first dry grain around 60 ^{o}C to approximately 2% above the target moisture content and then the grain was transferred to separate dryeration bin without cooling. In the dryeration bin, the grain was tempered 6 to 8 hours without aeration and then was slow cooled by using ambient air at 21.2 CFM for another 8 to 12 hours (Morrison 1979). Peterson (1979) has proved this method could save up to 25% grain drying energy.

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CHAPTER 2 OBJECTIVES AND HYPOTHESES

This study focused on evaluate the resultant pellet quality by using 100% corn-based DDGS, and to understand the what kinds of different pelleting conditions will affect the pelleting result. Grain drying project was conducted to assessment the drying efficiency and drying quality of a prototype low temperature closed-cycle grain drying system, and the LCA and TEA was also conducted to analysis this drying system. The objective and hypotheses were list as following:

(1) 100% DDGS was pelleted by using CPM CL-2 pilot-scale pellet mill, two dies were used in this experiment with three different DDGS moisture level for each die. Some pellet physical properties like bulk density and durability were measured to determine the quality of final DDGS pellets.

Ho: The die size and the DDGS moisture content level has no effect on resultant physical pellet quality such as pellets bulk density, flowability and color.

H_A: The die size and the DDGS moisture content level has an effect on final pellet quality such as pellets bulk density, flowability and color.

(2) CPM CL Type 5 laboratory pellet mill was used to conduct second pelleting project. 100% DDGS was used as ingredient with three different dies and three DDGS moisture content level for each die. The pellet physical properties were measured to determine the quality of final DDGS pellets.

Ho: The moisture content of DDGS and the die size has no effect on pelleting temperature and resultant pellet quality such as bulk density, angle of repose and color.

H_A: The moisture content of DDGS and the die size has effect on pelleting temperature and resultant pellet quality such as bulk density, angle of repose and color.

(3) Assessment of the drying efficiency and drying quality of a prototype low temperature closed-cycle grain drying system. The power consumption and drying efficiency were measured and calculated to determine the efficiency of this drying system. A germination test has been done to evaluate whether the drying process has an effect on corn germination performance.

Ho: The drying efficiency of present low temperature drying system was not higher than other commonly used on-farm drying system and the drying system will affect the seed germination performance.

H_A: The present low temperature drying system has greater drying efficiency than other commonly used on-farm drying system and has no negative effect on seed germination performance.

(4) LCA and TEA of low temperature closed-cycle drying system. The study was conducted by analyze the environmental and economic impact of three scales of this drying system.

Thesis Organization

Chapter 1 corresponds to the general introduction and literature review for this thesis.

Chapter 2 corresponds to the objectives and hypotheses of each chapter for this thesis. The thesis organization is also reported in this chapter

Chapter 3 corresponds to the study of DDGS pellet quality by using 100% corn based DDGS. This chapter is based on a manuscript to be submitted to journal Animal Feed Science and Technology or Cereal Chemistry.

Chapter 4 corresponds to the study of pilot scale DDGS pelleting. This chapter is based on a manuscript to be submitted to journal Biosystems Engineering or Food and Bioprocess Technology.

Chapter 5 corresponds to the evaluation of a low temperature closed-cycle grain drying system. This chapter is based on a manuscript to be submitted to journal Drying Technology or Food Engineering.

Chapter 6 corresponds to the TEA and LCA of the low temperature closed-cycle grain drying system. This chapter is based on a manuscript to be submitted to journal Industrial Crops and Products.

Chapter 7 corresponds to the summaries and conclusions of this thesis.

Chapter 8 corresponds to the future work of this thesis.

CHAPTER 3 PELLET QUALITY OF CORN-BASED DDGS

Abstract

The rapid growth of corn-based dry grind ethanol plants in the US has resulted in a great increase in production of the by-product DDGS (distillers dried grains with solubles). Since some physical properties like low bulk density and poor flowability can impact the market potential of DDGS, pelleting of DDGS can be one of the easiest ways to improve this situation. Pellet quality, and are the focus of this project. The pelleting process was conducted with three initial DDGS moisture content and two different dies, total six runs were complete to collect the DDGS pellets. The physical quality of pelleted DDGS was determined by measure the durability bulk density angle of repose and color of the DDGS pellets. The result showed that the pellets durability was ranged from 42% to 89% the highest pellets durability was occurred when the moisture content was 20% db and the die diameter was 1/8 in. The bulk density was increased while the DDGS moisture content decreased and the highest bulk density was observed when the moisture content was 10% db and the die diameter was 1/8 in.

Introduction

The cost of non-renewable fossil fuels has significantly increased in last several years due to the potential decline in overall fossil fuel supply in coming years. There are two solutions to this problem: using alternative energy sources and becoming more independent on energy sources (RFA, 2008). Ethanol, a renewable source of energy, is an alternative of fossil fuels. Various biomass materials can be used to produce this kind of biofuel. Currently, corn is the primary material utilized to produce biofuels in U.S. The corn ethanol industry has been well developed and the cost of using corn is much lower compared to other biomass sources. Therefore, the fuel ethanol industry has grown rapidly in recent years. For example, in the past few years, ethanol has been considered for 10 percent of the U.S. gasoline supply (RFA, 2014).

Currently, dry grind ethanol production processing dominates the ethanol production industry. Like many other industry processes, dry grind processing also has co-products, which are carbon dioxide and non-fermentable residual. The non-fermentable corn kernel components like fiber, protein and lipid are usually further processed and converted into DDGS (distillers dried grains with solubles) or to a lesser degree as DDG (distillers dried grains), DWG (distiller wet grains), and CDS (condensed distillers solubles) (Liu and Rosentrater, 2011). The DDGS was normally dried to around 10% moisture content, to extend the storage and selling life.

Although distiller grains can be utilized as high valued animal feed, there are different kinds of challenges when utilizing DDGS as animal feed. Low bulk density and has poor were the two main challenges when handling the DDGS (Rosentrater, 2006a, and Rosentrater, 2006b). Once the truck or train reaches the destination, DDGS was hard to discharge due to the particles locking together. Thus, low flowability forces strenuous manual unloading processes, which create extra labor cost for ethanol manufacturers. Another transportation problem of DDGS is the limited loading capacity of one car. DDGS is often filled to the volumetric capacity of railcars or trucks during shipping, but usually not at the maximum allowable weight, due to the low bulk density of the granular material. Thus, this wasted capacity causes additional potential economic loss to the ethanol manufacturers (Rosentrater and Kongarb, 2009). There is a way to increase the bulk density and flowability of DDGS, which utilizes the pelletizing equipment. Pelleting is a manufacturing process of compressing materials into the shape of pellet and improving the value of granular materials (Rosentrater, 2005). Rosentrater (2007a) has indicated that it is achievable to use conventional feed milling equipment to pellet DDGS.

Previous research studies have discussed the process variables that affect the physical qualities of resultant pellet and the impact of pelleting on the logistics of DDGS shipping. However, there is still very limited work has been done regarding analysis the physical qualities of DDGS pellets by using 100% corn-based DDGS. The aim of this research is to study the resultant pellet qualities of corn-based DDGS. The results of this research may be the reference for a large-scale facility producing DDGS pellets, and help the animal feed industry improve the value of DDGS while reducing the cost by utilizing DDGS as animal feed.

Materials and Methods

Material and equipment

The DDGS were collected from a local dry grind ethanol plant (Lincolnway Energy, LLC Nevada IA 50201). Total two bins of DDGS were stored in our lab at room temperature for further research. The pelleting process was completed by using a 1.5 kW pilot-scale pellet mill (CPM model CL-2, CPM Acquisition Corp. Crawfordsville, IN 47933). The pellet mill was made up with an ingredient hopper to hold the DDGS, a vibratory feeder to adjust the feeding rate of the DDGS that goes into the screw ingredient feeder, and then the screw feeder will push the DDGS into the mill. After the pelleting process, the DDGS pellets was come out from the discharge gate. The pellet mill was also equipped with a control panel to control the pelleting mill and change the ingredients feeding rate (Figure 3.1).

Experimental design

Table 3.1 shows the experimental design for this study. Two dies include diameter 1/8 in with the L/D ratio of 8 and diameter 3/16 in with the L/D ratio of 8 were used for this study. For each die, the DDGS was pretreated to three different moisture levels, which were 10% 15% and 20%, respectively. There were total six runs for various die size and DDGS moisture content in this study. For each run, two replications of the pelleting process were done to collect pellet samples. The pelleting throughput represents the production rate of converting raw DDGS to DDGS pellets. The throughput rate was adjusted based on the die size. The feeding rate of the ingredients was controlled by adjusting the vibratory feeder on the control panel.

Moisture content of DDGS and the DDGS pellets

The DDGS and DDGS pellets moisture content were measured based on the NFTA (National Forage Testing Association) 2.2.2.5 method (Shreve et al., 2006). Based on the instruction 3 g of DDGS or DDGS pellet sample were dried at 105 ^{o}C for 3 hours in the oven, and the moisture is reported in percentage point db. For each run the sample moisture content was measured three times, both mean and standard deviation was reported.

DDGS moisture content adjustments

The DDGS moisture content was adjusted to three levels: 10%, 15%, and 20%. Based on the measurement the 10% moisture content was the initial DDGS moisture content. To adjust the DDGS moisture content, the sample was initially put in a bucket and then adding water into the DDGS and mix them. The amount of water added to the DDGS for the pelleting process was calculated by assuming the weight of the dry matter remains constant. The calculated amount of water was added to DDGS samples directly by using a sprayer and then mixed by the mixer.

Bulk density of DDGS and DDGS pellets

The DDGS bulk density was measured based on the ASAE S269.5 procedure (ASAE, 2012). The DDGS and DDGS pellets sample flowed freely into a one-liter cup. Then a striking stick was used to brushed off the excesses sample with the gentle zig-zag strokes. The bulk density of DDGS or DDGS pellets was calculated by divided the DDGS or pellet mass by the volume of the container. The measured was repeated three times for each sample, means and standard deviation for each sample bulk density was also calculated and reported.

Angle of repose of raw DDGS and DDGS pellets

The angle of repose (AoR) is the steepest angle of inclination of the free surface to the horizontal of a granular material heap. It is one of the flow properties of the granular material that directly indicate the potential flowability (Carr, 1965). Based on Woodcock and Mason (1987) the material angle of repose ranged from 30^o to 38^o was considered as free flow while the angle of repose ranged from 38^o to 45^o was considered as fair flow. If the material angle of repose was between 45^o to 55^o the material was considered as cohesive material.

Pellet durability measurement

The pellet durability was also measured regarding ASAE S269.5 (ASAE, 2012). A seedburo pellet durability tester (Seedburo Equipment Co. Des Plaines IL 60076) was used in this measurement. Before the durability test of DDGS pellets, the pellets were first sieved and then randomly sampled 500g pellets for each run. The pellets sample was tumbled 10 min inside the durability tester, after tumbling the sample was sieved to separate the remaining pellet from the testing mass. The pellet durability was calculated by dividing the mass of remaining pellet by the initial mass of pellet sample. Three times of the test were done for each run; the mean and standard deviation were also calculated and reported in the results section.

Color of DDGS and DDGS pellets

A Minolta Chromameter (Chromameter CR-410 Konica Minolta Sensing Europe B.V.) was used to measure the color of DDGS and DDGS pellets. The color was determined by three parameters including L*, a* and b*, which L* represent the lightness level, a* represent the green – red level and b* represent blue – yellow level. For each pellet sample three replications were done to measure the color, means and standard deviations were calculated and reported in the results section.

Results and Discussion

Table 3.2 and Table 3.3 report the moisture content results and the statistic analysis. For both run 1-3 and run 4-6 the moisture content of DDGS pellets was various from 10% to 20 % which followed the trend with the initial DDGS moisture level increased. From the statistic analysis the die size has no significant influence on the final DDGS pellets moisture content, while the initial DDGS moisture level has a significant effect on the final DDGS pellets moisture content. This also results in the die size and moisture level together has a significant effect on final pellets moisture content.

For DDGS pellets bulk density, for run 1-3 the bulk density varied from 510.3 kg/m^3 to 571.4 kg/m^3 while for run 4-6 bulk density ranged from 482.1 kg/m^3 to 490.2 kg/m^3. All the pellets bulk density was significantly increased compared with the raw

DDGS bulk density which was 465 kg/m^3 (Table 3.4). The die size and the interaction between die size and DDGS moisture level has a significant effect on bulk density since the p-values were smaller than 0.0001 (Table 3.5). For each die, the pellet bulk density was decreased while the initial DDGS moisture content increased. Jaya Shankar Tumuluru et al. (2010) was also observed that for pilot scale DDGS pelleting, the DDGS bulk density was increased after pelleting process. The bulk density results were also very similar with Fasina and Sokhansanj (1993) result which for each different die, the pellet bulk density was decreased when the pellet moisture content increased.

The pellet durability result was reported in Table 3.6 and Table 3.7 For run 1-3 the durability of pellets varied from 73.2% to 89.27%; For run 4-6 the durability of pellets ranged from 42.5% to 60.5%. The statistic analysis shows that all the pellet durability data were significantly different from each other. Die size and the interaction between die size and DDGS moisture level have a significant effect on the DDGS pellets durability value. Comparing the results from run 1-3 with run 1-6, we can observe that even though these two dies have same L/D ratio, the die with smaller die diameter results in higher pellets durability and bulk density. The reason for this difference may be due to different pressure level generated during the pelleting process.

From Table 3.8, the values of angle of repose for run 1-3 were varied from 36.4^o to 43.8^o and for run 4-6 the angle of repose varied from 37.4 ^{o} to 44.8^o, which were very similar to run 1-3. From the results, it can be observed that after pelleting process the pellets angle of repose value was smaller than the initial DDGS angle of repose which was 47.0^o this means that the pelleting process could increase the material flowability. According to Woodcock and Mason (1987), all the DDGS pellets sample can be treated as fair flow or free flow. The pellets angle of repose was increased as the DDGS moisture level increased for the same die. The results were similar with Fasina and Sokhansanj (1993), the alfalfa pellets angle of repose was also increased as the alfalfa pellets moisture content level increased for the same pellet size. Table 3.9 shows the statistical analysis of the angle of repose results, the moisture content and the interaction of moisture content with die size has the significant effect on pellet angle of repose results.

The DDGS color L*, a* and b* results were reported in Table 3.10, 3.11, 3.12, 3.13, 3.14 and 3.15. The color L* results indicate that the DDGS became darker than the original DDGS after pelletized, which is very similar to the result of Rosentrater(2007a). For both of the die size, the L* value was decreased with the pellet moisture level increased. It was also observed that the color of the DDGS pellets became darker if the die with smaller diameter was used to pellet DDGS. The die size and DDGS moisture level were the main factors that affect the color L* value. The color a* and color b* results was similar with color L* results. The color a* and color b* values were all decreased after the pelleting process. For each die, the color a* and color b* values were decreased as the DDGS moisture content increased.

Conclusions

This present research was carried out to understand the physical properties of resultant DDGS pellets. As expected, adding water can get more durable pellet. If the two dies have same L/D value but one has larger die diameter, the resultant pellets durability lower than the other die. By using pilot-scale pellet mill, the DDGS bulk density can be increased and the DDGS flowability can be improved. Thus, the die size and DDGS moisture content has effect on the final pellet physical qualities. In further study, the temperature should be considering as a major variable quantity during the pelleting process.

