Title: Mobile Biomass Pelletizing System

Final Report

Author: Thomas K Mason

Company: Bonfire Biomass Conversions, LLC

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Abstract. This grant project examines multiple aspects of the pelletizing process to determine the feasibility of pelletizing biomass using a mobile form factor system. These aspects are: the automatic adjustment of the die height in a rotary-style pellet mill, the construction of the die head to allow the use of ceramic materials for extreme wear, integrating a heat exchanger network into the entire process from drying to cooling, the use of superheated steam for adjusting the moisture content to optimum, the economics of using diesel power to operate the system, a break-even analysis of estimated fixed operating costs vs. tons per hour capacity. Initial development work has created a viable mechanical model. The overall analysis of this model suggests that pelletizing can be economically done using a mobile platform.

Keywords. Pellet, mobile pelletizing, process control, steam drying, biomass waste, energy efficiency, cellulosic, renewable, co-firing, supplanting steam coal, decrease carbon emissions.

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Introduction The recent release of the "Uniform-Format Solid Feedstock Supply System Report" dramatically underscores the need for a mobile pelletizing system. Section Four states:

4.1 Advanced Uniform Design Performance Targets

The key feature of the Advanced Uniform design is preprocessing the biomass in the earliest stages of the supply systems. Preprocessing depots are central to this design, which complete preprocessing operations started in harvesting and collection to produce a final uniform material that is compatible with the grain storage and handling infrastructure.

As stated in the Uniform-Format Feedstock Supply System Report Draft, the closer to the source the biomass is densified, the more economically it can be handled using existing infrastructure.

A primary assumption was made at the onset of evaluation of this development project. The primary assumption is that because the process is already doable in a stationary format it can be duplicated with some form of equipment that is at least semi-mobile. But, mounting a complete set of pelletizing sub-systems (as current industry standard) on trucks is the extreme and least efficient form of mobile pelletizing. The entire success of the concept, then, hinges on re-designing the subsystems to become more efficient in each process. The result is an energy efficient mobile system that compares favorably to stationary systems. Consequently, all study was focused on process efficiencies to accomplish the goal of creating a highly efficient mobile platform.

Each aspect is developed in depth to understand the machine design parameters and their inter-relationships. These aspects are:

1. Pellet Mill Design Parameters
2. In Process Feeding Requirements (between processes)
3. Maximizing Energy Conservation
4. System Economics
5. Size Reduction Aspects and Parameters
6. Process Improvements

Prototype work was done to study concepts that might be included in the system design. These concepts related to the pelletizing die chamber.

Topics

1. Pellet Mill Design Parameters

1.1 The automatic adjustment of the die height in a rotary-style pellet mill

1.1.1 The standard rotary die head arrangement uses one die head and one or more solid rollers to press the material through the die holes. Using two die heads with holes in an opposed configuration creates twice as many die holes per revolution.

1.1.2 The relative motion of the die heads to vary the spacing between the heads must minimize the amount of mass in motion to minimize the amount of energy required for fast response. The ideal motion for this is a rotary adjustment mechanism that increases the spacing between the die heads when moved in the direction of die rotation. This utilizes the inertia of the die heads to open the gap in case of imminent jamming.

1.1.3 Feedstock motion will be from the outside of the die head toward the inside of the head due to the arrangement of the two opposed heads. The material will be compressed at the interface between the heads and flow through the die channels into the center of the die head's hollow shaft.

1.1.4 Using opposed rotation for die heads eliminates gyroscopic effects that would cause problems in mobile systems. A single die head acts like a gyroscope resisting motion outside the plane of rotation. This aspect is especially beneficial when the machine is being driven through a field at a few miles per hour and turning sharply.

