A biomass-fired grain dryer : system design, construction and performance
by Mark Anthony Little

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agricultural Engineering
Montana State University

Abstract:
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A project supported by the Montana Department of Natural Resources and Conservation was undertaken by the Southern Agricultural Research Center (SARC) and the Department of Agricultural Engineering at Montana State University to investigate the feasibility of using agricultural residue from crops raised in Montana to dry perishable grains. The project consisted of construction and testing of a commercially available biomass-fired corn dryer.

A direct-fired incinerator-type biomass furnace was constructed, operated, and performance evaluated to determine overall heat conversion efficiency and economics of operation. A computer-aided simulation model of the biomass burner was developed to help determine performance of the burner at conditions other than those tested. Design and operation recommendations were made based upon actual system operation and output from the simulation model of the burner.

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ABSTRACT

Alternative sources of low-grade energy are becoming more important as the costs of energy from nonrenewable resources rise. Agricultural biomass is a nonrenewable source of low-grade energy that could be used as a heat source, replacing propane fuel for crop drying and space heating. Fuel oil, electricity, and natural gas usage could also be reduced by supplemental heating with biomass-fired heat units.

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CHAPTER 1

BACKGROUND INFORMATION

Introduction

Purpose

The purpose of the research was to lessen the State's reliance on fossil fuels pursuant to the Title 90, Chapter 4, Part 1, MCA and the administrative rules adopted thereunder which states "The purposes of this part are to stimulate research, development, and demonstration of energy conservation and of energy sources which are harmonious with ecological stability by virtue of being renewable, thereby to lessen that reliance on nonrenewable energy sources which conflicts with the goal of long-range ecological stability and to provide for the funding and administration of such research. Furthermore it is the purpose of this part to stimulate the commercialization of alternative renewable energy and to allow the department to make loans through financial institutions in Montana for this purpose."

Scope

The scope of the project was to investigate, design, construct, and demonstrate a biomass combustion furnace fired by agricultural wastes for the purpose of drying high moisture corn. The technologies reviewed included gasification, fluidized bed, and direct combustion. The combustor was to produce a heat output of 800,000 to 1,500,000 BTU/hr.

Objectives

The first objective of this thesis was to outline the design and construction procedures for the biomass-fired grain drying system constructed at the Southern Agricultural Research Center located at Huntley, Montana. Secondly, the performance of the system was evaluated based upon data collected during tests run in November, 1983 and March, 1984. Thirdly, a computer model was developed to simulate the burner performance for the purpose of predicting system behavior to changes in input variables. Fourthly, the discussion section was included, giving the author's views of system performance based upon observations while operating the system and information published on similar research.

English units were used throughout this paper because this is standard industrial terminology in grain drying and handling equipment. There are several references to moisture content throughout this paper. The references were abbreviated as mc and refer to moisture content calculated on the wet basis unless otherwise noted.

Related Research

Gasifier Systems

A gasifier is a two-stage burner. The first stage gasifies the feedstock by using a limited air supply to drive off the volatiles, primarily carbon monoxide. The gas is channelled into a secondary combustion chamber where combustion is completed by introducing more air into the system. The feedstock is gasified in a fixed bed, ashes are removed through a grate at the bottom of the bed, and biomass settles into the gasification zone replacing that which was consumed.

The Agricultural Engineering Department at the University of California, Davis has devoted several years to the development of a downdraft gasifier using walnut shells and other biomass residues for feedstocks. In a downdraft gasifier, the air for gasification is pulled down through the unburned material and the gas is usually extracted from the area underneath the grate. The biomass fuel flows in the same direction as the air. A full-scale portable pilot plant was mounted on a semi-trailer and moved from place to place for demonstration purposes. Numerous publications related to this ongoing research effort are available (Goss, 1977; Goss, et al., 1979; Goss and Williams, 1977; Horsefield and Williams, 1976; Williams and Goss, 1979; Williams, et al., 1977). Current work at UC Davis centers on developing combustion systems and combustion management techniques to minimize objectionable gasifier emissions.