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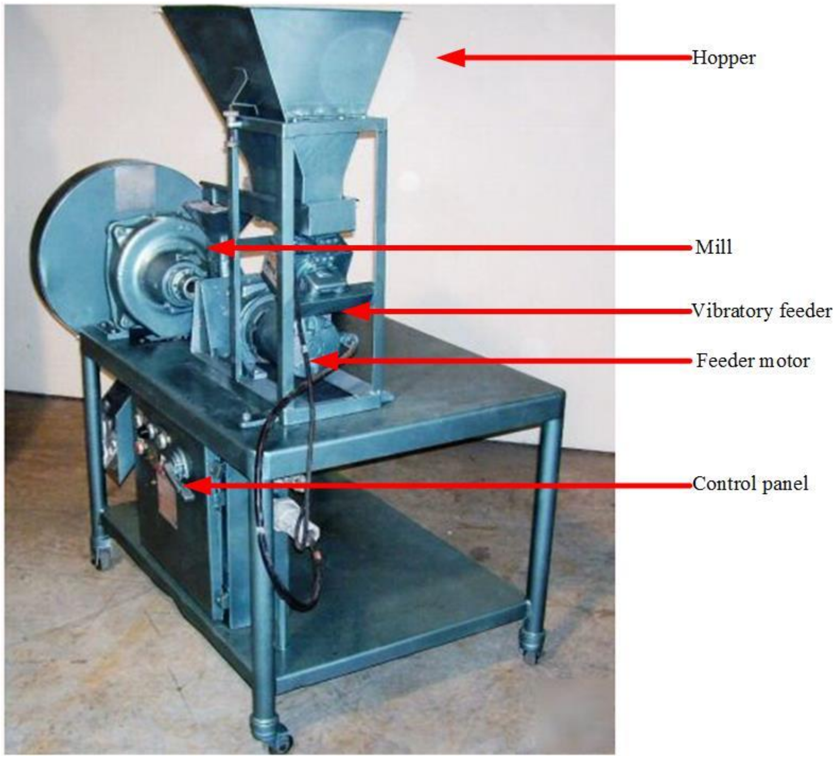

Figure 3.1 CPM CL-2 pelleting mill

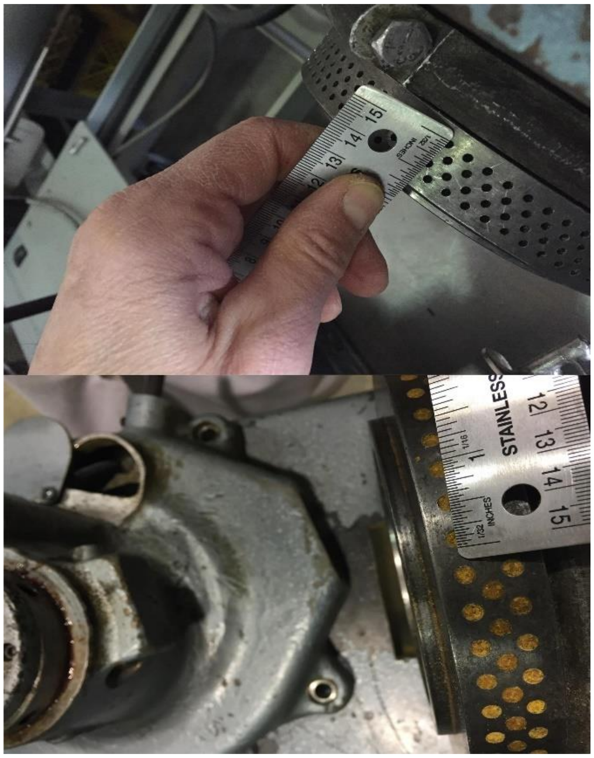

Figure 3.2 Different dies used in pelleting process

Table 3.1 Pelleting process conditions

Run	Die Size			Moisture (db%)	Throughput(lb/hr)
	Diameter	length	L/D		
1	1/8	1	8	10	37.5
2				15	
3				20	
4	3/16	1 1/2	8	10	52
5				15	
6				20	

Table 3.2 Moisture content for DDGS and DDGS pellets*

Run	Die (in)	Moisture level(%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	10.4	10.5	10.7	10.5a	0.15
1	1/8	10	10.6	10.3	10.3	10.4a	0.17
2		15	14.3	14.9	14.6	14.6b	0.30
3		20	19.7	20.3	20.5	20.1c	0.41
4	3/16	10	10.9	10.4	10.6	10.6a	0.25
5		15	14.7	15.5	15.3	15.1b	0.41
6		20	19.8	21.2	20.6	20.5c	0.70

Moisture content(%)

*Different letters after means in each level of the moisture content indicates significant difference at α=0.05

Table 3.3 ANOVA for moisture content

Factor	DF*	F value	$P_r > F$
Die Size	1	0.0371	0.8497
Moisture	2	777.0124	<.0001
Die size * Moisture	5	342.4788	<.0001

*Degree of freedom

Table 3.4 Bulk density for DDGS and DDGS pellets *

Run	Die (in)	Moisture level(%)	Bulk density(kg/m^3) Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	465.2	467.1	465.5	465.9a	1.02
1		10	572.4	571.8	569.9	571.4b	1.3
2	1/8	15	527.3	531.7	530.2	529.7c	2.2
3		20	512.4	508.1	510.3	510.3d	2.2
4		10	488.7	490.5	491.3	490.2e	1.3
5	3/16	15	485.5	484.9	484.7	485.0f	2.0
6		20	480.5	482.3	483.5	482.1g	1.5

* Different letters after means in each level of the bulk density indicates significant difference at α=0.05

Table 3.5 ANOVA for bulk density

Factor	DF*	F value	$P_r > F$
Die Size	1	31.7724	<.0001
Moisture	2	1.9863	0.1717
Die size * Moisture	5	1088.568	<.0001

*Degree of freedom

Table 3.6 Pellet durability for DDGS pellets*

Run	Die (in)	Moisture level(%)	Durability (%) Replication 1	Replication 2	Replication 3	Means	Standard deviations
1		10	72.6	72.9	74.1	73.2a	0.8
2	1/8	15	80.6	80.3	78.4	79.8b	1.2
3		20	89.4	89.2	89.2	89.3c	0.1
4		10	42.6	42.4	42.5	42.5d	0.1
5	3/16	15	48.6	46.2	57.6	57.5e	1.2
6		20	60.8	60.2	60.5	60.5f	0.3

* Different letters after means in each level of the durability results indicates significant difference at α=0.05

Table 3.7 ANOVA for pellet durability*

Factor	DF*	F value	$P_r > F$
Die Size	1	55.9509	<.0001
Moisture	2	1.960	0.1753
Die size * Moisture	5	1374.109	<.0001

*Degree of freedom

Table 3.8 Angle of repose for DDGS and pellets*

Run	Die (in)	Moisture level(%)	Angle of repose (°) Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	47.6	46.9	46.7	47.0a	0.47
1	1/8	10	35.9	36.5	36.9	36.4b	0.5
2		15	39.5	38.8	38.7	39.0c	0.4
3		20	43.3	43.9	44.2	43.8d	0.5
4	3/16	10	37.6	37.9	36.7	37.4e	0.6
5		15	40.9	39.9	40.5	40.4f	0.5
6		20	44.9	44.7	44.8	44.8g	0.6

* Different letters after means in each level of the angle of repose indicates significant difference at α=0.05

Table 3.9 ANOVA for pellets angle of repose*

Factor	DF*	F value	$P_r > F$
Die Size	1	0.5455	0.4709
Moisture	2	145.4527	<.0001
Die size * Moisture	5	158.6061	<.0001

*Degree of freedom

Table 3.10 Color L* for DDGS and pellets*

Run	Die (in)	Moisture level(%)	Color L* Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	56.58	55.83	56.76	56.39a	0.8
1	1/8	10	35.22	37.43	35.18	35.94b	1.28
2		15	30.36	31.47	30.25	30.69c	0.67
3		20	26.91	29.64	26.37	26.64d	0.27
4	3/16	10	46.93	45.19	45.71	45.94e	0.89
5		15	39.09	41.22	39.07	39.79f	1.23
6		20	32.89	32.92	38.77	34.86b	3.38

* Different letters after means in each level of the color L* indicates significant difference at α=0.05

Table 3.11 ANOVA for Color L*

Factor	DF*	F value	$P_r > F$
Die Size	1	17.1830	0.0008
Moisture	2	5.7635	0.0139
Die size * Moisture	5	51.7294	<.0001

*Degree of freedom

Table 3.12 Color a* for DDGS and pellets*

Run	Die (in)	Moisture level(%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
			Color a*				
DDGS		10	12.14	12.36	11.98	12.16a	0.2
1	1/8	10	9.33	9.56	10.32	9.74b	0.52
2		15	8.72	8.77	8.61	8.70c	0.08
3		20	7.92	7.83	7.47	7.74d	0.23
4	3/16	10	11.22	11.44	11.29	11.31a	0.11
5		15	10.25	10.14	10.24	10.21e	0.06
6		20	9.31	9.14	9.42	9.29f	0.14

* Different letters after means in each level of the color a* indicates significant difference at α=0.05

Table 3.13 ANOVA for Color a*

Factor	DF*	F value	$P_r > F$
Die Size	1	13.3542	0.0021
Moisture	2	7.9258	0.0045
Die size * Moisture	5	74.7460	<.0001

*Degree of freedom

Table 3.14 Color b* for DDGS and pellets*

Run	Die (in)	Moisture level(%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
			Color b*				
DDGS		10	22.3	23.1	22.5	22.6a	0.4
1	1/8	10	17.17	15.76	15.29	16.07b	0.97
2		15	13.82	14.86	13.93	14.23c	0.57
3		20	13.26	14.17	13.57	13.67c	0.46
4	3/16	10	23.33	21.42	22.83	22.52d	0.99
5		15	19.86	19.82	19.41	19.69e	0.24
6		20	17.84	17.34	17.68	17.62f	0.25

* Different letters after means in each level of the color b* indicates significant difference at α=0.05

Table 3.15 ANOVA for Color b*

Factor	DF*	F value	$P_r > F$
Die Size	1	39.5126	<.0001
Moisture	2	2.2657	0.1381
Die size * Moisture	5	79.3773	<.0001

*Degree of freedom

CHAPTER 4. PHYSICAL PROPERTIES OF PILOT SCALE PELLETING

Abstract

The DDGS has been broadly used as animal feed due to the high nutrition level and relatively low cost. However, the poor flowability and low bulk density became the main disadvantage of handling and utilizing DDGS. Pelleting process as the popularly used food processing technology could improve the flowability and bulk density of DDGS. The present study was conducted to understand what kind of pelleting condition will affect the resultant pellets quality. The experiment was using 100% of DDGS as the pelleting ingredient with three moisture content level. The pellets durability was tested to obtain the pellets quality. The experiment result showed that with high die L/D ratio and high moisture content, the pellets would lead to a relatively high durability. The result shows that with higher L/D value and higher moisture content, the highest pellet durability was 91%. For bulk density, the highest value 579.3 kg/m^3 comes from the pellets with higher L/D value die and lower DDGS moisture level.

Introduction

The high nutrition level and relatively low cost have made DDGS a valuable by-product from corn ethanol plant. However, the poor flowability and low bulk density became the major issues in shipping and storage DDGS. After long distance shipping the cohesive DDGS was even harder to unload and cause increasing labor cost and unload times and also has the potential risk of damage the railcars or trucks since other force will need to remove the DDGS during unloading (Fahrenholz, 2008). Furthermore, low bulk density means that the DDGS needs extra storage space and will be filled up the railcars or trucks before reaching maximum weight capacity which result in the increase of shipping costs.

Pelleting could be a valid way to improve the handling issues of DDGS. Rosentrater and Kongar (2009) showed that pelleting DDGS was highly cost-effective and it will reduce the overall transporting costs. Pelleting 100% DDGS has been shown to be possible (AURI, 2005), and could be done directly at the ethanol plant before shipping. The increase in bulk density have been noticed after pelleting process, and the bulk density was increased as the die L/D ratio increased (Wilson and Mckinney, 2008).

There were few works about pelleting DDGS, most of the works were only treated DDGS as part of the pelleting ingredients. Wang et al. (2007a) reported when the DDGS level increased in the ingredients the pellet quality decreased and it can be observed visually. Stender et al. (2008) also indicated that the pellet durability was decreased as the DDGS level increased. The aim of this research is to study pilot scale pelleting process by using 100% corn-based DDGS. The results of this research may be the reference for a large-scale facility producing DDGS pellets, and help the animal feed industry improve the value of DDGS while reducing the cost by utilizing DDGS as animal feed.

Materials and Methods

Material and equipment

The corn-based DDGS were provided by Lincolnway Energy (Lincolnway Energy LLC Nevada IA 50201) a local dry grind ethanol plant. The DDGS held in a bin and stored in our lab at room temperature for further research. The 5 hp 1800 RPM CPM laboratory pellet mill (CL-5 CPM Acquisition Corp. Crawfordsville, IN 47933 - USA) was used for the pilot scale pelleting study. Figure 4.1 shows the pellet mill used in this study. The pellet mill was made up with an ingredient hopper to hold the DDGS, a vibratory feeder to adjust the flow of the DDGS into the conditioner and a screw feeder to push the DDGS into the mill to complete the pelleting process. The pellet mill was also equipped with a PLC interface to control the pelleting mill and change the ingredients feeding rate.

Experimental design

Table 3.1 shows the experimental design for this study. Three dies include die diameter 1/8 in with L/D (length to diameter) ratio of 8, die diameter 3/16 in with L/D (length to diameter) ratio of 5.5 and die diameter 1/4 in with L/D ratio of 6 were used for this study. For each die, the DDGS was pretreated to three different moisture levels, which were 10% 15% and 20%, respectively. There were total nine runs for various die size and DDGS moisture content in this study. The pelleting throughput represents the production rate of converting raw DDGS to DDGS pellet. The throughput rate was adjusted based on the die size. The feeding rate of the ingredients was controlled by adjusting the vibratory feeder on the control panel. The highest pelleting throughput was run 7-9 which was 95 lb/hr.

DDGS moisture content adjustments

The moisture content of DDGS was adjusted to three levels: 10%, 15%, and 20%. The 10% moisture content was the initial DDGS moisture content. To set the DDGS moisture content, the samples of DDGS were initially put in a bucket and then adding water into the DDGS and mix them. The amount of water added to the DDGS for the pelleting process was calculated by assuming the weight of the dry matter remains constant. The calculated amount of water was added to DDGS samples directly by using a sprayer and then mixed by the mixer.

Moisture content of DDGS and the DDGS pellets

The moisture content was measured based on the NFTA (National Forage Testing Association) 2.2.2.5 method (Shreve et al., 2006). Based on the instruction 3 g of DDGS or DDGS pellet sample were dried at 105 ^{o}C for 3 hours in the oven, and the moisture is reported in % dry basis (db). The moisture content was measured three times for each sample; both mean and standard deviation was presented.

Bulk density of DDGS and DDGS pellets

The bulk density of DDGS was measured based on the procedure given by ASAE S269.5 (ASAE, 2012). The DDGS and pellet sample flowed freely into a one-liter cup. Then a striking stick was used to brushed off the excesses samples with the gentle zig-zag strokes. The bulk density of DDGS or DDGS pellets was calculated by divided the DDGS or pellet mass by the volume of the container. The measured was repeated three times for each sample, means and standard deviation for each sample bulk density was also calculated and reported.

Pellets durability measurement

The pellet durability was also measured regarding ASAE S269.5 (ASAE, 2012). A seedburo pellet durability tester (Seedburo Equipment Co. Des Plaines IL 60076) was used in this measurement. Before the durability test of DDGS pellet, the pellet was first sieved and then 500g of the pellet was sampled for each run. The pellet sample was tumbled 10 min inside the durability tester, after tumbling the sample was sieved to separate the remaining pellet from the testing mass. The pellet durability was calculated by dividing the mass of remaining pellet by the initial mass of pellet sample. Three times of the test were done for each run, the mean and standard deviation were also calculated and reported in the result section.

Angle of repose of DDGS and DDGS pellets

The angle of repose (AoR) is one of the factors that can indicate the material potential flowability. (Carr, 1965). The angle of repose value was to measure the steepest angle between free flow material inclination surface and the horizontal. Woodcock and Mason (1987) suggest that if the angle value between 30° to 38° this material was considered as free flow material and the angle value between value between 38° to 45° this material was considered as fair flow material. If the material angle of repose value between 45° to 55°, this material was considered as cohesive material. The angle of repose measured in this study could also be called as the emptying angle of repose which the DDGS pellets was filled in a box, and then the pellets were free flow out of the box.

Color

A Minolta Chromameter (Chromameter CR-410 Konica Minolta Sensing Europe B.V.) was used to measure the color of DDGS and DDGS pellets. The color was determined by three parameters including L*, a* and b*, which L* represent the lightness level, a* represent the green – red level and b* represent blue – yellow level. For each pellet sample, three replications were done to measure the color, mean and standard deviation were calculated and reported in the results section.

Results and Discussion

The pelleting temperature measured during the pelleting process was listed in Table 4.2, the temperature value for each run was ranged from 23.3 °C to 44.3 °C. For each die size, the pelleting temperature was decreased along with the increase of DDGS moisture level. For run 7, the temperature did not follow the trend for pelleting temperature change, 23.3 °C was the average pelleting temperature for this run. The reason was that there were no pellets generated from run 7 the DDGS was just flowed through the pellet mill and die, there was no sufficient friction between DDGS, die and pellet mill wheel. Table 4.3 shows the statistic analysis for DDGS pellets temperature. Die size and the interaction between die size and moisture content have significant effect on DDGS pellets temperature.