1.2 The construction of the die head must allow the use of ceramic materials for extreme wear.

- 1.2.1 Opposed head configuration keeps the die head under compression rather than tension as is the case for inner roller style dies. The fact that the die material does not need excessive tensile strength allows the use of high-wear ceramic materials which exhibit excellent compression properties.
- 1.2.2 Ceramic components must be segmented to allow for practical fabrication. They must be designed to shapes that are "moldable" as opposed to machinable. Silicon Nitride meets the necessary requirements for wear, corrosion-resistance, mold-ability and strength. Still to be determined is the coefficient of friction with biomass at high pressures inside the die channel.
- 1.2.3 Ceramic components must be retained by compression mechanisms such as clamps rather than tension mechanisms such as bolts and threads.
- 1.3 The diameter of the pellet die holes must be optimized using a combination of maximum particle size, particle size distribution, and average of feedstock asymptotic moduli for the probable variations of biomass, processing die temperature, processing feedstock temperature, processing throughput rate.
- 2 Determine the volume of feedstock through the system at each point and what conduit cross-sectional area at the input and output of each process.
 - 2.1 Infeed material is wet-and-clumping to dry-and-rocky.
 - 2.2 Conveyor augers, belt conveyors, pneumatic conveyors and gravity are available methods at each step of the process.
 - 2.3 Material should occupy the smallest practical percentage of the conduit cross-section. This will minimize jamming during processing. It will also minimize wear due to compressive forces that result from over-loading.
 - 2.4 The conclusion regarding this aspect of the design is that the conduits should be as short as possible. This leads to closely arranged components separated by openings, gates, or very short conveyors that are easily accessed. Actual cross-section of the feeding conduits will be determined to some extent by the length.
 - 2.5 Shorter conveyors also require less power which in turn lends to the overall efficiency.
- 3 Energy Conservation within the System is a key element of creating sub-assemblies that are compact and light enough to be mobile.
 - 3.1 The use of superheated steam for optimizing the moisture content is very efficient from a heat transfer aspect. Steam from the dryer can be recompressed into 10-20 bar by using a screw or turbo steam compressor and used as the heating media in the superheater. This type of energy recovery is called Mechanical Vapor Recompression, MVR. Power consumption is normally 150-200 kWh/ton evaporated water.

3.2 temperature of steam vs. efficiency of drying needs to be evaluated.

4 Economic considerations must be satisfied in order to have a system that is deployable across a broad range of applications. The most important consideration is the amount of fuel that will be used for pellet production.

4.1 The economics of using diesel power to operate the system

- 4.1.1 Determine the ratio of energy input from fossil fuel to the energy input from biomass (see spreadsheet).
- 4.1.2 The amount of energy required by the pelletizing process varies widely from gathered sources. The widest variation is in the drying process. By using the rejected heat from the Diesel generator, the drying energy can be reduced or removed from the overall energy requirements from direct fuel expenditures. As stated above, the use of superheated steam brings a consistent efficiency to drying.
- 4.1.3 Sizing the generator to match the electrical loads from the grinding, pelleting and auxiliary equipment, the total kilowatt hours indicates a generator size of perhaps 400-500 effective kilowatt hour capacity. This number is from the Estimated energy usage (per ton) times the output of five (5) tons per hour.
- 4.1.4 Diesel fuel usage is estimated to be in the wide range of 4gallons to 8 gallons per ton of finished product. This is based on published information from generator manufacturers.

The following spreadsheet energy usage data collected from industrial sources. The first two columns show high and low usage. They include the thermal drying energy because standard operations generally have a separate fuel cost for this process. The MOPET Estimate column does not include the drying energy in the Total Energy requirement for the system. The drying energy is reclaimed from the diesel engine and the heat exchanger network which recovers thermal energy from the other heat sources in the system.

Energy Estimate	High	Low	MOPET Estimate	Unit
Total Energy	1106	161	80	kWh/t
Drying Energy	973	83	(200)	(Thermal) kWh/t
Grinding Energy	83	50	25	(Electrical) kWh/t
Pelleting Energy	50	28	45	(Electrical) kWh/t
Auxiliary Energy	40	25	10	(Electrical) kWh/t

Standard thermal energy sources consist of coal, natural gas, propane, wood waste and other biomass, etc.

Conventional Heat Flow Diagram For Pelletizing Operation

Illustration 1: Diagram Represents Data From Spreadsheet

4.2 Break-even analysis for energy

- 4.2.1 The cost of pelletized product will vary the most from the cost of raw material. A mobile system can be used for a variety of biomass. The cost to obtain biomass feedstock may be lessened if accepting biomass (as waste) results in a payment to the mobile pelletizing provider. It is possible that the operator of the equipment may be paid a dumping fee of up to \$25/ton, while more commonly the material will be free. Notwithstanding, the spreadsheet below shows the cost of

biomass being \$20/ton. In an established commodity market, paying for biomass can be expected. Once pelletized biomass becomes part of the energy stream, there will be far fewer sources that are considered "waste biomass". The spreadsheet below shows equipment cost, cost of fuel, cost of labor, cost of raw material, maintenance and insurance. Fuel usage is a mid-range estimate of six (6) gallons per ton.