The Agricultural Engineering Department at Purdue University has developed a downdraft gasifier using corn cobs as the main feedstock (Richey, et al., 1980; Richey, et al., 1981; Foster, et al., 1982; Jacko, et al., 1982). Corn cobs, having a relatively uniform size, shape and density, were found to work well as a feedstock in this gasifier.

The Agricultural Engineering Department at the University of Kentucky has worked with biomass combustion using corn cobs, stalks and grain from corn as feedstock for an updraft gasifier (Payne, et al., 1979). The air for an updraft gasifier enters from underneath the grate, while the gas from gasification is discharged through at least some of the feedstock. In this type of gasifier the air and fuel flow are countercurrent. This aids in drying the feedstock before it reaches the gasification zone. Corn cobs were found to be the most desirable feedstock of the three types mentioned for this particular design.

Direct-Fired Systems

A direct-fired biomass burner works on the same principles as an incinerator. All combustion takes place in one chamber and the biomass is fed into the combustion zone upon demand. The burn chambers are designed to be larger than those in gasifiers to allow complete combustion before the exhaust exits the burner. Larger chambers also help accommodate volatile materials such as straw and corn stover.

The Agricultural Engineering Department at Washington State University has built and tested a direct-fired burner using baled hop residue as the feedstock (Ebeling, et al., 1982). Continuous feeding was accomplished by using a hydraulic ram to slice off a portion of the bale and inject it into the furnace. Problems were encountered in getting efficient combustion because of the compacted nature of the feedstock. A concentric vortex air flow pattern in the firebox was utilized in this unit to help remove particles from the exhaust stream.

The Agricultural Engineering Department at Iowa State University developed an incinerator-type biomass burner that uses unprocessed biomass (straw, corn stalks, or similar material) as the feedstock (Sukup and Bern, 1982). A standard 9-inch screw conveyor was used for continuous feeding of the feedstock. A large burn chamber design made it possible to burn volatile material in this unit. The particulate emission rate was comparatively equal to or less than two gasifier units which were tested at the same time (Barrett, et al., 1981). Versions of the unit are being built commercially at the Sukup Manufacturing Company in Sheffield, Iowa.

Work has been done on cord wood gasification in the Department of Agricultural Engineering at Clemson University (Payne, et al., 1981). Cord wood is usually batch-loaded into the gasifier. This feeding system increased labor requirements in operating the system. It was not possible to top load the hot gasifier on a continuous basis, and efficiency was reduced as the diameter of the cord wood feedstock increased.

Montana Based Fuel Sources

Cord Wood

Some Montana residents use cord wood as an alternative fuel for residential space heating. A great quantity of fuelwood is not readily available in many of Montana's crop growing areas. As a result, a cord wood combustion system was not considered for the research and development effort being reported.

Cereal Straw

The following cropland acreages are utilized for production of the four major grains in Montana and are expressed in millions of acres (Pratt, 1982).

wheat	-	5.82
oats	-	0.11
barley	-	1.32
corn	-	0.08

Cereal straw was the after-harvest residue from 98-99% of cropland in Montana that was planted into the four major crops. Unprocessed straw has a tendency to bridge which could cause problems in a fixed-bed gasifier. Unprocessed straw has a very low bulk density. Most straw contains about 6-7% ash, approximately half of which is silica (Staniforth, 1979). Silica tends to fuse into a slag at temperatures above 1,200 ^{o}F. Fused ash can affect gasifier performance by restricting the air and fuel flow, and makes it difficult for the ash to fall through a grate. Wheat and barley straw have typical heat contents of 7570-7750 BTU/lb dry matter and typical moisture contents at harvest time of 9-13%.

Corn Cobs And Stover

The material referred to as stover in this paper is defined as the stalks, leaves, and husks of the corn plant. Corn stover burns in a manner similar to cereal straws. It is highly volatile, and has similar heat value and density. The corn cobs and stover can be collected with a combine-mounted attachment that blows the stover and cobs into a wagon, or by using a flail chopper. Corn cobs are dense as compared to stover or straw. Corn cobs have an average ash content of 1.6% and a gross heat of combustion of 8023 BTU/lb (Payne, et al., 1980). Corn cobs have been collected separate from the stover. One possible method is to open the combine sieves allowing both the corn and the cobs to discharge into the grain tank. The cobs could then be separated from the corn at the grain storage facility. It is simpler to collect all of the cobs and stover that are discharged from the combine.