Table 4.4 and Table 4.5 report the moisture content results and the statistic analysis. The DDGS pellets moisture content has followed the trend with the moisture level increased. From the statistic analysis the die size has no significant influence on the final DDGS pellets moisture content, while the DDGS ingredients moisture level has a significant effect on the final DDGS pellets moisture content. This also results in the die size and moisture level together has a significant effect on final pellets moisture content.

For run 1-3 the DDGS pellets bulk density varied from 531.3 kg/m^3 to 579.3 kg/m^3 while for run 4-6 bulk density ranged from 490.4 kg/m^3 to 518.2 kg/m^3 and for run 8-9 the pellets bulk density was ranged from 469.7 kg/m^3 to 475.3 kg/m^3. (Table 4.6) All the pellets bulk density was significantly increased compared with the raw DDGS bulk density. The die size and DDGS moisture level together have a significant effect on bulk density (Table 4.7). The bulk density value was decreased along with the increase of raw DDGS moisture content level. The results of the DDGS pellets bulk density were similar to Jaya Shankar Tumuluru et al. , (2010) the change in the bulk density was significant. The bulk density results were also similar with Fasina and Sokhansanj (1993), the pellets bulk density was decreased along with the increase of pellets moisture content.

The pellet durability result was reported in table 3.6 and table 3.7 For run 1-3 the durability of pellets varied from 78.0% to 91.8%; For run 4-6 the durability of pellets varied from 62.6% to 75.8% while for run 8-9 the durability pf pellets varied from 80.6% to 85.9%. (Table 4.8) The statistic analysis shows that all the pellets durability data were significantly different from each other. Die size and die size together with moisture level all has a significant effect on the pellets durability value (Table 4.9). Comparing the results from run 1-3 with run 1-6, we can observe that even though these two dies have same L/D ratio, the die with smaller die diameter results in higher pellets durability and bulk density. The reason for this difference may be due to different pressures generated during the pelleting process.

The values of angle of repose for run 1-3 were varied from 34.3° to 42.6°, and for run 4-6 the angle of repose ranged from 35.5° to 43.1° while for run 8 and 9 the angle of repose value was ranged from 39.7° to 44.6° (Table 4.10). The angle of repose value indicated that after pelleting process the DDGS pellets could be considered as fair flow or free flow. Compare to the raw DDGS angle of repose which was 47.0° From the results; we can see that after pelleting process the pellets angle of repose value was smaller than the raw DDGS this means that the pelleting process could increase the material flowability. For each dies, the pellets angle of repose was increased along with the DDGS moisture level increased. Compare to other pellets angle of repose results, Fasina and Sokhansanj (1993) found that the pellet size and moisture content has a significant effect on alfalfa bulk properties. The angle of repose for alfalfa pellets was increased while the pellets moisture content increased which was similar to our finding. Table 4.11 shows the statistical analysis of the angle of repose results, the moisture content and the interaction of moisture content with die size has the significant effect on pellet angle of repose results.

The color L* for DDGS and pellets was reported in Table 4.12 and Table 4.13. The color L* value indicates that the DDGS became darker than the original DDGS after pelletized, which is very similar to the result of Rosentrater(2007a). For both of the die size, the L* value was decreased with the moisture level increased. It was also observed that the color of the DDGS pellets became darker if the die with smaller diameter was used to pellet DDGS. The die size and the die size together with moisture level was the main factor that affects the color L* value. Table 4.14, 4.15, 4.16 and Table 4.17 shows the reuslts for color a* and color b*. The color a* and color b* results were similar with color L* results. The color a* and color b* values were all decreased after the pelleting process. For each die, the color a* and color b* values were decreased as the DDGS moisture content increased.

Conclusions

The present pelleting project showed the similar results with the first pelleting project. Adding moisture into the DDGS and using the die with larger L/D value can get more durable pellets. This highest pellet durability occurred when the DDGS moisture content was 20%, and the die L/D value was 8. Compare with the first pelleting project, under the similar pelleting condition the pellet durability was higher due to the different pilot scale pelleting mill used for each pelleting studies. For pelleting temperature, the die with a smaller diameter will result in the higher pellet temperature, while for each different die the highest pellet temperature was observed when the DDGS moisture content was

10%. By using pilot-scale pellet mill, the bulk density can be increased, and the bulk density was larger with the larger L/D value.

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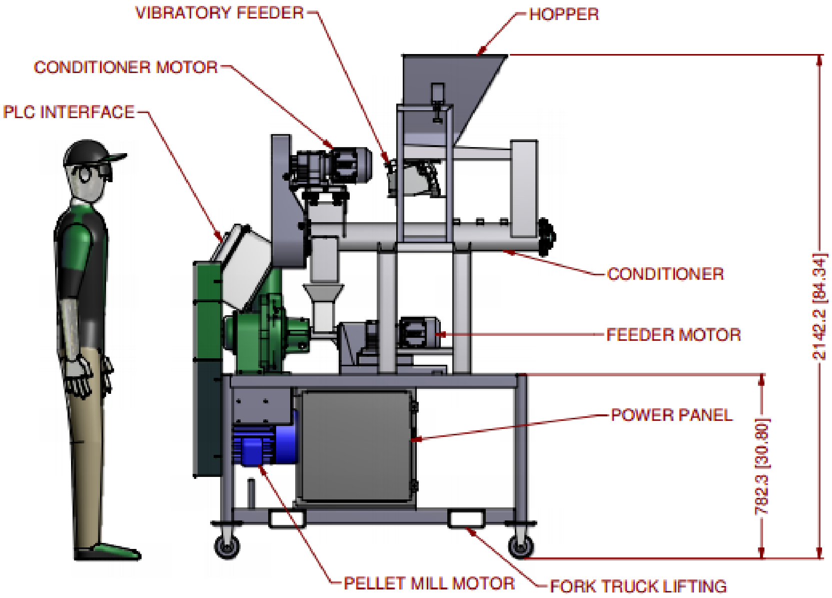

Figure 4.1 CPM CL-5 pelleting mill (CPM Acquisition Corp, 2010)

Figure 4.2 Different dies used in pelleting process

Table 4.1 Pelleting process conditions and experimental design

Run	Die Size			Moisture (db%)	Throughput(lb/hr)
	Diameter	length	L/D		
1	1/8	1	8	10	45
2				15	
3				20	
4	3/16	1	5.5	10	67
5				15	
6				20	
7	1/4	1 1/2	6	10	95
8				15	
9				20	

Table 4.2 DDGS and pellets temperature*

Temperature (°C)							
Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	22.5	22.2	22.4	22.3a	0.15
1	1/8	10	44.5	44.3	44.1	44.3b	0.20
2		15	41.6	40.9	41.3	41.3c	0.35
3		20	38.9	39.3	39.4	39.2d	0.26
4	3/16	10	38.5	37.9	38.3	38.2e	0.31
5		15	36.5	37.1	36.9	36.8f	0.30
6		20	31.8	31.0	31.5	31.4g	0.40
7	1/4	10	23.5	23.2	23.3	23.3h	0.15
8		15	36.6	36.5	37.1	36.7f	0.32
9		20	30.3	31.9	31.5	31.2g	0.83

* Different letters after means in each level of the temperature indicates significant difference at α=0.05

Table 4.3 ANOVA for pellet temperature

Factor	DF*	F value	$P_r > F$
Die Size	2	18.0989	<.0001
Moisture	2	1.2902	0.2936
Die size * Moisture	5	704.0689	<.0001

*Degree of freedom

Table 4.4 Moisture content for DDGS and pellets*

Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
			Moisture content (%)				
DDGS		10	10.4	10.6	10.5	10.5a	0.10
1	1/8	10	10.6	10.5	10.5	10.5a	0.06
2		15	14.8	14.5	14.7	14.7b	0.15
3		20	19.5	19.3	19.8	19.5c	0.25
4	3/16	10	10.8	10.9	10.6	10.7a	0.15
5		15	15.3	14.8	14.9	15.0b	0.26
6		20	19.6	20.5	21.3	20.5d	0.85
8	1/4	15	15.7	15.2	14.8	15.2b	0.45
9		20	20.4	20.6	20.4	20.5d	0.11

* Different letters after means in each level of the moisture content indicates significant difference at α=0.05

Table 4.5 ANOVA for moisture content

Factor	DF*	F value	$P_r > F$
Die Size	2	1.1513	0.3354
Moisture	2	774.3772	<.0001
Die size * Moisture	7	344.2883	<.0001

*Degree of freedom

Table 4.6 Bulk density for DDGS and pellets*

Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
			Bulk density(kg/m^3)				
DDGS		10	465.2	467.1	465.5	465.9a	1.02
1	1/8	10	579.7	578.6	579.5	579.3b	0.58
2		15	545.9	548.7	549.6	548.1c	1.92
3		20	531.7	528.6	533.7	531.3d	2.56
4	3/16	10	518.9	517.5	518.3	518.2e	0.70
5		15	508.3	511.2	509.7	509.7f	1.45
6		20	489.7	491.2	490.2	490.4g	0.76
8	1/4	15	475.5	474.7	475.8	475.3h	0.57
9		20	470.2	469.2	469.7	469.7i	0.50

* Different letters after means in each level of the bulk density indicates significant difference at α=0.05

Table 4.7 ANOVA for bulk density

Factor	DF*	F value	$P_r > F$
Die Size	2	52.9369	<.0001
Moisture	2	5.3120	0.0136
Die size * Moisture	7	2320.145	<.0001

*Degree of freedom

Table 4.8 Pellet durability for DDGS pellets*

			Durability (%)				
Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
1	1/8	10	78.5	78.7	76.9	78.0a	0.98
2		15	85.6	83.7	84.6	84.6b	0.95
3		20	89.4	92.5	93.7	91.8c	2.21
4	3/16	10	63.7	61.5	62.6	62.6d	1.10
5		15	70.5	68.2	69.5	69.4e	1.15
6		20	76.8	75.4	75.3	75.8f	0.84
8	1/4	15	79.9	80.4	81.7	80.6b	0.93
9		20	86.6	86.4	84.7	85.9g	1.04

* Different letters after means in each level of the durability indicates significant difference at $\alpha=0.05$

Table 4.9 ANOVA for pellet durability

Factor	DF*	F value	$P_r > F$
Die Size	2	21.1748	<.0001
Moisture	2	6.8477	0.0051
Die size * Moisture	7	305.2842	<.0001

*Degree of freedom

Table 4.10 Angle of repose for DDGS and pellets*

Angle of repose (°)							
Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	46.6	46.9	46.7	46.7a	0.15
1	1/8	10	34.7	33.8	34.3	34.3b	0.45
2		15	38.7	38.8	38.2	38.6c	0.32
3		20	42.6	42.9	42.2	42.6d	0.35
4	3/16	10	35.6	35.7	35.1	35.5e	0.32
5		15	39.8	39.7	39.2	39.6f	0.32
6		20	43.2	43.5	42.7	43.1d	0.40
8	1/4	15	39.7	39.5	39.9	39.7f	0.20
9		20	44.5	44.8	44.6	44.6g	0.15

* Different letters after means in each level of the angle of repose indicates significant difference at α=0.05

Table 4.11 ANOVA for angle of repose

Factor	DF*	F value	$P_r > F$
Die Size	2	2.3306	0.1219
Moisture	2	215.8844	<.0001
Die size * Moisture	7	369.6365	<.0001

*Degree of freedom

Table 4.12 Color L* for DDGS and pellets*

Color L*							
Run	Die (in)	Moisture level(%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	56.58	55.83	56.76	56.39a	0.8
1	1/8	10	45.33	45.43	45.67	45.47b	0.17
2		15	38.82	39.56	39.44	39.27c	0.39
3		20	36.42	36.01	36.93	36.45d	0.46
4	3/16	10	53.62	53.92	53.21	53.58e	0.35
5		15	49.72	49.33	49.71	49.58f	0.22
6		20	45.23	47.54	45.78	46.18b	1.20
8	1/4	15	54.91	55.07	55.62	55.20g	0.37
9		20	51.68	51.32	50.24	51.08h	0.74

Different letters after means in each level of the color L indicates significant difference at α=0.05

Table 4.13 ANOVA for color L*

Factor	DF*	F value	$P_r > F$
Die Size	2	29.9463	<.0001
Moisture	2	1.2749	0.3002
Die size * Moisture	7	386.0057	<.0001

*Degree of freedom

Table 4.14 Color a* for DDGS and pellets*

Color a*							
Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	12.14	12.36	11.98	12.16a	0.2
1	1/8	10	8.72	9.52	9.33	9.19b	0.41
2		15	7.98	7.57	6.68	7.41c	0.66
3		20	6.12	6.08	5.71	5.97d	0.22
4	3/16	10	10.26	11.01	10.93	10.73e	0.41
5		15	9.33	8.97	9.04	9.11b	0.19
6		20	7.54	7.14	7.59	7.42c	0.24
8	1/4	15	10.59	10.78	10.07	10.4e	0.36
9		20	9.56	9.96	9.68	9.73b	0.21

Different letters after means in each level of the color a indicates significant difference at $\alpha=0.05$

Table 4.15 ANOVA for color a*

Factor	DF*	F value	$P_r > F$
Die Size	2	7.6642	<.0001
Moisture	2	4.8285	0.0188
Die size * Moisture	7	60.1517	<.0001

*Degree of freedom

Table 4.16 Color b* for DDGS and pellets*

Color b*							
Run	Die (in)	Moisture level (%)	Replication 1	Replication 2	Replication 3	Means	Standard deviations
DDGS		10	22.3	23.1	22.5	22.6a	0.4
1	1/8	10	13.22	14.71	14.91	14.28b	0.92
2		15	12.66	11.59	11.92	12.05c	0.55
3		20	10.81	10.52	10.63	10.65d	0.15
4	3/16	10	18.21	19.78	19.34	19.11e	0.81
5		15	16.76	16.56	16.86	16.72f	0.15
6		20	14.54	14.73	15.54	14.93b	0.53
8	1/4	15	19.21	19.57	19.89	19.55e	0.34
9		20	14.76	15.58	14.46	14.93b	0.58

Different letters after means in each level of the color b indicates significant difference at α=0.05

Table 4.17 ANOVA for color b*

Factor	DF*	F value	$P_r > F$
Die Size	2	15.8029	<.0001
Moisture	2	2.9992	0.0715
Die size * Moisture	7	90.2169	<.0001

*Degree of freedom

CHAPTER 5. ASSESSMENT OF LOW TEMPERATURE CLOSED-CYCLE GRAIN DRYING SYSTEM

Abstract

This study was about to analyze the drying efficiency of a prototype low temperature closed-cycle grain drying system. The main principle of this drying system was the heat pump system working as a dehumidifier. The main component of this drying equipment including a compressor, a condenser, twin evaporators, and a fan. Two drying processes including trial 1 and trial 2 were conducted to assess the overall drying performance of this low temperature drying system. To calculate the drying efficiency, the total energy consumption was divided by the amount of water removal for each trail; the drying efficiency was reported in the form of Btu/lb of water removal. We also ran corn seed germination test to check if the drying process has an effect on seed germination performance. The drying efficiency results for trail 1 and 2 was 1036 Btu/lb water removal and 869 Btu/lb water removal respectively, compare to other on-farm drying methods this drying system had high drying efficiency. The germination test results showed that this drying system had no adverse effect on germination performance.

Introduction

For corn production in Iowa, on-farm drying was the major way for post harvest corn drying. Most of the on-farm grain dryers were high temperature dryer. Although high temperature grain drying was much faster, it will result in reduce of the grain quality and germination performance. Seyedin, Burris, and Flynn (1984) reported that the corn seed germination performance could be significantly reduced by high temperature drying and by analyzing the shoot and root dry matter the seedling vigor was also significantly reduced. The maximum grain drying temperature was reported by Hall (1980), for corn used as seed the maximum safe temperature was 43 °C while for commercial corn the maximum safe drying temperature was 54 °C. The highest 82 °C safe drying temperature was the corn used as animal feed. This indicates that low temperature grain drying was important for seed or commercial used corn.

From energy usage perspective, grain drying is an energy intensive process (Gunasekaran and Thompson, 1986). For most of the grain production, the energy required for grain drying often higher than the energy usage for producing grain from seed to harvest (Verma, 1982; Enlow, 1982). The heat pump grain drying concept was early investigated by Davis (1949), Shove (1953), and Flikke et al. (1957) they found the system was not attractive economically for the then-prevailing fuel prices. More recently, since the fossil fuel price has increased a lot, Prasertsan and Saen-saby (1998) found that the heat pump drying was more competitive than electrically heated dryers and direct-fired dryer due to the lowest operating cost.

This study was conducted to analyze the efficiency of the prototype low temperature closed-cycle grain drying system and its effects on seed germination. Two trials have been done in this study. The energy consumption and amount of moisture removal were measured for each trail.

