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Project Number: P13432

BIOMASS COMPACTOR

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Abstract

Team 13432 has been tasked with creating a biomass compactor to create 2.5 or 5 pound bricks of biomass to be used as either an alternative energy source or animal feed. Our customer has built a prototype using a log splitter; it is very unsafe, takes nearly five minutes to create a brick, and is labor intensive. The goals of our project were to create a machine that can produce 720 bricks an hour, can create both types of bricks, and is safe. Team 13432 has designed a new prototype and built it in Pro Engineering. Every part has been modeled in ANSYS to confirm it will not fail during operation. The machine will produce a brick every five seconds, based upon the team's design and timing diagram. Currently it is not economically feasible to sell the bricks as an alternative energy source; the team has created an Excel model that calculates this required oil price. From the team's designs and models, our customer can build a new prototype. The project scope has been satisfied with a complete design proposal. This proposal consists of drawings of complete system design, a bill of materials, an economic analysis, an energy balance calculation, in depth biomass material testing, and additional design documentation.

Introduction

In the spring of 2013, Overmoyer Farm (PI on NYSERDA contract 10827) and Comtech approached Multidisciplinary Senior Design team 13432 with the idea of a biomass compactor. The purpose was to create biomass bricks that would be sold as either a heat source or animal feed. The customers had designed and built a prototype; however, this machine did not have the capacity required for the mass production of bricks. In order to commercialize the bricks, the customers desired a machine with the capability of producing 720 bricks per hour.

Before the designing phase of the project, it was essential for the team to gather all the necessary information on this fairly new concept. The team extensively researched the few existing biomass compressing solutions and collected fundamental data about the forces required to reach the density desired by the stakeholders. In addition, the team gathered and analyzed data provided by the customers, which included visiting the site where the prototype is located. Furthermore, the team tested the biomass, as well as other similar materials, to acquire even more information. Through this information, the team was able to move forward with creating a solution for this project.

The final design consists of three main components. The biomass is fed into a hopper with a feedscrew in the center that controls the flow rate into the system. It is fed into the weigh chamber, where the five lb weight is measured. From there, it enters the compression chamber and is compacted in two stages, with the final compression being done by a flywheel powered piston (images 1 and 2.) The machine will be controlled by a custom coded PLC. Input from sensors regarding the state of the machine and biomass will coordinate timing of all moving parts. U.S. customary units are used throughout per customer requirements.

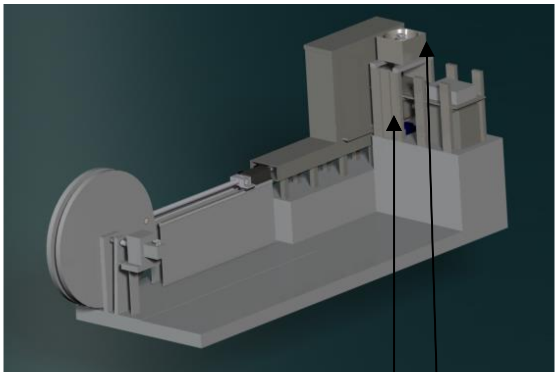

Image 1 (biomass compactor)

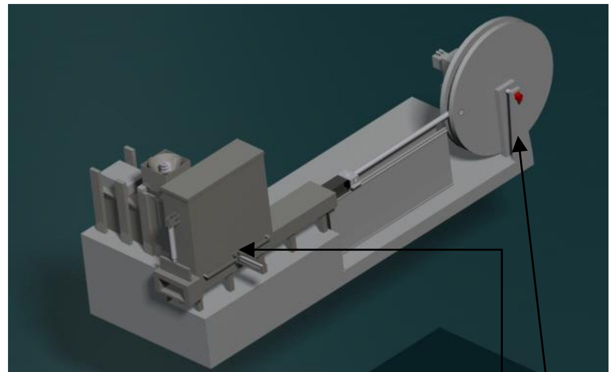

Image 2 (compactor rotated 180 degrees)

Weigh chamber
Hopper

Compression chamber
Flywheel

Analyzing Customer Data

At the beginning of the project, team 13432 was given a Project Readiness Package, or PRP, that had been compiled by the customer and the team's faculty guide. It contained sample data for the compressive forces required to produce the biomass bricks. The first information given to us in the PRP was the reason for the creation of this project. According to the PRP, using hay for fuel for heating is much more efficient that using heating oil. Argonne National Labs preformed a study that suggested that a 40 pound bale of hay has the same heating value at 2.5 gallons of heating oil. The 40 pound bale of hay costs about $3, while the 2.5 gallons of heating oil costs about $10. This study provided the customer the economic motivation to pursue a project that would mass produce biomass bricks for sale for heating fuel. It was also believed that the same machinery used to create the biomass bricks could be used to create the same bricks for use as animal feed. Creating biomass bricks for animal feed would be advantageous because unlike bagged or baled hay, bricks of hay would be insect free, sterilized by high pressure, can easily have specific vitamins added during the brick creation process, and would be efficient to store and stockpile in case of an emergency situation such as a drought.