Pelletizing Operational Costs Example			
Feedstock Cost	\$20	\$/ton	\$45 per acre corn stover
Fuel Cost	\$18	\$/ton	((30 gal/hr) / 5) * \$3.00/gal
Labor Cost	\$16	\$/ton	(\$40/hr * 2 persons) / (5 tons/hr)
Setup Cost	\$1	\$/ton	(Including transportation) / 1000 ton
Equipment Amortization	\$6	\$/ton	Run
Insurance Costs	\$1	\$/ton	60,000 hrs (300,000 tons)
Maintenance Costs	\$6	\$/ton	Includes truck and trailer
Total Costs per Ton	\$68	\$/ton	

- 4.2.2 "BTUs - In" vs. "BTUs - Out". The only BTU input for pelletizing is through the Diesel fuel used in generating electricity. Eight gallons of Diesel fuel contains 1.044 MBTU. The conversion of raw chips to pelletized wood increases the Btu content from 6MBTU per ton to 14 MBTU per ton. The net energy gain from this process alone is 7 MBTU per ton. This is due to removal of water and creating a more evenly combustible product (when used for thermo-electric power). While this process does not actually add energy, it does densify the material's energy for purposes of combustion and logistics.

5 Size Reduction Design Parameters

- 5.1 Is it better to perform size reduction prior to or after drying? Should compression be used in collaboration with chipping? Compression of the biomass is an excellent first step in processing due to the fact that important minerals are removed without alteration. These minerals can be recycled to the soil as nutrients. A study done in the Netherlands in 2002 determined that up to 45% of water content was removed from ensiled miscanthus. The moisture contained 35% of the N and P content, 47% of K and 56% of Cl.

(International Conference on Crop Harvesting and Processing, 9-11 February 2003 (Louisville, Kentucky USA) Publication Date 9 February 2003. ASAE Publication Number 701P1103e)

- 5.2 Should moisture content affect the path through size reduction? Ideal moisture content for pelletizing is in the range of 8% - 12% depending on the material. All material entering the system will be heated for pelletizing. The heating process naturally dries the biomass. Using temperature controlled steam over time, the exact moisture content can be attained. Biomass entering the system with a content of 12% or less needs heating but not drying. In this case, the system will inject a mist of water to condition the feedstock while it is being heated to the correct temperature. This operation can be done in the same chambers without selecting a different path.
 - 5.3 Fibrous biomass uses different cutting geometry for size reduction. In all cases, it is found that a sharper edge will use less energy to cut the biomass. The use of hammers is a matter of convenience rather than efficiency. A study in 2005 showed that sharper blade angle cut all biomass with less net energy than a blade with a more blunted angle. Furthermore, some results of that study showed that biomass with more moisture content required less net energy to shear than the same biomass in a drier state. (Paper No: 056058 An ASAE Meeting Presentation)
 - 5.4 Lignin is the primary binding chemical in the pelletizing process. It must soften and flow in order for the pellet to maintain its shape when cooled to ambient. The melting point of Lignin is about 284°F.
- 6 Common practice in pelletizing operations relies on friction to generate the heat necessary to allow the Lignin to flow. If excessive heat is applied to the die for the purpose of allowing better flow, there is commonly some charring and degradation of the product that occurs. Heat transfer from the die surface to the center of the pellet also becomes more time/rate dependent. In other words, the faster the pelletizing rate becomes, the less heat is transferred into the pellet from the die surface.
- 7 Following is excerpted from "Binderless Pelletization of Biomass" – 2005 ASAE #056061 Sokhansanj, et. al.

7.1

Effect of temperature

Apart from moisture content of the feed materials, temperature also plays a major role in stability and durability of the product and power requirement. The method of adding heat to the densification system is by means of preheating of feed materials or the use of heated die apart from the frictional heat generated due to compression. Reece (1966) reported that heating the feed material to between 60°C and 70 °C could produce more stable compacted product than was possible with unheated material (Orth and Lowe, 1977). Hall (1958) found that the higher the temperature, the lower the force needed to

provide a given degree of compaction. They also concluded that grass having relatively high moisture content could be compacted at an elevated temperature, whereas it was not possible at ambient conditions. Smith et al. (1977) studied the effect of temperature on the stability of wheat straw briquettes. Based on their work, they found that temperature had much greater effect along with initial moisture content on stability of wheat straw briquettes. Working with closed dies, Smith et al. (1977) achieved very high-relaxed density of between 1200 to 1300 kg/m³ at die temperatures of 80 to 140°C though an excessively long heating time of 40 min was used. But as the temperature increased above 110°C, the initial moisture content had little effect on the stability. At higher temperatures, discoloration of briquettes was observed due to chemical degradation.