Materials and Methods

The drying apparatus assessed in this study is a low temperature closed-cycle grain drying system provided by the Loebach Brothers (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc.,). Figure 5.1 shows overall layout of this drying system, the drying apparatus connected with the wagon by two air pipe, the dried air goes into the bottom of the wagon and the moist air goes into the drying apparatus through the top of the wagon. Figure 5.2 shows the simple diagram of this low temperature drying system. The core part of this drying apparatus including a compressor (Copeland CF06K6E-PFV-979, Emerson Climate Technologies Incorporated, Sidney, OH 45365), a condensation-evaporation system including a condenser and twin evaporators, and a centrifugal blower (GE motors 5KCP39KGV804S, 0.5 hp, GE Energy Management, Atlanta, GA 30339). Electricity was the only energy source for this system. By controlling the four solenoid valves this drying system could run with one evaporator cooling and other evaporator heating, at present, the timer will reverse the solenoid value to allow the first evaporator to defrost and heat and the second evaporator to cool and remove moisture.

The corn was harvested by Richard Vanderpool's group and stored in Bio-Century Research Farm (Iowa State University, 1327 U Avenue, Boone, IA). The initial corn wet basis moisture content is 28.1% to 28.3%.

The energy consumption was measured by a power meter (Landis+Gyr MX-92-270-908, Landis+Gyr AG, Alpharetta, GA 30022) that was attached to the drying system. Four temperature loggers (Omega OM-EL-USB-2-LCD, Omega Engineering, Inc., Stamford, CT 06907) were applied to record the air relative humidity and air temperature, separately for high moisture air out from the corn, dry air from drying equipment, air from 12 inch below the corn surface, and ambient air for both of the drying trails (Figure 1). The moisture content of corn was measured by using the mini GAC handheld moisture analyzer (mini GAC plus DICKEY-john Corp.) and the corn moisture content recorded every 24 hours to track the moisture content change from time to time. Three replications were done to measure the corn moisture content, and the average and standard deviation were calculated and reported in the results section.

For trail 1, the corn with the weight of 2880 pounds and moisture content of 28.1% wet basis was placed into the wagon before the drying process. Based on the corn moisture content results during the drying process and the suggestion of the Loebach brother’s the drying process was operated for 68 hours after drying process started.

For trail 2, the corn with the weight of 3200 pounds and moisture content of 28.3% wet basis was placed into the wagon before the drying process. Based on the corn moisture content results during the drying process and the suggestion of the Loebach brother’s the drying system was operated for 66.5 hours after drying process started. Corn was sampled before and after the drying process for a germination test.

For airflow rate about this low temperature grain drying system, the airflow static pressure was measured during the trial 2. The total air flow rate during trial 2 was calculated based on Shedd’s curve which is about resistance to airflow of grains and seeds (ASAE, 2011). Figure 3 shows the dimension of the wagon that hold the corn, which use to compute the aeration area and the corn depth.

The corn germination performance was tested by using an incubator (Fisher Scientific Isotemp Incubator 650D, Thermo Fisher Scientific, Waltham, MA 02451). The germination test has followed the procedure that provided by Williams et al. (2014) which randomly picked up 50 kernels of corn and put them between two pieces of wet paper towels. Then rolled the two wet paper tower together with corn kernels and sealed them in a plastic bag. Put the plastic bag in an incubator for seven days at 30 °C. After accounted the number of germinated corn kernels, the germination rate was computed by dividing the germinated corn kernels number by the initial 50 corn kernels. The germination test was done three times both mean and the standard deviation were calculated and reported in the results section.

The drying efficiency was determined by calculating the ratio between power consumption (Btu) and water removal (lb) and the result Btu/lb of water removal was reported.

$$Drying\ efficiency = \frac{\text{energy consumption (kWh)}}{\text{water removal (lb)}}$$

The water removal (lb) was calculated by subtracting the amount of water (lb) in the corn after drying process from the total amount of water (lb) in the corn before drying process.

Results and Discussion

Drying data collection and calculation

The drying data for the two drying trails was reported in table 5.1 mean and standard deviation for each drying parameter were also calculated and reported. The initial corn moisture content was measured as 28.1% and 28.3% for trial 1 and trial 2 respectively with the average value 28.2% and the standard deviation 0.1. For trial 1 the overall drying time was recorded as 68 hours and 66.5 hours respectively for trail 1 and trail 2. The average dry time for this drying system was calculated as 67.25 hours. The initial corn weight for trial 1 was measured as 3460 lb while for trial 2 the initial corn weight was 4000 lb. The mean of initial corn weight was calculated as 3730 lb with the standard deviation value 270. The drying power consumption were measured as 170 kWh (580064 Btu) and 180 kWh (614185 Btu) for trial 1 and trial 2 respectively. The average power consumption for this drying system was calculated as 175 kWh (597125 Btu) with the standard deviation of

5 kWh (17060.7 Btu). The final corn moisture content was measured as 14.3% and 12.9% for trial 1 and trial 2 respectively. The average dried corn moisture content was 13.6% and the standard deviation was 0.7%. The total water removal during drying process was 560 lb in trial 1 and 707 lb in trial 2. The drying efficiency was calculated as 0.30 kWh/lb of water removal (1036 Btu/lb of water removal) and 0.25 kWh/lb of water removal (869 Btu/lb of water removal) for trial 1 and trial 2 respectively. The system average drying efficiency was calculated as 0.275 kWh/lb of water removal (953 Btu/lb of water removal) of water removal with the standard deviation of 0.025 kWh/lb of water removal (68.9 Btu/lb of water removal). Compare drying equipment efficiency from trial 1 and trial 2, the equipment in trail 2 was 16% more efficient than the equipment in trial 1. The trail 1 and trail 2 was conducted under a similar temperature condition which was 13 to 25 degree Celsius, the main reason caused the efficiency difference was before we started the trial 1 the whole drying system had not been operated for a while, and it took time to get the drying system work in the best condition and start to remove water from the corn. Zhang (2015) conducted a similar corn drying project which used the same drying system with the present study. In Zhang’s study, two trials including fall trial and winter trial were conducted to measure the drying efficiency. The drying efficiency in Zhang’s work was reported as 1480 Btu/lb of water removal and 2760 Btu/lb of water removal for fall and winter trial respectively. Compare to Zhang’s result the drying system in the present study was 36% and 65% more efficient. The reason for the drying efficiency difference could be because of the difference of the initial corn moisture content and dried content. The original corn moisture content in Zhang’s study was 18.9% which was about 33% lower than that in the present study. The drying system will always run at low efficiency when the initial

grain moisture content is relatively low. The air temperature also had a significant effect on drying efficiency. In Zhang's winter trial the corn was dried from 18.9% moisture content to 14.1% moisture content, and the working air temperature was between -3 ^{o}C to 10 ^{o}C, while in the present study the average working air temperature was 24.3 ^{o}C. Hanna et al. (2014) reported the energy consumption during grain drying by using several different drying methods including batch in bin system and counter-flow style dryer; the result showed that the drying efficiency ranged from 2000-3000 Btu/lb of water removed, which consume 52%-68% more energy to remove one pound of water. Compared to the energy efficiency result Morey et al. (1978) observed 5.7 MJ/kg (2461 Btu/lb), the present system was more efficient. Compared to Wilcke and Bern (1986) result, which was 3.02 MJ/kg (1300 Btu/lb), the present system was more efficient and had a shorter drying period.

For air flow rate, the static air pressure during trial 2 was measured as 0.41 in of water, based on the calculation the average aeration area was 39 ft^2 the corn depth was 1.65 ft. The pressure drop per unit depth was computed as 0.25 in of water per 1 foot of corn which means from the Shedd's curve the air flow for shield corn was 25 cfm per 1 square foot. The total airflow rate was computed as 975 cfm.

Air temperature and relative humidity results

Figure 5.4, 5.5, 5.6, and 5.7 shows the trial 1 air temperature and relative humidity value recorded by the four temperature. It was clear to see that all the air temperature and dew point temperature for logger 1, logger 2 and logger 3 all has the similar trend with logger 5. Also, at the same period, all the temperature value remained at the same level, except for the air temperature before drying the corn was higher than air temperature after drying the corn. For trial 2 the temperature result was resembled with trail 1, since the drying system operated under similar temperature (Figure 5.7, 5.11).

For air temperature result the means and the standard deviation were calculated and reported in Table 5.2 and Table 5.3 For trial 1 the average air temperature was 22.9 °C, 17.7 °C, 18.6 °C, and15.9 °C for logger 1, logger 2, logger 3, and logger 5 respectively. For trial 2 the average air temperature was 25.5 °C, 20.1 ºC, 22.5 °C, and 18.9 °C for logger 1, logger 2, logger 3, and logger 5 respectively. The statistical analysis showed that all the temperature results were significantly different from each other. For different logger, the average air temperature was 24.3 °C, 18.9 °C, 20.6 °C, and 17.5 °C for logger 1, logger 2, logger 3, and logger 5 respectively. From figure 5.11 and 5.12 it was clear to observe that the dry air temperature was higher than other air temperature. The air temperature will decrease when carrying water out from the corn.

For dew point temperature results the means and the standard deviation were calculated and reported in Table 5.2 and Table 5.3. For trial 1 the average air temperature was 11.3 °C, 14.2 °C, 14.5 °C, and 3.7 °C for logger 1, logger 2, logger 3 and logger 5 respectively. For trial 2 the mean dew point temperature was 13.8 °C, 16.6 °C, 16.2 °C, and 9.0 ºC for logger 1, logger 2, logger 3, and logger 5 respectively. The statistical analysis showed that all the temperature results were significantly different from each other. For various logger, the average air temperature was 12.6 °C, 15.4 °C, 15.3 °C, and 6.42 °C for logger 1, logger 2, logger 3, and logger 5 respectively. From figure 5.12 and 5.13, it was evident to observe that the dry air dew point temperature was lower than the moist air and the air inside the corn mass, which means the drying system work ideal for move the moisture out of the system.

For relative humidity result, compare the relative humidity value before and after drying the corn. A significant 20 to 30 percentage point relative humidity drop can be observed (Figure 5.11), which illustrates the drying system could effectively change the relative humidity. The figure 3 shows the relative humidity change happened inside the corn.

For relative humidity result, approximate 40 percentage point relative humidity drop can be observed between the relative humidity value before and after drying the corn (Figure 5.8 Figure 5.9). This illustrates that the drying apparent can effectively change the relative humidity and compare this value with trail 1, which was 20 to 30 percentage point relative humidity drop, the drying system was more efficient on trial 2. For the air relative humidity inside the corn, a significant decrease can be observed after the drying process started 1440 minutes while in trail 1 the air relative humidity inside the corn dropped at 1800 minutes after the drying process started. This time, the difference also shows that the drying system was more efficient on trial 2.

Corn seed germination test

Table 5.4 shows the germination test results. For the initial corn, the average germinated corn was 44.3, and the germination rate was 0.88, while for the dried corn the average germinated corn was 45 and the germination rate was 0.9. The statistical analysis showed that for germinated corn and germination rate there was no significant difference between initial corn and dried corn at $\alpha=0.05$. The results indicated this low temperature grain drying system has no negative effect on corn seed germination performance.

Conclusions

The present study shows that the closed cycle low temperature drying system is more efficient than most of the drying system that used for the on-farm operation. The heat pump system could remove water effectively by reducing the air dew point temperature. Air temperature and corn initial moisture content could have an effect on overall drying efficiency. Compare to other low temperature drying system; the present system will significantly save the overall drying time. The present drying system had no negative effect on seed germination performance.

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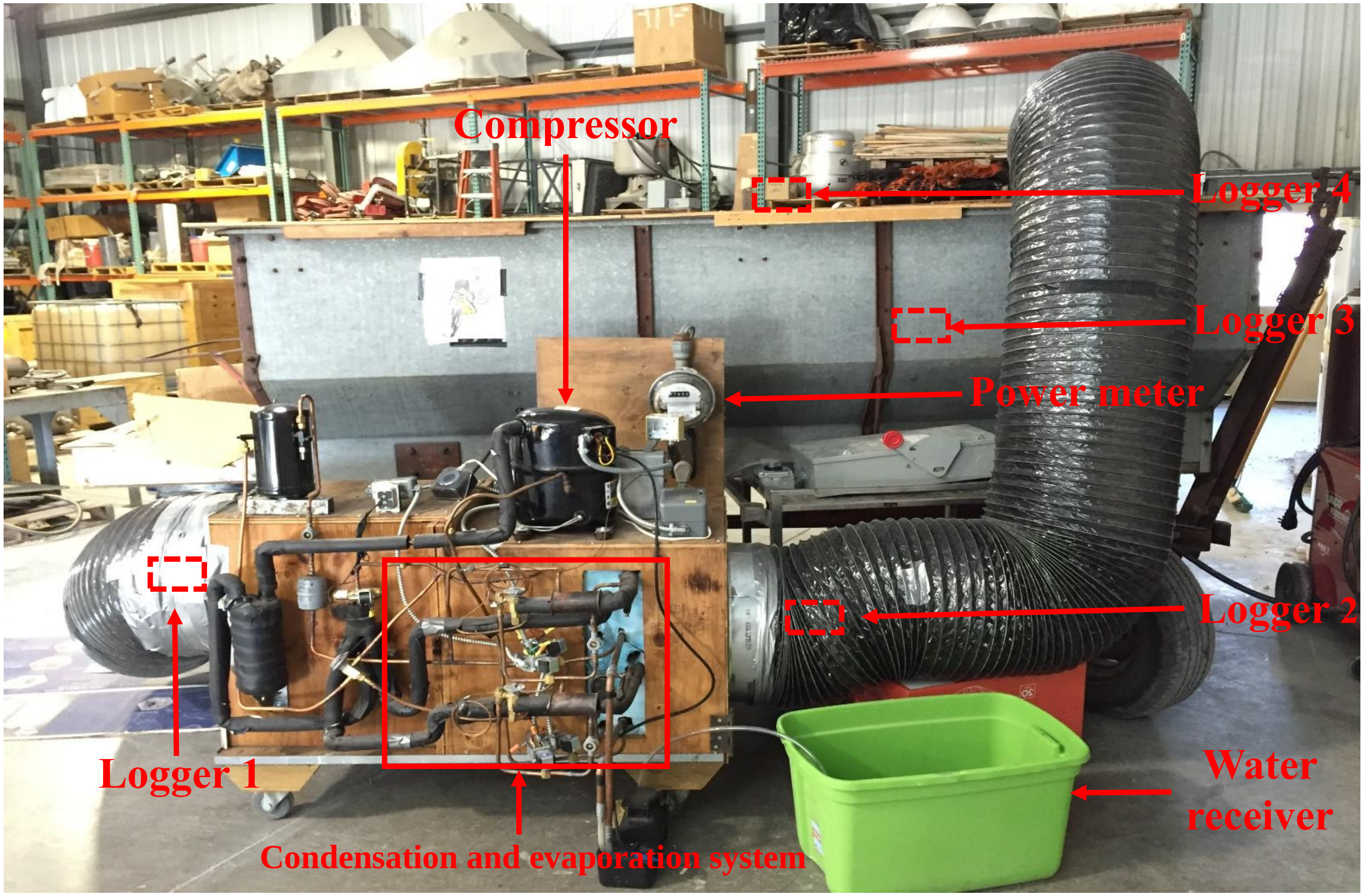

Figure 5.1 Low temperature closed-cycle (Loebach) Drying system and logger positions