Wood Chips

Wood chips are available in some locations in Montana, especially around concentrated areas of the timber industry. They are of small and uniform size, but may tend to bridge in some feeding mechanisms. The bulk density of wood chips is low, requiring large feeder storage volume. Wood chips would be a satisfactory feedstock for burner systems installed close to the fuel source.

CHAPTER 2

SYSTEM DESIGN

Selection Criteria

Furnace Selection Criteria

A biomass furnace, for use in Montana, must be able to use cereal straw as a main feedstock. It should also accommodate other secondarily available agricultural biomass fuels such as corn stover, hay, and wood chips.

Consideration of the combustion characteristics of the available fuels indicated that an incinerator-type, direct-fired biomass furnace would be the most successful in terms of fuel use efficiency, day-to-day operation and management. Unprocessed straw and corn stover could be fed into this type of unit, eliminating the problem and expense of processing the feedstock into the uniform size and density necessary for gasification. Usual practices associated with collection and storage such as piling or baling were acceptable. To avoid excessive labor costs, the prototype system specifications included semi-automatic operation.

Selection Of Commercially Available Biomass Burner Unit

A decision was made to purchase a commercially available biomass burner for the following reasons:

1. The time frame for the project completion did not allow adequate time for design and construction of a furnace.

2. Past research could be most efficiently utilized with the purchase of a 'field-proven' burner.

3. A burner on the market could easily be adapted to burning Montana-based fuels.

There were three units readily available on the market with the required combustion rate of 800,000-1,500,000 BTU/hr.

Stormor Manufacturing Company built an incinerator-type burner that used large round bales as the feedstock. The bales were loaded whole and burned in batches. Problems were anticipated in getting the bales to burn at a constant combustion rate. Difficulty in controlling the output temperature, emissions, and combustion rates were also anticipated. A possible solution would be to use a propane burner as a supplemental heat source in series with the furnace to maintain a constant drying air temperature.

Clayton and Lambert Manufacturing Company manufactured an updraft gasifier that was designed to use corn cobs as the feedstock. Primary Montana fuels (straw, hay and stover) could not be burned in this unit without prior processing. An adequate supply of corn cobs is normally available from the harvest of a corn crop to supply the fuel necessary to dry the corn produced, but other sources of biomass are necessary if the heat unit is used for purposed other than corn drying.

Sukup Manufacturing Company built a direct-fired burner than could utilize unprocessed biomass (straw, corn cobs and stover) as a feedstock. This unit was developed at Iowa State University and subsequent improvements were made by the manufacturer.

The direct-fired incinerator type biomass burner, manufactured by Sukup Manufacturing Company, Sheffield, Iowa was selected for this application for the following reasons:

1. The unit had an output range of 310,000 to 1,930,000 BTU/hr (Sukup and Bern, 1982).

2. The unit had been on the market for a few years and was field proven.

3. Automatic controls were supplied.

4. It had the capability of burning unprocessed cereal straw with no apparent further modification.

5. It could accommodate other secondary feedstocks, including corn cobs and stover.

6. It did not utilize a combustion grate that could be plugged by slag-forming high-silica ash.

7. One of the feeding systems utilized a feed wagon that was already available on the experiment farm.

8. A heat exchanger could easily be adapted to the system with little modification of the unit.

9. The unit was immediately available, and reasonably priced.

Biomass Feed System Selection Criteria

The biomass feeding system was selected to be compatible with the material to be handled and the burner it fed. Two systems were readily available for this purpose. One system used a 10 ft x 16 ft stack feeder to tear apart large round bales and loose biomass material. The alternative was a 4 RPM gearmotor electric drive unit that adapted to the PTO shaft of a John Deere chuck wagon for feeding chopped straw or corn cobs and stover.

The feeding system was designed to deliver enough biomass to the burner to maintain the desired burner output. It had an automatic control system to turn the feeding system on and off as biomass was demanded by the furnace. Either baled or loose biomass could be handled by the stack feeder.