- 7.2 Consequently, the most functional point in the process to increase the material heat is **prior** to entering the pelletizing chamber. In this case, the heat of the die should be cooler than the incoming material.

7.3

Moisture Removal Heat Calculations

The thermal mass of wood with 50% moisture averages about "0.70".

It requires (0.70 Btu) to raise the temperature of one pound of wet wood by 1°F.

Dry wood has a thermal mass of about .42.

To raise the temperature of **dry wood** to 284°F from 32°F requires 62kWh per ton,

$$284^{\circ}\text{F} - 32^{\circ}\text{F} = 252^{\circ}\text{F } \Delta t$$

$$(.42) \times (2000 \text{ lb.}) \times (252^{\circ}\text{F}) = 211,680 \text{ BTU (62kWh) per ton.}$$

Assuming a rise in temperature for the water of 80°C from 0°C (176°F At from 32°F or 208°F) with water having a thermal mass of 1.0. The energy required is

$$176^{\circ}\text{F} \times 2000 \text{ lb.} \times 1.0 = 352,000 \text{ BTU (103 kWh) per ton.}$$

$$\text{Total energy required is } 62\text{kWh} + 103\text{kWh} = 165 \text{ kWh / ton}$$

- 7.4 This calculation is theoretical and does not consider residence time / rate of heat transfer nor does it consider inefficiency or heat loss in the process. However, the **total energy required approaches the theoretical requirement as the particle size decreases and as the heat loss is minimized.**

The above diagram shows the energy streams that the heat exchanger will manipulate. The primary thermal source comes from the heat rejection of the Diesel power plant. The usable heat exceeds the mechanical energy.

MOPET Flow Diagram

Maximum Use of Energy For the Process

The two MOPET flow diagrams schematically represent the material flow from biomass input to pelletized output. They are similar except that the single-pass is hydraulically driven and has a combine head/chopper at the input.

Single-pass equipment must have high flotation tires to avoid damage to cropland.

Die Design Extrusion Experiments

Since the die design's novel capabilities are key to optimizing pelleting efficiency, a series of experiments were done to study various changes to the die chamber for pelletizing. It was determined by these experiments that using a new method of construction for the die head of the pellet mill allows very different geometry possibilities beyond the standard reamed holes that are currently used. These first experiments were exploratory in nature rather than specific, controlled science. This is due to the developmental nature of this project. Once the concepts have been finalized, controlled experimentation will serve to optimize the processes.

One experiment examined whether gradual tapers may mitigate some of the friction at the interface of the rolls where the compression of the material begins. A second concept was studied wherein vents were introduced to the die chamber.

Experiment #1

The extrusion mechanism was tested using the Nozzle Stack Assembly 7410. The assembly (shown below) has a series of vents in the body of the die to allow the escape of moisture and steam while the material is under pressure.

Ambient temperature was 55F.

No heat was used for either the die or the feedstock material.

Feedstock was raw White Oak sawdust from using a chainsaw.

Hydraulic pressure was set at 1700 psi.

Material was fed into the chamber while the extrusion piston was cycled up and down using limit switches at either end of the stroke and a delay timer on the upper end of travel to allow feedstock to enter the chamber.

Some of the feedstock fell through the Nozzle Stack at the beginning of cycling. This was blocked to allow the material to build up inside the stack.

After the material began to compress in the stack, moisture in the form of water droplets came out of the side holes as predicted. This moisture indicated that the venting was functioning correctly and that water was migrating out to the edge of the chamber and through the vents. The vents are in four places equally spaced around the periphery and at intervals of .67" so as to have five equally spaced sets of vents down the sides of the chamber within the Nozzle Stack.

The pressing cylinder was 2 3/4" in diameter which translates to about 10,000lbf on the extrusion piston. The extrusion piston area is about one square inch.

The total pressure was insufficient to force the wood through the end extrusion orifice which is about .72" diameter. The sawdust compacted into a tight, flaky cone that retained considerable moisture even after the pressing process.

Experiment 1 Conclusions

The angle of the taper was determined to be too high. There was too much internal friction to overcome within the feedstock material to allow it to extrude or flow at the temperature used. While higher temperatures might improve the flow, the moisture level could cause the material to separate and blow forward rather than to properly extrude as it should.

The pressure behind the extrusion piston (10,000 psi) was too low.