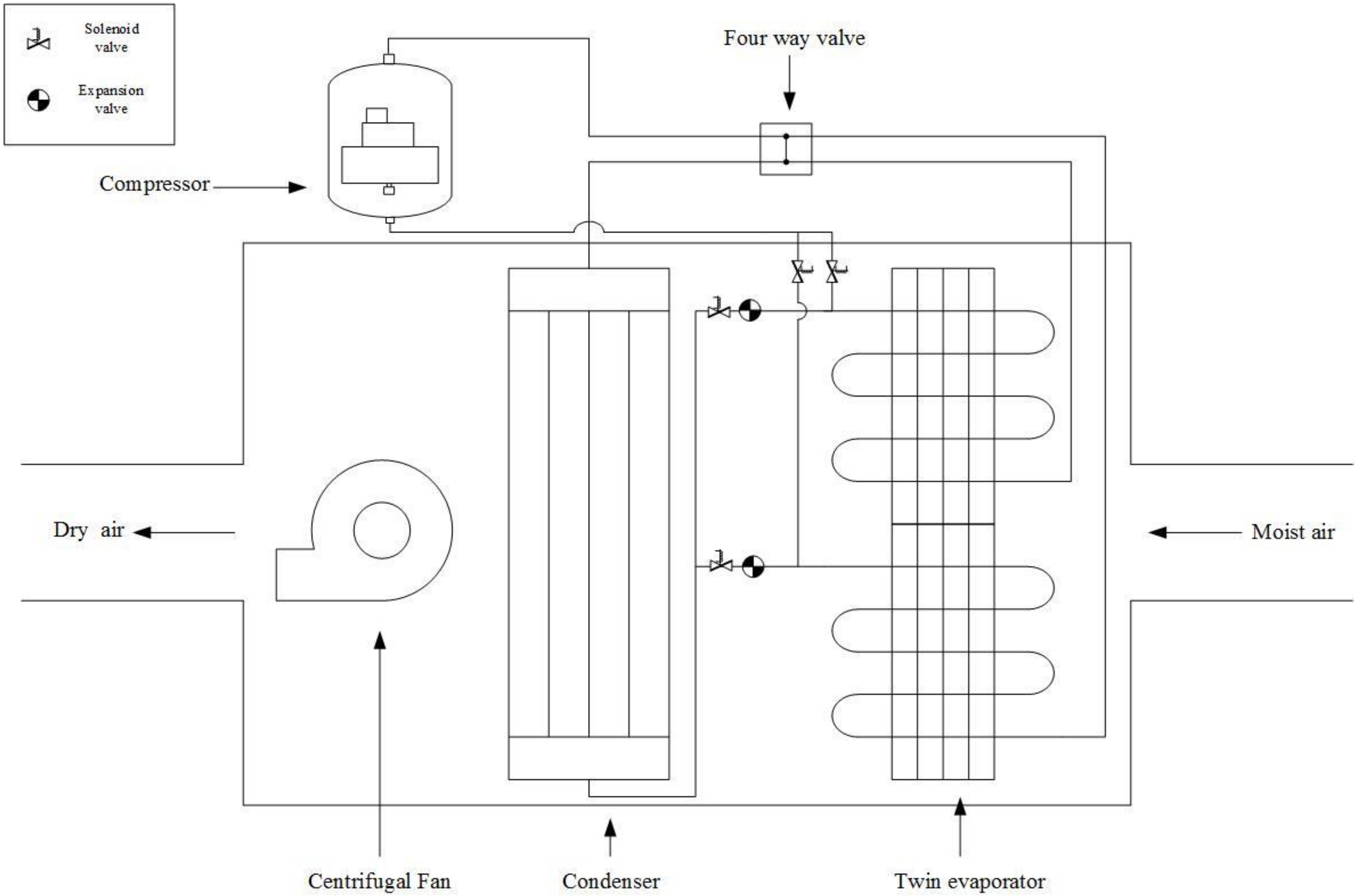

Figure 5.2 The drying system flow diagram

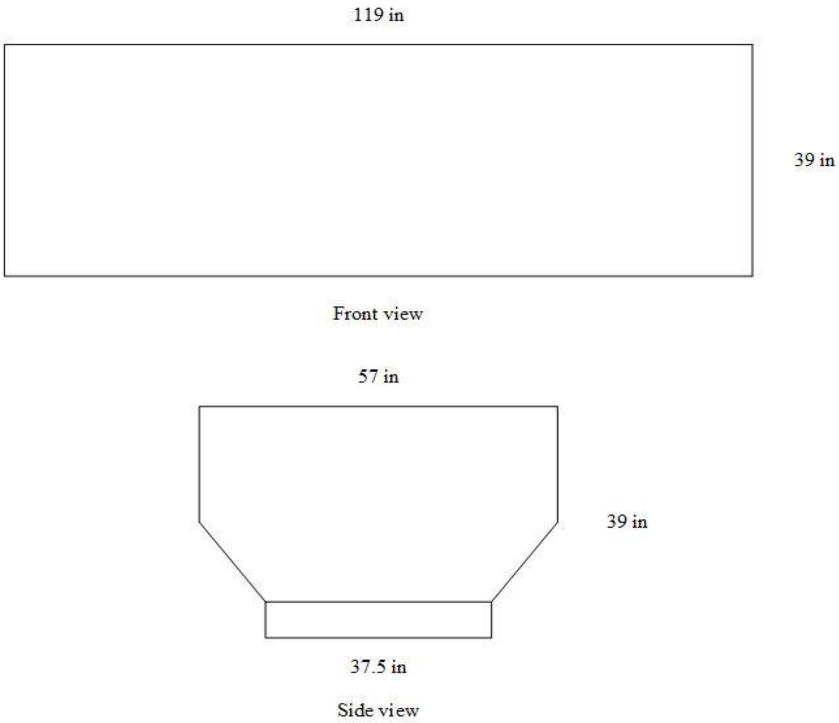

Figure 5.3 The dimension of the corn wagon

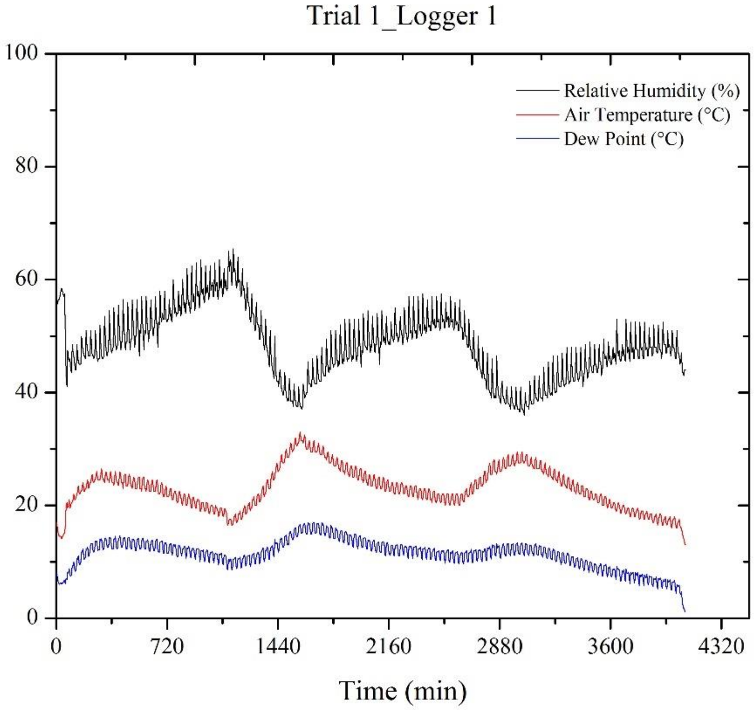

Figure 5.4 Temperature and relative humidity recorded of the air before drying the corn

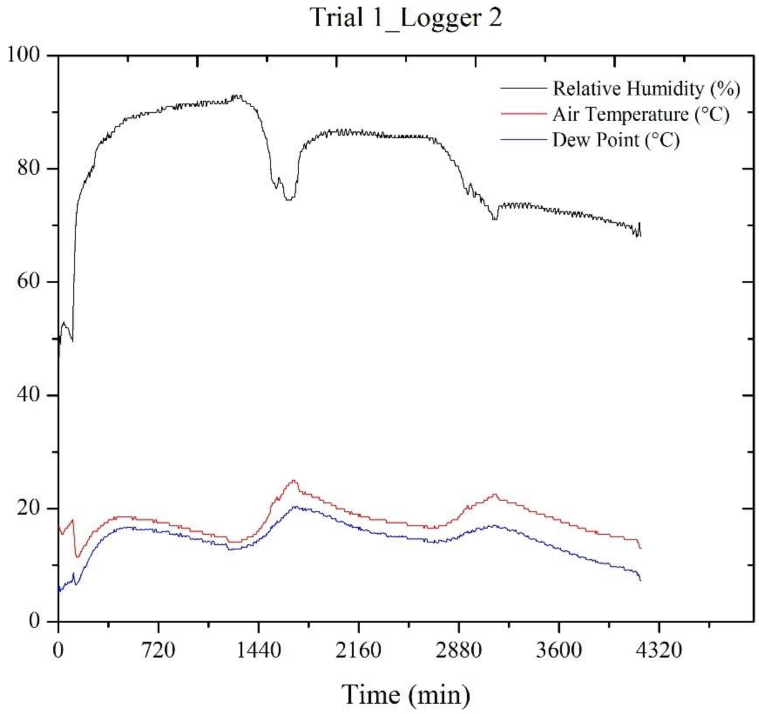

Figure 5.5 Temperature and relative humidity recorded of the air after drying the corn

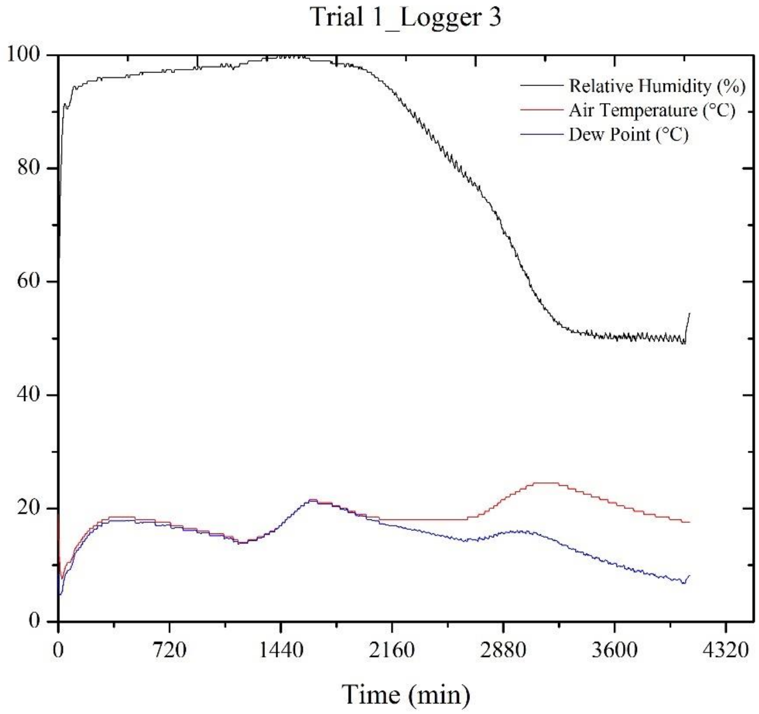

Figure 5.6 Temperature and relative humidity recorded of the air inside the corn mass

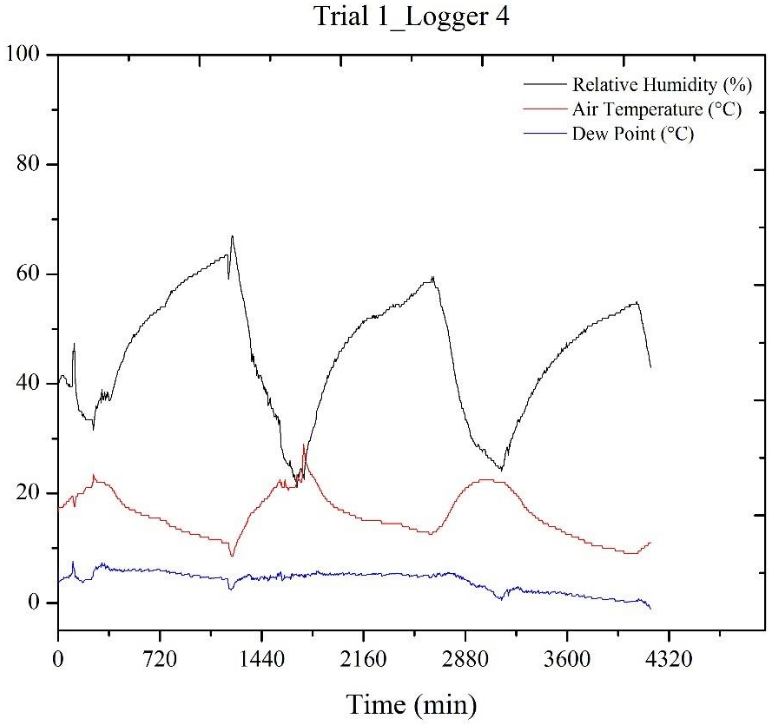

Figure 5.7 Temperature and relative humidity recorded of the ambient air

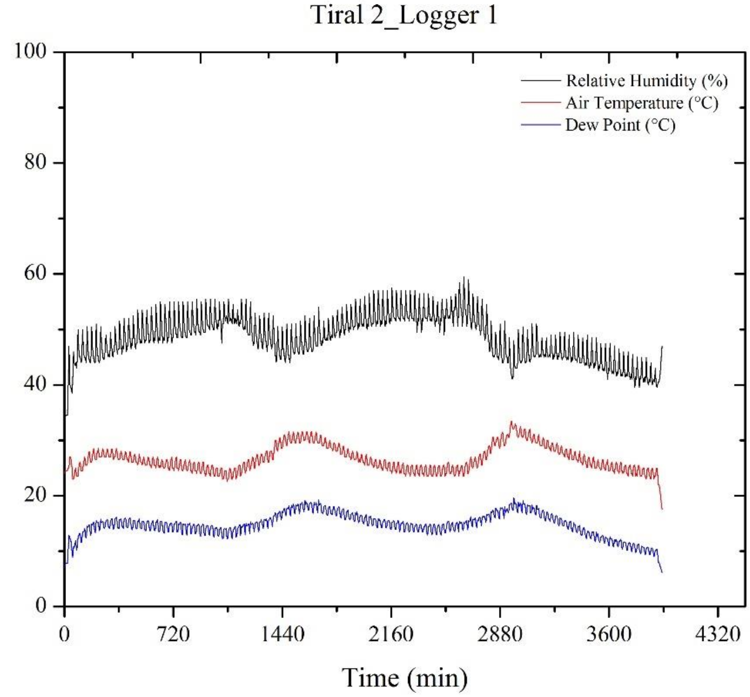

Figure 5.8 Temperature and relative humidity recorded of the air before drying the corn

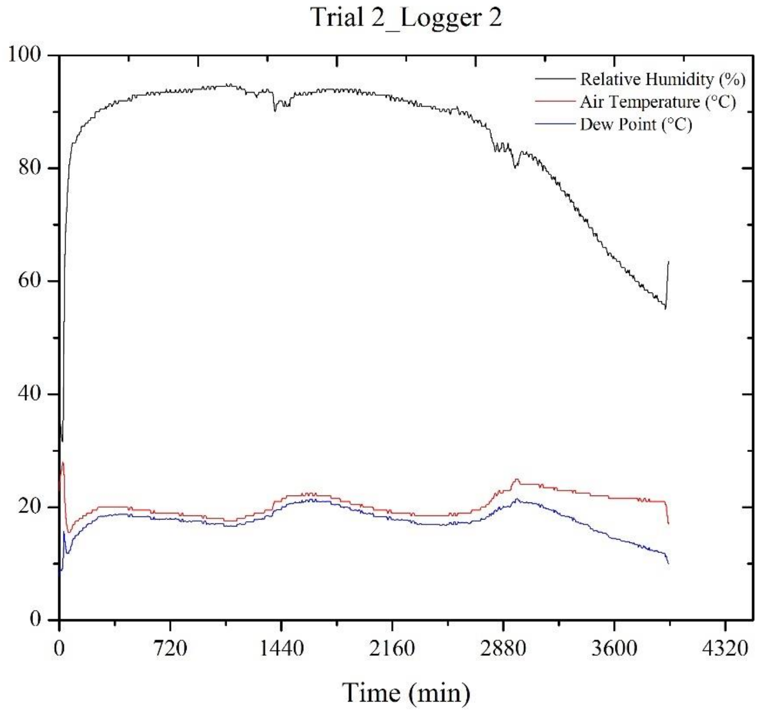

Figure 5.9 Temperature and relative humidity recorded of the air after drying the corn

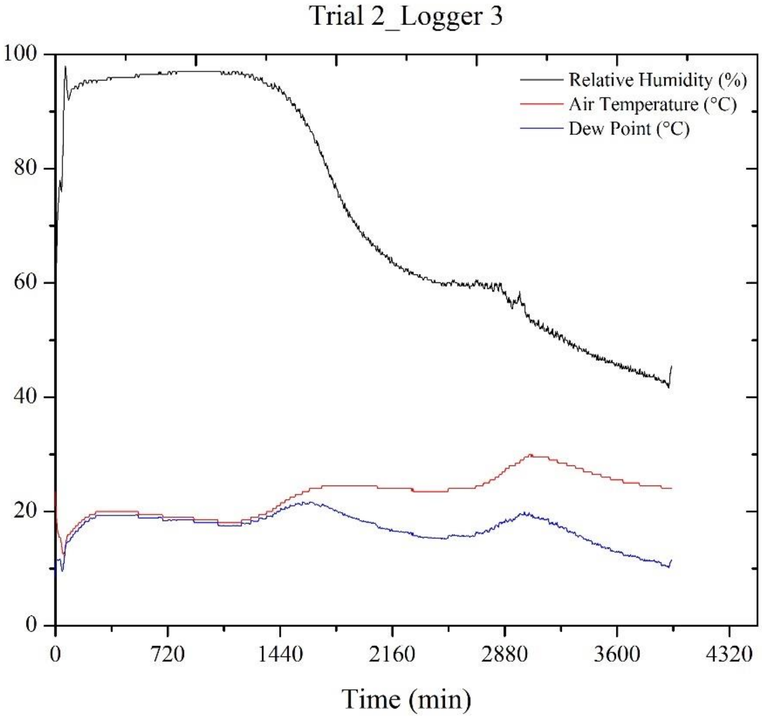

Figure 5.10Temperature and relative humidity recorded of the air inside the corn mass