Other information given to the team in the PRP was the amount of force that would be required to create the biomass bricks. The customer requested that the bricks be the same density of oak, which is roughly 0.75 grams per cubic centimeter. A graph of compression distance versus force was given to the team as a launching point for design.

Biomass Testing

Biomass samples, obtained from the customer, were tested for the coefficient of static friction, ejection force, and force versus piston displacement. The ejection force was recorded for the original compression tests, which compressed the bricks to a higher density than the tests mentioned below. Poisson's Ratio proved to be difficult to obtain; therefore, work from other sources was used to estimate the values.

Two different kinds of biomass were used during the friction testing: compressed hay and Sorghum-Sudan bricks. The coefficient of static friction can be found using only one measured variable: the angle at which a brick will slide down a surface. The testing was done on T304 stainless steel and 1018 steel. Only static friction was the concern of the team, since it was directly related to the max ejection force. This max force was needed for the design and analysis of the machine.

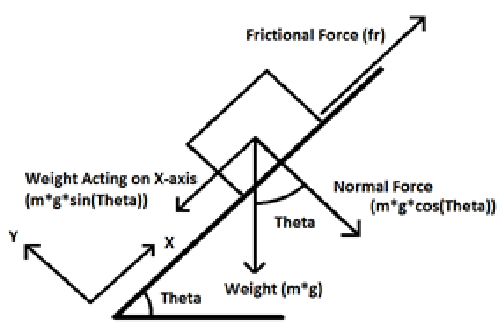

Image 3-friction testing apparatus

The four largest sides of the bricks were placed upon the plate and each was tested five times. The slip angle of the plate was recorded at three in line locations during the tests using stainless steel: one measurement near the end of the plate on the table, one near the other end of the plate, and one placed in the middle of the other two measurements. This was to verify that the angle given was accurate along the entire length of the plate. For the 1018 steel, the angle was only recorded once because a smaller plate was used.x

Through the testing, the average coefficient of static friction for Sorghum Sudan on stainless steel was determined to be 0.21. The average coefficient for hay on stainless steel was also 0.21. Finally, the average coefficient for hay on 1018 steel was determined to be 0.371.

To analyze and compare the behavior of the biomass during compression and ejection, small bricks were made using the designed test rig. The test rig was used in conjunction with the Tinius Olsen machine. Multiple hay samples of differing weights were used to test if there were scaling issues. A total of five different small bricks were made for scale testing. The values of pressure required to achieve the needed densities were graphed for each brick as well as the original test data obtained from Mr. Gutterman. The pressure value created from the small brick pressure versus density trend lines differed at the most by 9.14% from the pressure value created from Mr. Gutterman's five lb data.

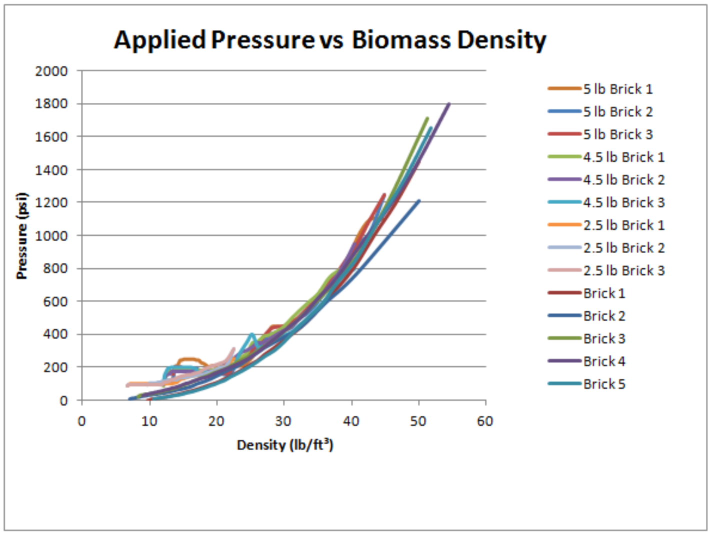

Image 4-applied pressure vs density

To start the last test, hay samples of differing weights were bagged and numbered. The test ram/piston was marked at 1/8" intervals starting at 40 (1/8") from the inserted end. First, the final height of the brick was calculated using the given cross-sectional area, density of 49.94 lb/ft³, and weight of the hay. The hay was then compressed to or close to this calculated ideal height, using the marks on the piston as a guide. Force was recorded from each readable 1/8" marker to the stopping distance of the sample. Bricks 3-5 were slightly over compressed due to rounding the stopping distance to the nearest whole 1/8". The bricks were then hammered out and bagged with their label.