The biomass feed rate was calculated as follows:

$$M_b = Q/(q \times e) \qquad (2.1)$$

where:

e = overall thermal efficiency of heat unit

M_b = biomass mass flow rate in lbs/hr

Q = maximum heat output of burner in BTU/hr

q = net heat content of biomass in BTU/lb

Using Q = 1,800,000 BTU/hr, q = 4300 BTU/lb, and e = .75 yields M_b = 698 lb/hr for the calculated maximum biomass feed rate.

Drying System Criteria

Figure 1 is a schematic illustration of the biomass-fired grain drying system constructed at Huntley. The grain drying system was designed to match the burner specified above. Specifications also included completely drying a batch in one working day to eliminate the need for night operation or reheating the corn to drying temperatures. A start-up time of one-half to one hour, necessary to produce clean exhaust, was included in the calculation of the drying time.

The design value for the temperature of the drying air was chosen to be between 120 °F and 160 °F for effective drying. Temperatures higher than 160 °F could damage the grain. Temperatures lower than 120 °F result in an excessively long drying time, increasing the labor requirements and reducing system capacity.

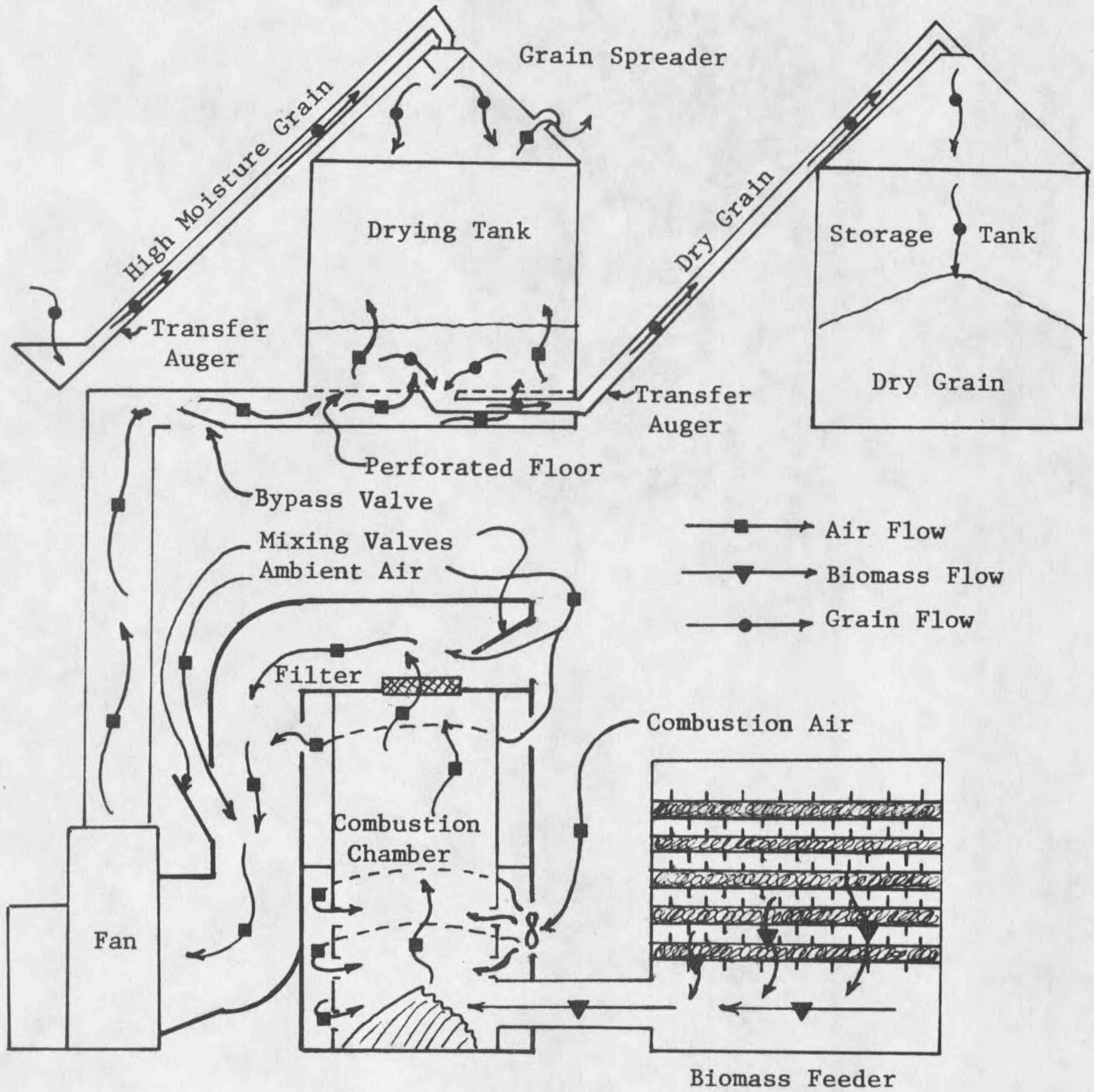

Figure 1. Grain drying system schematic illustration.

Air Handling System Design

Drying Air Temperature Rise

The difference in temperatures between the drying air and the ambient air was calculated, assuming a standard ambient air temperature of 60 ^oF and a minimum desired drying air temperature of 120 ^oF. Substituting these values in Equation 2.2 results in a temperature rise of 60 ^oF.

$$T_o = T_2 - T_1 \tag{2.2}$$

where:

T_o = temperature rise, ^oF

T_1 = ambient air temperature, ^oF

T_2 = drying air temperature, ^oF

Air Flow Rate And Pressure Drop

The air flow rate of the fan, calculated using Equation 2.3, was selected to match the desired temperature rise and the heat output of the biomass heat unit.

$$M_a = Q/(C_p T_o r K) \tag{2.3}$$

where previously undefined variables are as follows:

C_p = air specific heat, BTU/lb dry air

K = constant = 60 min/hr

M_a = air flow rate, cfm

Q = average heat output of the heat unit, BTU/hr

r = air density, lbs/ft^3