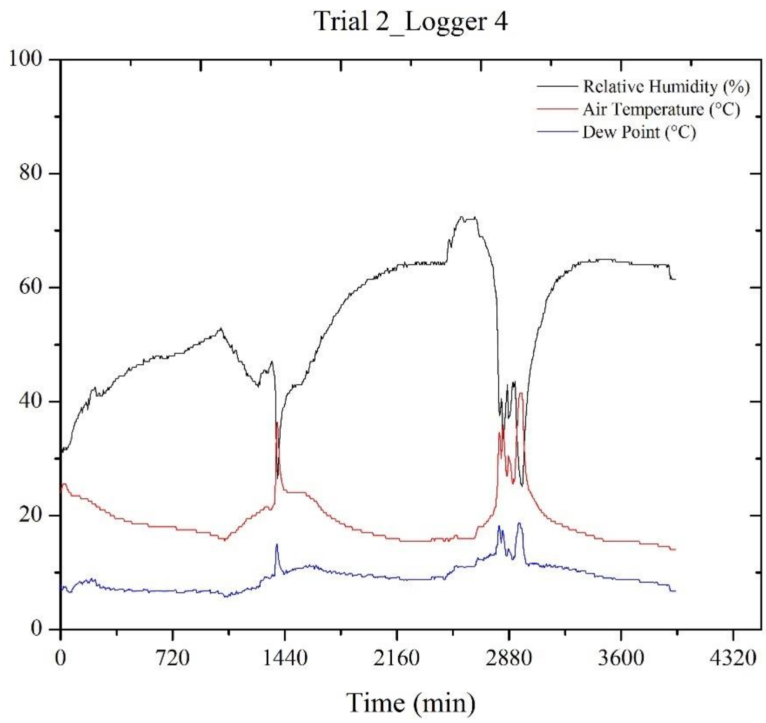

Figure 5.11 Temperature and relative humidity recorded of the ambient air

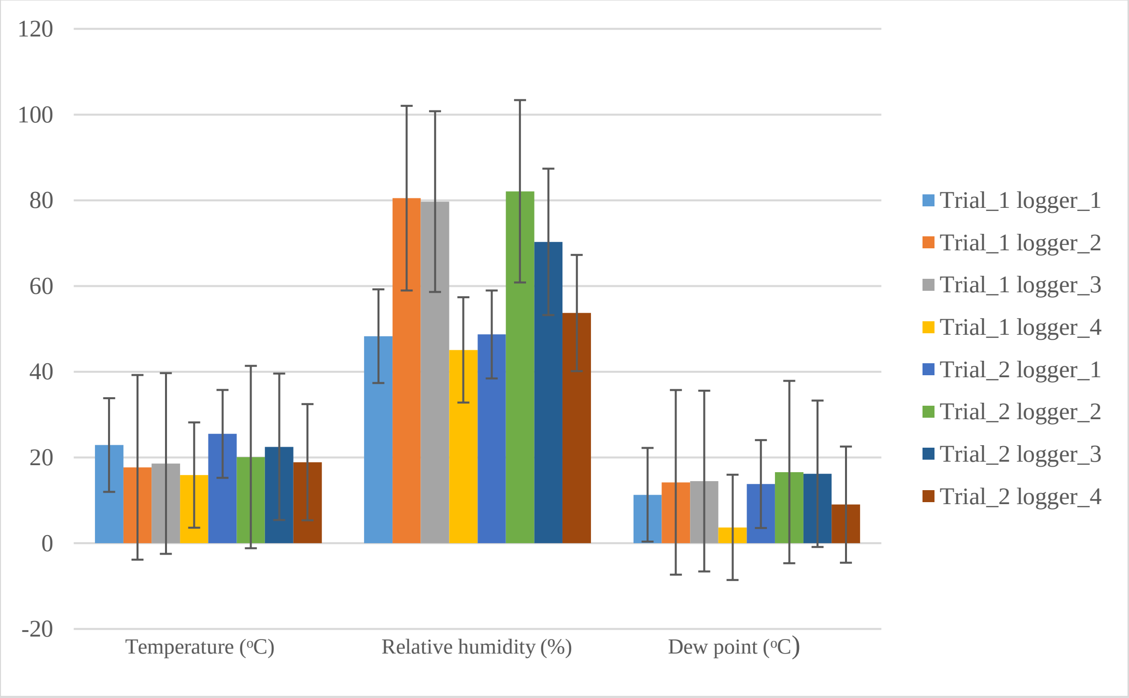

Figure 5.12 Air temperature and relative humidity for trial_1 and trial_2
(Error bars indicates the standard deviation)

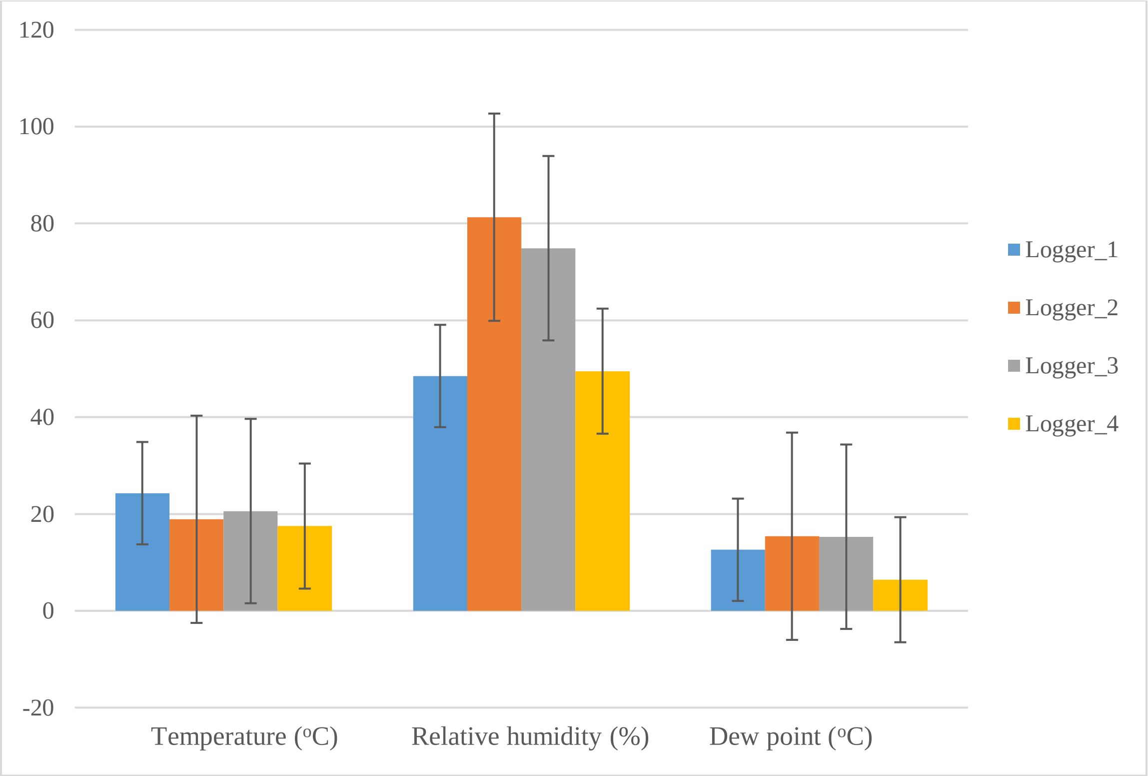

Figure 5.13 Average air temperature and relative humidity with various loggers
(Error bars indicates the standard deviation)

Table 5.1. Drying data

Grain drying data	Trial 1	Trial 2	Mean	St Dev
Drying time (h)	68	66.5	67.25	0.75
Initial corn moisture content (%)	28.1	28.3	28.2	0.1
Initial corn weight (lb)	3460	4000	3730	270
Moisture content after drying (%)	14.3	12.9	13.6	0.7
Corn weight after drying(lb)	2880	3200	3040	160
Water removal (lb)	560	707	633.5	73.5
Power consumption (kWh)	170	180	175	5
Drying efficiency (Btu/lb water removed)	1036	869	952.5	83.5
Drying efficiency (kWh/lb water removed)	0.30	0.25	0.275	0.025

Table 5.2. Air temperature and relative humidity data with various trials and loggers*

Air properties	Logger1	Logger2	Logger3	Logger4
Trial 1				
Temperature (°C)	22.9(3.7) a	17.7(2.7) b	18.6(2.8) c	15.9(4.1) d
Relative humidity (%)	48.3(6.1) a	80.5(9.5) b	79.7(20.5) b	45.1(10.9) c
Dew point (°C)	11.3(2.6) a	14.2(3.3) b	14.5(3.9) b	3.7(2.1) c
Trial 2				
Temperature (°C)	25.5(3.8) a	20.1(2.3) b	22.5(3.66) c	18.9(4.2) d
Relative humidity (%)	48.7(4.4) a	82.1(14.6) b	70.3(20.4) c	53.7(10.3) d
Dew point (°C)	13.8(3.2) a	16.6(3.6) b	16.2(3.7) c	9.0(2.2) d

* Different letters after means in each level of the air properties indicates significant difference at $\alpha=0.05$
the standard deviation is reported in value with parentheses

Table 5.3. Average air temperature and relative humidity data for each logger*

Air properties	Logger1	Logger2	Logger3	Logger4
Temperature (^oC)	24.3(3.9)	18.9(2.7)	20.6(3.8)	17.5(4.4)
Relative humidity (%)	48.5(5.2)	81.3(12.4)	74.9(20.9)	49.5(11.5)
Dew point (^oC)	12.6(3.2)	15.4(3.7)	15.3(3.9)	6.42(3.4)

The standard deviation is reported in value with parentheses

Table 5.4. Germination test results*

Germination test	Replication	Corn Seed number	germinated corn	germination rate
Initial Corn	1	50	43	0.86
	2	50	44	0.88
	3	50	46	0.92
	Mean	50	44.3a	0.88a
	St Dev	0	1.5	0.03
Dried Corn	1	50	45	0.9
	2	50	44	0.88
	3	50	46	0.924
	Mean	50	45a	0.9a
	St Dev	0	1	0.02

*Similar letters after means in each level of the germination rate indicates insignificant difference at α=0.05

CHAPTER 6 TECHNO-ECONOMIC ANALYSIS (TEA) AND LIFE CYCLE ASSESSMENT (LCA) OF LOW TEMPERATURE CLOSED-CYCLE GRAIN DRYING SYSTEM

Abstract

This study was about to understand the environmental and economic impact of the low temperature closed-cycle grain drying system that mentioned in the previous chapter by using techno-economic analysis (TEA) and life cycle assessment (LCA). For TEA, three scales including small (60 bu/batch), medium (600 bu/batch) and large (6000 bu/batch) were chosen for analysis the total annual drying cost and unit drying cost. For LCA, the greenhouse gasses emission was the only environmental impact that considered in this study, since the electricity was the only energy source for this drying system. The TEA result shows that the drying cost for one bushel of corn were $0.62, $0.49, $0.46 for the small, medium and large scale of the drying system respectively and the drying cost could be lower than a grain elevator. The LCA result indicates that the greenhouse gas emission will increase along with the expansion of the drying system and since the electricity comes from a local coal plant, the drying system greenhouse gas emission was higher than other drying systems. Farmers can use this method to make their decision when handling the grain.

Introduction

LCA (Life Cycle Assessment) is a procedure to assess environmental influence associated with a a product’s life from the cradle to the grave. In 1970 the Midwest Research Institute first invented this tecnology (Hunt and Franklin, 1996), and the LCA procedure mostly used today of was defined by ISO, including goal and scope definition, inventory analysis, impact assessment and interpretation. There is very limit work done in the analysis the LCA of grain drying system and grain drying process.

TEA (Techno-Economic Analysis) can be defined as a systematic analysis used to assess the economic feasibility aimed to recognize opportunities and threats of projects, considering the capital, operational (variable), and fixed costs (Simba et al., 2012), benefits as well. Annual operating expenses and fixed costs are critical parameters in TEA and are the basic parameters for cost estimation, process optimization, and project evaluation (Marouli and Maroulis, 2005). In this study, the TEA was conducted using an MS-Excel spreadsheet to determine the cost of drying system.

The aim of this study was to analyze the environmental and economic impact for the low temperature closed-cycle grain drying system. This study could help farmers to make a decision when choosing a new on-farm grain dryer in terms of drying cost and environmental impact.

Materials and Methods

The TEA and LCA were based on the prototype on-farm low temperature closed-cycle grain drying system that was provided by Loebach Brothers. The concept for this drying system was the heat pump working as a dehumidifier. Figure 6.1 shows the flow chart of this drying system, the condensation and evaporation system will remove the moisture from the air that comes out of the corn container and the fan will force the dry air into the container to drying the corn.

The system boundary is shown in Figures 6.2. The drying system was a closed cycle system; electricity was the only energy source that goes into the drying system, the system boundary for this system only includes the whole drying process. The environmental impact came from the production of the electricity from the local coal plant. The functional unit for this TEA and LCA study was based on 1 bushel of corn (56 lb of corn at 15.5% moisture content) dried through the drying process. This study analyzed annual total impacts and impacts for one bushel of corn.

All the TEA and LCA of the drying system were based on three scales, which included small (60bu/batch), medium (600bu/batch), large (6000bu/batch). The system baseline 60 bu/batch was based on the prototype drying apparatus built by Loebach Brothers. The baseline system cost and drying system component list were provided by Loebach Brother's, and the energy consumption of the baseline system was measured and reported in the previous chapter. The main assumptions of this study are listed:

(1). The corn initial moisture content was assumed as 28%, and the corn was dried to 15% moisture content.

(2). The drying system was operated two months per year since the harvesting dates for corn in Iowa is from September to November (USDA, 2011).

(3). The drying operation time for each scale was assumed based on a suggestion from Shove (1970), which was for 1 ton (12000 Btu/h) of refrigeration which could dry 20-bushel corn per day. For baseline system, the capacity of the compressor is 6690 Btu/h which is 0.56 ton.

(4). The 60 bu/batch drying time was measured as 2.7 days while for 600 bu/batch and 6000 bu/batch the drying time was assumed as 6 days and 15 days.

(5). The energy consumption for drying was assumed based on our measurement and Shove’s (1970) suggestion, which was 3 kWh/bu of corn. The base system energy consumption was measured as 2.83 kWh/bu of corn.

For LCA the environmental impact considered in this study contained energy consumption and greenhouse gas emission. The air emission categories considered were carbon dioxide, methane, and $NO_{x.}$ Table 6.1 shows the greenhouse gas emission converting factor for coal energy plant. The global warming potential has also been calculated and reported. Table 6.2 is the global warming potential factor which used to calculated the global warming poterntial for the drying system.

For TEA, the cost of each drying system component was obtained from online sources like Alibaba and PEX supply house. The cost for drying one bushel of corn was calculated by dividing energy cost, labor cost and annual drying system cost by the bushel of corn.

The assumption for TEA are listed:

- The corn storage bin for 600 bushels of corn was 14 feet in diameter with a height of 11 feet.
- The corn storage bin for 6000 bushels of corn was 24 feet in diameter with a height of 18 feet.
- Fan size for 600 bushels was 5hp while for 6000 bushels was 20hp (Sadaka, 2014).
- The life span of the drying system was assumed as 25 years.
- The insurance rate was 0.5% per year and the interests rate was 7% per year (Hellevang and Reff, 1987).
- The maintenance and repair rate was 3% of total capital cost per year (Hellevang and Reff, 1987).

- Labor cost for handling the corn is 0.061$ per bushel of corn (Plastina and Johanns, 2016).
- At the end of service life, the savage value was assumed as 0.
- The electricity rate was 10.5 cent per kWh (EIA, 2016).