It should be noted that this experiment involved only one feedstock, that is -- White Oak. While this is very limited, it is necessary to consider this as a sufficient functional test. The reason is that this machinery will be used where this feedstock would be entirely ordinary.

Experiment #2

The extrusion mechanism was tested using the Nozzle Stack Assembly 7410, Revision B

The revision involved reducing the piston diameter to about .45 square inches and sleeving the cylinder to the same size. The nozzle stack was extended at the bottom and the top three segments were removed. This change was made to reduce the overall compression ratio at the throat.

Ambient temperature was 45F.

No heat was used for either the die or the feedstock material.

Hydraulic pressure was set at 1700 psi.

Material was fed into the chamber while the extrusion piston was cycled up and down using limit switches at either end of the stroke and a delay timer on the upper end of travel to allow feedstock to enter the chamber.

Feedstock was raw White Oak sawdust from using a chainsaw and a variety of chopped dead leaves soaked in water (mainly Oak and Maple).

The leaves were fed through without any sawdust. They came out the nozzle quite easily as there was little compression. The leaves did not form into a tight mass. They came out still wet but crushed together nonetheless.

Sawdust was added to make a 1:1 mixture of the two materials. This was mixed until evenly distributed. The mixture was fed into the nozzle in the same manner as before. This mixture offered more resistance to compression and responded similarly to the sawdust mix in Experiment #1.

More sawdust was added until the mixture was an even 2:1 (sawdust:leaves). The mixture again behaved more like sawdust, offering increased resistance to compression. Water extraction became more noticeable at this point.

The pressing cylinder was 2 3/4" in diameter which translates to about 10,000lbf on the extrusion piston. The extrusion piston area is about .45 square inch. This translates into an available force of 22,000 psi. No jamming occurred and all material was able to be processed without increasing the force.

Experiment #2 Conclusions

The procedure was reiterated for 3:1, 4:1 and 5:1 with predictable results. With an increase in resistance comes greater water extraction.

Experiment #3

This experiment was the first attempt at pelletizing. Earlier experiments concentrated on the removal of moisture. This experiment concentrated on the end product.

The material used for pelletizing (feedstock) was sawdust/dry leaf mix with approximately 10% dry leaves (by weight). This material was steamed in a closed container of approximately five (5) cubic feet. Material was fed into the pressing chamber directly from the steamer at about 160°F.

Pellet die diameter was .400"

Heat set point was 310°F

Ambient temperature was 55°F

Hydraulic pressure was 1500 psi

Pressing cylinder diameter was 2.50" (4.9 sq in piston area)

Effective pressing force was 7360 lbf

Piston diameter was .50" (.20 sq in pressing piston area)

Pelletizing ram pressure 36,800 psi
Temperature controller mode was "on/off"

Material was fed into the throat of the chamber and pressed at a controlled rate which was set using a hydraulic flow control. Most effective rate for this experiment was about .3 inches per second.

The steamed, preheated material processed smoothly and consistently. There was no tendency for the die to become clogged. Material exited the pellet die with a surface temperature close to that of the die temperature – about 280°F. The experiment was run for about ½ hr to validate the consistency of the process. Sufficient pellets were collected for study and samples. Pellet quality was inconsistent because the process was not a true steady-state in this prototype model.

Conclusions

Novel construction of the pellet die allows venting as well as reshaping the die cavity. These possibilities need to be studied in depth with a small scale, full-function die set. Venting of the chamber could allow higher moisture content materials to be extruded to the same net moisture content as standard pellet techniques. The fact that material could be pelletized from the raw state is hopeful. By shaping the cross-section of the die chamber to minimize the maximum thickness of the pellet, the moisture will be allowed to travel to the surface of the pellet in the minimum time, allowing higher feed rates.

The use of molded and sintered ceramic materials could be justifiable due to the greatly increased wear characteristics of the ceramic materials.

The various aspects of machine design that have been studied reveal no major obstacles to continuing development work. The over-arching efficiency requirements indicate higher wear components and lower coefficient-of-friction die materials. These material challenges have currently available solutions. Any improvements will only enhance the efficiency of the system.

The next phase of development is to create a prototype pellet mill and steam drier combination. The steam drier will have single batch capacity for development. These single batch driers will be ganged into the final optimal capacity configuration for the production system.

This prototype system will study the majority of parameters for pelletizing. Initial experiment will maintain the type and shape of feedstock as a constant and vary temperature and moisture. Throughput is to be monitored for quality and energy requirements as each of the two parameters are varied.