Using Q = 1,000,000 BTU/hr, C_p = .241 BTU/lb °F, r = .071 lb/ft^3 @ 100 °F and pressure of 29.92 inches of mercury and T_o = 60 °F yields M_a = 16,234 cfm.

Figure 2 in ASAE D272.1 (Baxter, 1982) is a design aid for determining the pressure drop through a layer of grain. It requires the use of the airflow rate in units of cfm/ft^2 of perforated floor area in the drying tank. The type of grain being dried was also needed to find the pressure drop. The airflow rate per unit area was calculated as follows:

$$M_a' = M_a/A \tag{2.4}$$

where previously undefined variables are:

A = area of perforated floor, ft^2

M_a' = airflow rate, cfm/ft^2 of floor area

Using M_a = 16,500 cfm and A = 303.9 ft^2 yields M_a' = 54.29 cfm/ft^2.

From ASAE D272.1, the pressure drop is 0.8 inches of water per foot of shelled corn for the conditions noted above. Calculation of the pressure drop yields:

$$P = p \times d \times F \tag{2.5}$$

where previously undefined variables are:

d = grain depth, ft

F = factor to account for compaction, fine materials and perforated flooring, F = 1.5 for the conditions noted

p = pressure drop per foot of grain, inches of water

P = total pressure drop through layer, inches of water

Using p = 0.8 in/ft of grain and d = 4 ft of grain yields a P of 4.8 inches of water.

The calculated pressure drop did not equal the initial pressure drop assumption, so the calculations were reworked with a new assumption. Assuming P = 4.5 inches of water and reworking yielded P = 4.6 inches of water with a fan output of 16,000 cfm.

Literature on commercially available fans, indicated that a 27-inch diameter centrifugal wheel turning at 1750 RPM would deliver 16,500 cfm at 4 inches of static pressure and require 19.3 horsepower. These fan specifications were used.

Drying Tank Design

Bin size selection was achieved by obtaining a suitable volume of corn to fully utilize the heat generation capacity of the burner while maintaining a corn depth suitable for effective drying. The calculations below were performed using several standard bin diameters. A tank diameter of 19.67 ft was selected as the smallest feasible for this system. A larger tank could have been utilized if the purchase price was justified. A 1000 bu/hr automatic unloading system, and a 1000 bu/hr grain spreader were specified for effective handling of the grain.