Results and Discussion

Life cycle assessment (LCA)

Based on the assumptions for unit drying energy consumption the total annual electricity usage for 60 bushels, 600 bushels, and 6000 bushels was calculated and reported in Table 6.3 as 3735.6 kWh/y, 18000 kWh/y and 72000 kWh/y respectively. The total annual electricity usage value was fit both the linear increase regression and power increase regression model very well; the R-square value was 0.9891 and 0.999 respectively, which was very close to 1 (Figure 6.3). The reason was that the unit power consumption was assumed at 3kWh for medium and large scale and for small scale the power consumption was 2.83kWh, the total power consumption was mostly determined by the amount of the corn. Table 6.3 also shows CO_2 emission, CH_4 emission, and NO_x emission data. For CO_2 emission, the total annual air emission data were 3735.6 kg per year, 18396 kg per year, and 73584 kg per year for small, medium, and large scale respectively. For CH_4 emission, the average 3.39 kg per year, 16.38 kg per year, and 65.52 kg per year for 60 bu/batch, 600 bu/batch, and 6000 bu/batch respectively. The NOx emission was calculated as 12.51 kg per year, 30.3 kg per year, and 241.2 kg per year for small, medium, and large scale respectively. Figure 6.4 shows the annual total CO_2 emission with various drying system capacity. The CO_2 emission value fit both the linear model well and the R-square value was 0.9864 which was very close to the R-square value for total annual electricity usage.

The reason was that the emission data was calculated by multiply the air emission covert factor with the annual electricity usage data. From the Figure 6.5 and Figure 6.6, it was easy to observe both CH_4 and NO_x emission was increased along with the system scale increased. All the emission data fit both linear model and power model very well, with the R-square value 0.9864 and 0.9987 respectively for both CH_4 and NO_x emission. The results were similar to CO_2 emission results, and the reason was the CH_4 and NO_x emission data was also calculated by energy usage during drying process times the air emission factors.

The global warming potential was calculated as 7229.25kg CO_2 eq., 34834.14kg CO_2 eq. and 139336.56kg CO_2 eq. for small, medium and large scale respectively. Figure 6.7 shows the trend for global warming potential, and the global warming potential was increased as the drying system capacity increased. The global warming potential value fit both the linear and power model well with the R-square value 0.9864 and 0.9987. This result was also similar with annual total electricity usage results since the global warming potential results were highly related with the system electricity usage.

Bern (1998) raised a report about energy usage and CO_2 emission for preserving the corn in Iowa. In this report, several different drying systems and methods including off-farm dry, farm net air dry, farm HTDC dry and farm comb dry were mentioned and discussed. The CO_2 emission data was calculated based on preserving 38.8×10^6 Mg Iowa corn. Compare the CO_2 emission data with the present LCA data which were converted as 113.86 kg/Mg corn, 119.14 kg/Mg corn, and 120.7 kg/Mg corn for 60 bushels, 600 bushels, and 6000 bushels respectively. The present drying system CO_2 emission was only lower than farm net air dry method which was 262 kg/Mg corn. The present drying system was release 41.5% to 70% more CO_2 than other on farm or off farm drying method. Because the electricity was the only energy sources, the energy sources that produced the electricity was crucial for greenhouse gas emission. The electricity used in this study was produced from the coal power plant which leads to higher CO_2 emission level. If the electricity came from a cleaner power plant like wind power or hydro power, the greenhouse gas emission could be much lower than the present study.

Techno-Economic Analysis (TEA)

The general TEA results were reported in Table 6.4, 6.5, 6.6, 6.7, 6.8 and 6.9. The annual economic impact for each operation capacity of this drying system was considered including capital cost and operating cost. The annual cost was $886.06 per year, $2913.25 per year and $10992.53 per year for small (60 bu/batch), medium (600 bu/batch), large (6000 bu/batch) respectively, and it was increased while the drying capacity increased. Figure 6.8 shows the annual drying cost results; it is evident to see that the annual drying cost could fit both linear and power model very well. The increase linear regression model has R-square value 0.9883 while the power model has R-square value 0.999. The annual total drying cost has the similar trend with annual electricity usage results, and the R-square value for both results were also approximately the same, this was because the majority drying cost every year came from the energy cost for the drying system.

The drying cost for drying one bushel of corn was calculated by divided the annual drying cost by whole corn dried per year. The drying cost was reported as 0.62 USD per bushel, 0.49 USD per bushel, 0.46 USD per bushel for year for small (60 bushels/batch), medium (600 bushels/batch), large (6000 bushels/batch) respectively. From Figure 6.9, it was clear to observe that the drying cost for drying one bushel of corn decreases while the drying capacity increases. The relationship among the three scales fit the power decrease well with the R-square value equal to 0.8913 while for linear regression the R-square value was only 0.485. The reason caused the R-square value difference was because the energy cost for one bushel of corn was similar for each scale due to the energy consumption for one bushel of corn was assumed as 3 kWh, and the capital cost per bushel of corn dried was very close to medium and large scale.

To compare the drying cost for the present drying system with other drying systems, the beginning moisture of grain was set as 28%, the ending moisture of grain was 15%. The grain elevator drying cost was 0.0425 USD per point per bushel (West Central, 2016). If the corn was dried from 28% moisture content to 13% moisture content the drying cost for one bushel of corn was computed as 0.553 USD per bushel, which was lower than small scale drying cost and much higher than medium and large scale drying system. The result indicates that the three scale of present drying system could save money compare to other drying systems under similar drying conditions.

Conclusions

Based on the TEA and LCA results, both total annual environmental impacts and the total annual cost was increased while the system scale expanded. The LCA results showed that this drying system would release more CO_2 than most of others off farm and on farm drying methods since the electricity came from the local coal plant. The greenhouse gas emission could be improved by using cleaner electricity like wind power electricity or hydropower electricity. The unit cost of drying corn was decreased as the operation system scale expanded. The result indicated that the large scale system had lower operation cost and compared with other on farm drying methods the medium scale and the large scale low temperature closed cycle drying system was cheaper. This gives the farmer an idea when they are trying to apply a new drying system on their farm.

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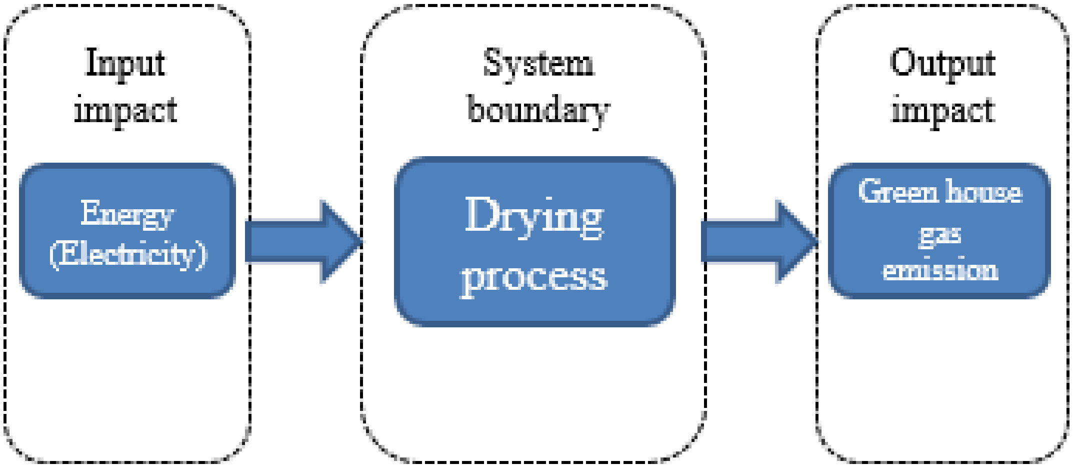

Figure 6.1 The system boundary of drying system

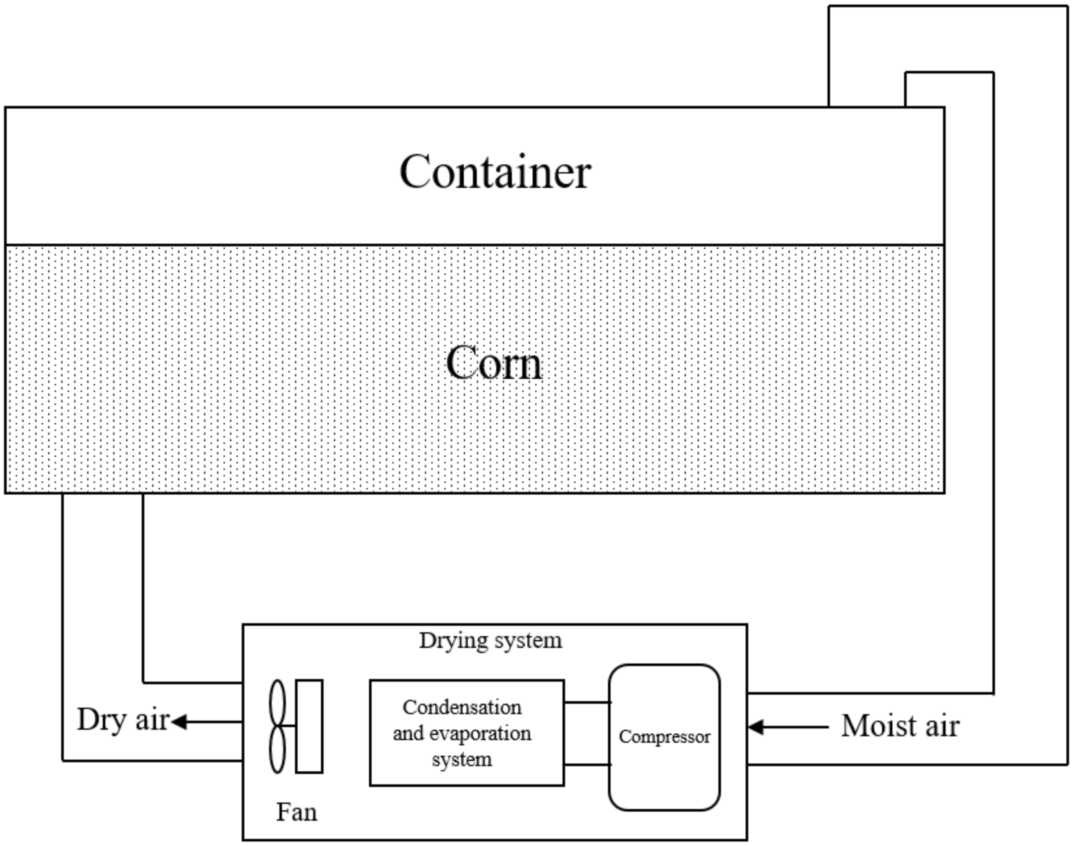

Figure 6.2 The Flow chart for drying system

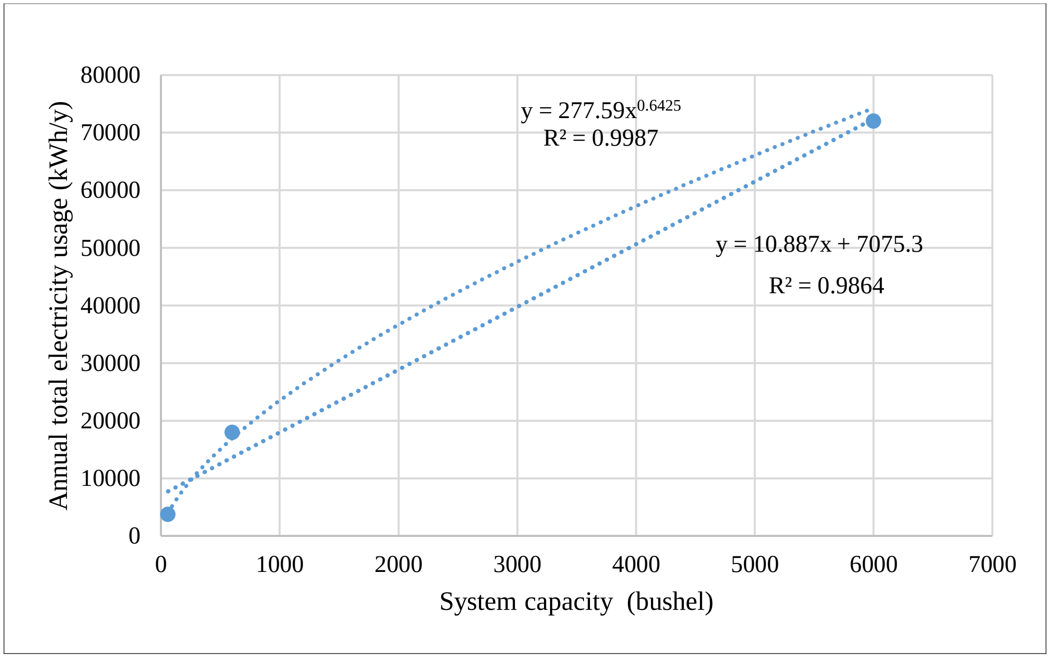

Figure 6.3 Annual drying electricity usage with various drying capacity

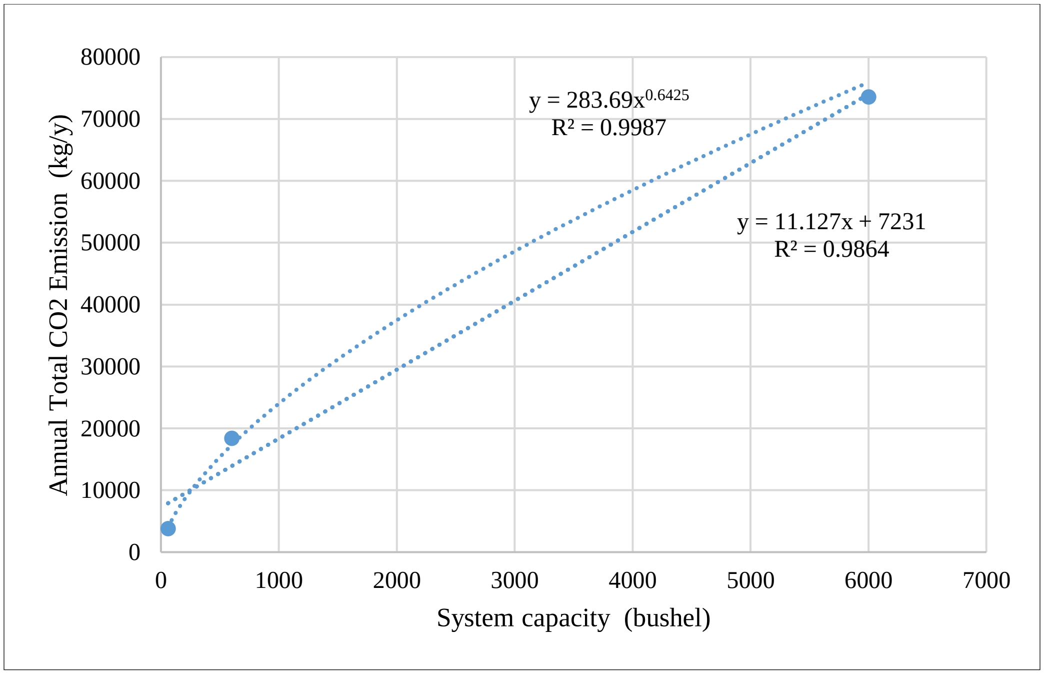

Figure 6.4 Annual total CO_2 emission with various drying capacity

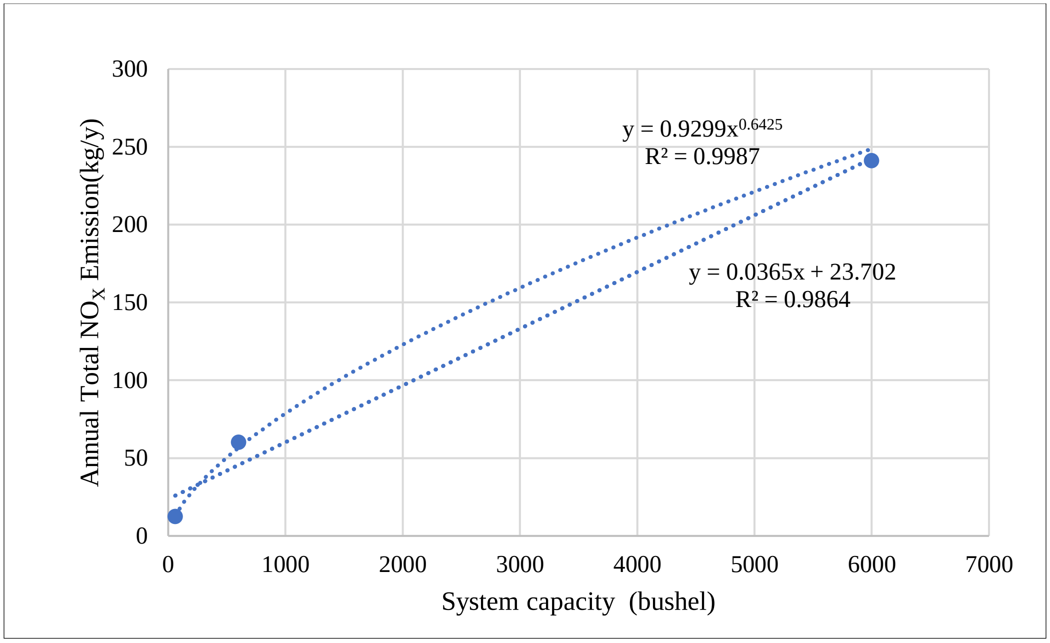

Figure 6.5 Annual total NO_X emission with various drying capacity

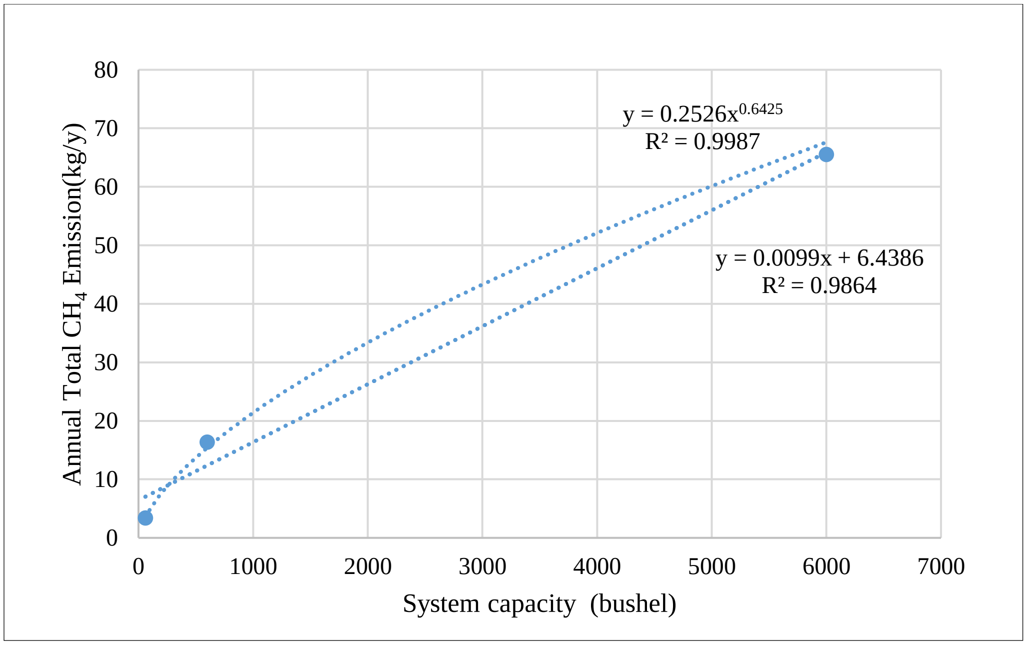

Figure 6.6 Annual total CH_4 emission with various drying capacity

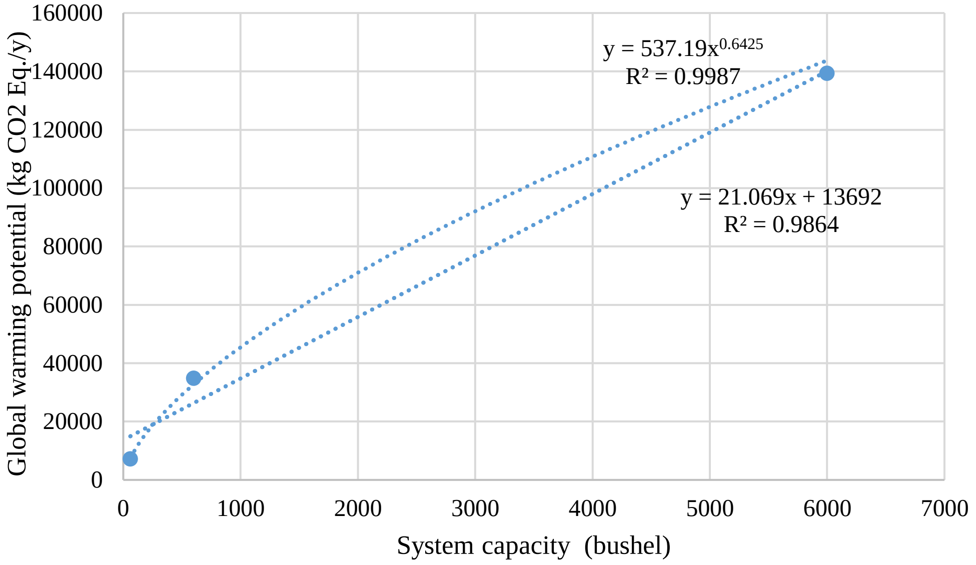

Figure 6.7 Annual total global warming potential with various drying capacity

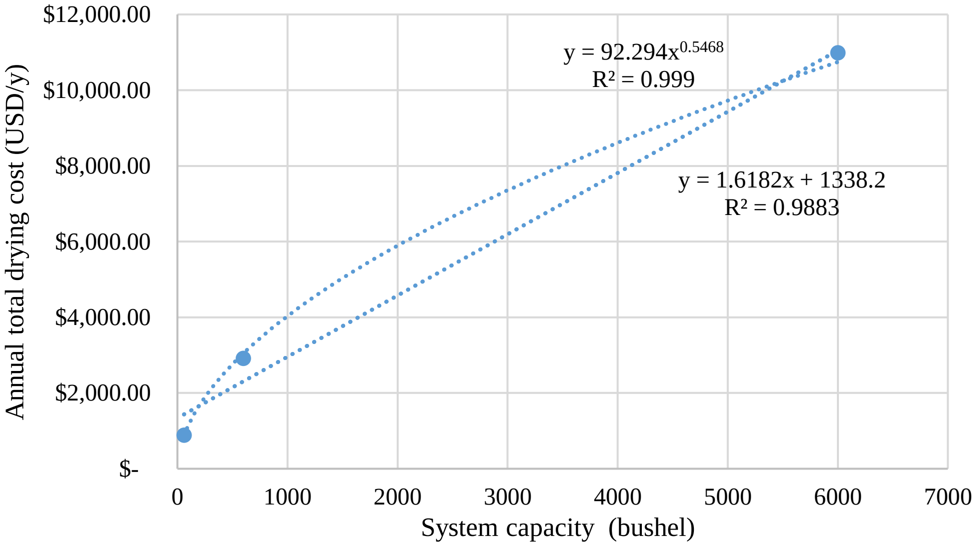

Figure 6.8 Annual total drying cost with various drying capacity

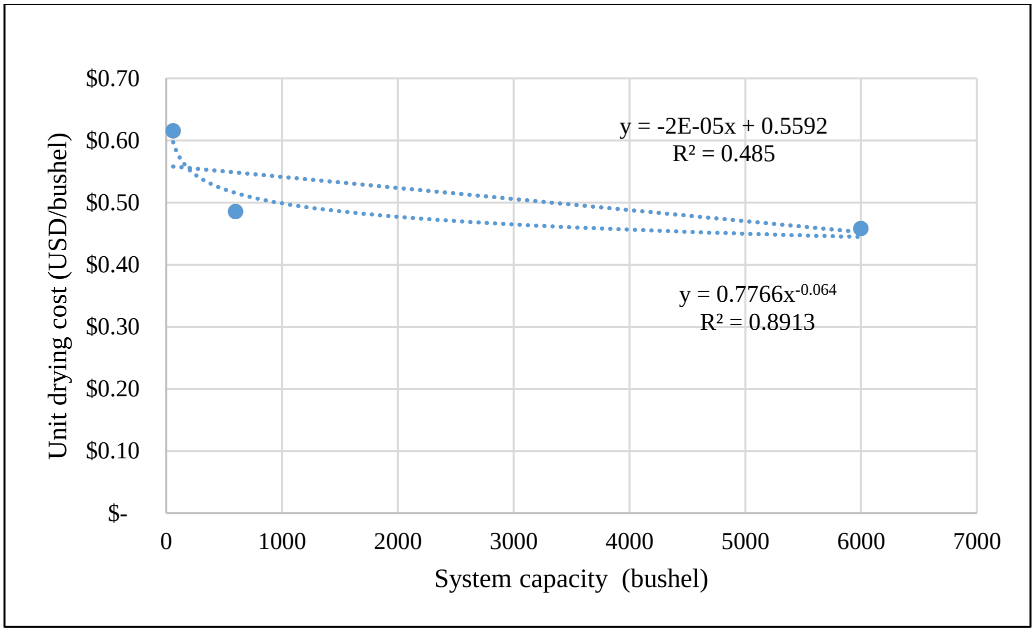

Figure 6.9 Unit drying cost with various drying capacity

Table 6.1. Air emission of producing electricity from coal.

Emission category	**g/kWh**
CO_2	1022
CH_4	0.91
NO_x	3.35

Spath, P. L., Mann, M. K., and Kerr, D. R.. (1999).

Table 6.2 Converting factor for global warming potential

GWP converting factor (100 years)	**mass CO_2 eq.**
CO_2	1
CH_4	28
NO_x	256

IPCC 2013 – AR5 (Stocker et al., 2013)

Table 6.3 LCA for Drying system

Capacity	**60 bushel**	**600 bushel**	**6000 bushel**
Environmental impact	**Total annual impact (per year)**	**Total annual impact (per year)**	**Total annual impact (per year)**
Electricity usage (kWh)	3735.6	18000	72000
CO_2 emission (kg CO2)	3817.78	18396	73584
CH_4 emission (kg CH4)	3.39	16.38	65.52
NO_x emission (kg NOx)	12.51	60.3	241.2
Global warming potential (kg CO_2 eq.)	7229.25	34834.14	139336.56

Table 6.4 60 bushels drying system capital cost

Component	**Price ($/each)**	**Quantity**	**Total Cost ($)**
Compressor	890.00	1	890.00
Evaporators	170.00	2	340.00
Accumulator	40.00	1	40.00
Receiver	87.00	1	87.00
Expansion valves	65.00	2	130.00
Solenoid valves	71.00	4	284.00
Timer	40.00	1	40.00
Head pressure control	100.00	1	100.00
Headmaster valve	140.00	1	140.00
Blower	160.00	1	160.00
Equipment initial Costs			2,211.00
Electrical wiring and controls			88.44
Equipment installation			884.40
Equipment freight			22.11
Total equipment initial costs			3,205.95
Engineering and design			224.42
Total capital costs			3,430.37
Capital costs per year			294.36

Table 6.5 60 bushels drying system operating cost

Fixed costs	
Insurance	16.03
Subtotal	16.03
Variable costs	
Labor cost	80.52
Electricity	392.24
Maintenance and repair	102.91
Subtotal	575.67
Total costs	886.06
Drying cost per bushel	0.62

Table 6.6 600 bushels drying system capital cost

Component	**Price ($/each)**	**Quantity**	**Total Cost ($)**
Compressor	1,000.00	1	1,000.00
Evaporators	499.00	2	998.00
Accumulator	121.00	1	121.00
Receiver	123.00	1	123.00
Expansion valves	77.00	2	154.00
Solenoid valves	120.00	4	480.00
Timer	40.00	1	40.00
Head pressure control	100.00	1	100.00
Headmaster valve	140.00	1	140.00
Blower	360.00	1	360.00
Equipment initial Costs			3,516.00
Electrical wiring and controls			140.64
Equipment installation			1,902.40
Equipment freight			47.56
Total equipment initial costs			6,896.20
Engineering and design			482.73
Total capital costs			7,378.93
Capital costs per year			633.19

Table 6.7 600 bushels drying system operating cost

Fixed costs	
Insurance	25.49
Subtotal	25.49
Variable costs	
Labor cost	366.00
Electricity	1,890.00
Maintenance and repair	163.65
Subtotal	2,419.65
Total costs	2,913.25
Drying cost per bushel	0.49

Table 6.8 6000 bushels drying system capital cost

Component	**Price ($/each)**	**Quantity**	**Total Cost ($)**
Compressor	5,200.00	1	5,200.00
Evaporators	1,000.00	2	1,000.00
Accumulator	123.00	1	123.00
Receiver	151.00	1	151.00
Expansion valves	97.00	2	97.00
Solenoid valves	234.00	4	234.00
Timer	40.00	1	40.00
Head pressure control	100.00	1	100.00
Headmaster valve	140.00	1	140.00
Blower	10,000.00	1	2,600.00
Equipment Initial Costs			11,484.00
Electrical wiring and controls			755.36
Equipment installation			7,553.60
Equipment freight			188.84
Total equipment initial costs			27,381.80
Engineering and design			1,916.73
Total capital costs			29,298.53
Capital costs per year			2514.12

Table 6.9 6000 bushels drying system operating cost

Fixed costs	
Insurance	83.26
Subtotal	83.26
Variable costs	
Labor cost	1,464.00
Electricity	7,560.00
Maintenance and repair	356.35
Subtotal	9,380.35
Total costs	10,992.53
Drying cost per bushel	0.46

CHAPTER 7 SUMMARY AND CONCLUSIONS

The major work presented in this thesis include four parts: Resultant pellets quality of corn-based DDGS, Physical quality of pilot scale pelleting result, Assessment of low temperature closed-cycle grain drying system, Techno-economic analysis (TEA) and Life cycle assessment (LCA) of low temperature closed-cycle grain drying system.

After pelleting process, the results showed that the moisture content of DDGS and the die size or die L/D value had a significant effect on pellets physical qualities. The higher moisture content which was 20% moisture content will result in higher pellets durability. In this study, the two dies have same L/D value, but one has larger die diameter. The results showed that the die with larger die diameter would lead to lower pellet durability. By using pilot-scale pellet mill, the bulk density can be increased, the main factor that affects the pellet bulk density was the DDGS moisture content and the interaction between die size and moisture content.

The second pelleting project showed the similar results with the first pelleting project. Adding moisture into the DDGS and using the die with larger L/D value can get more durable pellets. This highest pellet durability was occurred when the DDGS moisture content was 20%, and the die L/D value was 8. Compare with the first pelleting project, under the similar pelleting condition the pellet durability was higher due to the different pilot scale pelleting mill used for each pelleting studies. For pelleting temperature, the die with a smaller diameter will result in the higher pellet temperature, while for each die the highest pellet temperature was observed when the DDGS moisture content was 10%. By using pilot-scale pellet mill, the bulk density can be increased, and the bulk density was larger with the larger L/D value.

The results of the prototype low temperature grain drying system assessment showed that the closed cycle low temperature drying system could save 52%-68% energy to remove one pound of water compare with other drying systems like batch in bin system and counter-flow sytle dryer we used for the on-farm operation. Compare to other low temperature drying systems, such as drying use natural air the present system will significantly save the overall drying time. The corn seed germination test result showed that this low temperature drying system had no negative effect on germination performance.

Based on the TEA and LCA results for the low temperature grain drying system, both total annual environmental impacts, and the total annual cost was increased while the system scale expanded. The LCA results show that this drying system will release more CO_2 than most of the others off farm and on farm drying methods since the electricity came from the local coal plant. The greenhouse gas emission could be improved by using cleaner electricity like wind power electricity or hydropower electricity. The unit cost of drying corn was decreased as the operation system expanded. The result indicates that the large-scale system had lower operation cost and compared with other on farm drying methods the medium scale and the large scale low temperature closed cycle drying system was cheaper. This give the farmer an idea when they are trying to apply a new drying system on their farm.

CHAPTER 8 FUTURE WORK

For DDGS pelleting study, the present study only used water to help complete the pelleting process. More work could be done using DDGS binder to help complete the pelleting process, and test the physical quality of the DDGS pellet. Also, to conduct experiments on a larger scale is also important. It will be a different story in commercial scale. More pelleting conditions and pelleting energy consumption could be considered and tested. TEA and LCA could also be done to analysis the whole pelleting process. Thus, it can help ethanol producer and animal feed producer to make a better pelleting decision and increase the DDGS profit.

For low temperature grain drying study, more work could be done to evaluate the drying efficiency when this drying system applies to a larger scale. The drying system could also test in a different location across the Iowa state or U.S. to evaluate the different air condition affect to the drying performance. The TEA and LCA study of this low temperature grain drying system, more work could be conducted to compare the drying cost for different grains instead of corn.