Area Of Perforated Floor

A 12-inch air plemum beneath a perforated drying floor was specified. The area of the perforated floor was calculated using the formula for determining the area of a circle.

$$A = 3.14 \times D^2/4 \tag{2.6}$$

where:

A = area of perforated floor, ft^2

D = drying tank diameter, ft

Using $D = 19.67$ ft yields $A = 303.9\ ft^2$.

Batch Volume

For thin-layer batch drying the grain depth should be between 2-4 ft (Brooker, et al., 1974). Less than 2 ft would result in inefficient use of available burner heat and greater than 4 ft would cause overdrying, less airflow due to increased pressure drop, and/or heat stress to the bottom layer of grain before the top layer is completely dry. Batch volume was calculated by:

$$B = A \times d \times K' \qquad (2.7)$$

where previously undefined variables are as follows:

B = batch volume, bu

d = grain depth, ft

K' = constant = 0.8 bu/ft^3

Using the maximum recommended depth of $d = 4$ ft, and $A = 303.9\ ft^2$ yields $B = 972.5$ bushels.

Drying Time

Drying time was estimated as follows. The required amount of water to be removed from the batch of wet corn was determined. That value was multiplied by the estimated drying efficiency and then divided by the estimated burner output.

The weight of a bushel of wet corn was determined using Equation 2.8.

$$WB = DB \times (\%dm\ of\ DB)/(\%dm\ of\ WB) \tag{2.8}$$

where:

DB = weight of a dried bushel of corn, lbs

WB = weight of a wet bushel of corn, lbs

% dm = percent of dry matter in a bushel of corn

Assumptions used in the calculations were as follows: Corn initially at 25% mc was to be dried to 15.5% mc. A bushel of 15.5% mc corn weighed 56 lbs. This yielded WB = 63.09 lbs/bu of 25% mc corn.

The weight of water per batch of corn was determined as follows:

$$w = (WB - DB) \times B \tag{2.9}$$

where previously undefined variables are as follows:

w = water removed from a batch of corn, lbs

B = batch volume, bu

Using WB = 63.09 lbs, DB = 56 lbs and a batch size of 972.5 bu yields w = 6895 lbs of water to be removed from the batch of grain.

The drying time was calculated using Equation 2.10.

$$t = (E \times w)/Q \tag{2.10}$$

where previously undefined variables are:

t = drying time for a batch of wet corn, hrs

E = estimated efficiency of the dryer system, BTU/lb of water removed

Q = burner output, BTU/hr

Using E = 2,000 BTU/lb of water, w = 6,895 lbs of water removed and maximum burner output of Q = 1,800,000 BTU/hr yields t = 7.6 hrs drying time. This allowed 2.4 hrs for system start-up, shut-down and cleanup in a 10 hr day.

Additional Equipment For Grain Handling And Storage

A storage tank of the same diameter as the drying tank was specified to make it possible to purchase one unload auger and one sweep auger for use in both tanks. An adequate flush-floor aeration system was installed in the storage tank to facilitate conditioning of the grain. Center unload tubes were installed to protect the bins from uneven side loading during grain transfer operations.

CHAPTER 3

SYSTEM CONSTRUCTION

Construction on the project began in June of 1983 and was completed in October of 1983. Most of the work was done by the author and employees of the Southern Agricultural Research Center. Specialized work such as concrete, backhoe work, and electrical wiring was subcontracted because of the lack of equipment and tools. Time, cost, and quality of work were major considerations in selecting the best means of construction of each stage of the project.

Site Selection And Preparation

The site was selected to give adequate room to build the existing facility and for expansion in the future. It was necessary to plan the facility to accommodate semi-tractor and trailer vehicle access. Location of electricity, soil conditions, overhead power lines, and site work were other considerations in the final site selection.

A backhoe and operator were hired to remove old foundations prior to site preparation for the new facility. Figure 2 shows the removal of unwanted material from the site. Gravel was hauled in from a pit located on the farm to raise the facility above the present grade. This was needed to keep runoff water levels below the unload tubes.