The pressure calculated from the small scale tests was 1479.94 psi. This value was reasonably accurate, just a 2.5% difference from the value calculated from the full scale testing brick. The pressures and densities of the varying sizes follow similar trends after reaching a density of 30 lb/ft³. The reason why the five lb brick data has a 9.14% difference is yet unclear. One possible reason could be that the hay batches had different water content levels.

Feedscrew

The purpose of the hopper and feed screw system is to regulate the rate at which input biomass is fed into the system, such that the desired output rate of one brick every five seconds is achieved. Since this is the entire purpose for this system, the most important aspects of the total system to consider during design would be the total volume of the hopper and the rate at which the feed screw moves the biomass. The volume of the hopper must be equal to the volume of loose biomass required in order to produce one five pound brick, to maintain a smooth rate of production. The amount of material moved by the feed screw in five seconds must also be equal to this volume.

These values must be considered, along with other subsystem requirements, during dimensioning and material selection.

Early information provided by the customer along with research regarding the material properties of dried switchgrass showed that and input of 2,304 cubic inches of switchgrass was required to create a single five pound biomass brick of 153 cubic inches. Therefore, the total volume of the hopper must exceed this value. On top of this basic criterion, the end of the system needed to neatly feed into the weighing chamber subsystem. To that end, the largest available piping that would appropriately dispense biomass into the given dimensions for the weighing chamber was determined to be low carbon steel piping with a six inch diameter. The initial design for the hopper was then designed as a large cube capable of holding two bricks worth of loose biomass that then fed down into the piping. However, with the concern of biomass being able to clog in corners, a cone shape was the final design selection.

Now that the hopper had a design, the feedscrew and the motor driving it needed to be sized in order to move the biomass in the time allotted in the system's timing diagram. On top of this, the motor would ideally operate at the same speed as the flywheel's driving motor in order to simplify system timing and reduce the impact of any vibrations caused by the motors; which was thirty rpm. From there, it was determined that the cheapest custom feedscrews started at nine full thread rotations and that the feedscrew would have a similar dimension if possible. Dimensions were then nailed down knowing the height of the hopper, the length of the piping, the volume to be moved in five seconds, and the rate at which the feedscrew would be rotating. Therefore, each full rotation moved enough hay to keep on track with brick production. The feedscrew was also sized with its positioning in mind: hanging in the middle of the hopper and piping while attached to a top mounted motor in a separate chamber to prevent loose biomass from coming into contact with the motor. Two bearings were selected as well in order to secure the position of the feedscrew in the hopper while still allowing for unimpeded rotation.

After the designs were finalized, stress analyses were performed both using an Excel spreadsheet as well as ANSYS finite element modeling. The forces taken into consideration were any internal forces due to the bearings and any connections between the motor and the feedscrew. External forces were calculated considering the force applied to any biomass in the hopper by the motor and the expansion of the biomass created by this application. The stress analysis was performed with the minimum material thickness for the hopper, with all items being comprised of eighth of an inch low carbon steel. The analyses showed that the stresses experienced by the hopper would not meet or exceed the yield strength of the steel by a large margin. Deflection nodal analysis also showed that the system would not give to any degree which would be noticeable or would hamper system operation in any way.

On top of this, it was determined that a key, or a mechanical fuse, would be used to attach the motor to the feedscrew. The purpose of this key is to prevent motor or feedscrew shaft failure in the event that a foreign object should become lodged in the hopper. This key was selected to have a yield point at approximately ninety percent of the maximum torque of the motor, ensuring that the key does fail first in most failure modes.

Weigh Chamber

The weigh chamber subsystem is the transition point from the feedscrew system to the compression chamber. The weigh chamber weighs the biomass to ensure the correct amount is inserted into the compression chamber. This subsystem contains a weigh module, two actuators, six vertical supports, five horizontal supports, a piston with brushes, a weigh chamber, and door with brush system.

When the biomass leaves the feed screw, it is guided into the weight chamber where the weigh module terminal collects live data. The weigh module works within a tolerance of 0.0022 lb as provided by the specification sheet. When the total weight of the biomass reaches five pounds, the weigh module sends a signal to the door actuator and the feed screw actuator; the door slides shut, trapping any excess biomass and the feed screw stops. After the door slides shut, a signal is sent to the piston actuator, and the piston extends and moves the biomass from the weigh chamber into the compression chamber.

The SWB505 Compression weigh module produced by Mettler-Toledo is the best option for this machine. It provides the highest accuracy for both static and dynamic applications, which best models the biomass compactor. There is a self-aligning rocker pin that provides 360º checking for ease of installation and maximum built in safety functions. The rocker pin also insures accurate repeatable weigh measurements. The SWB505 includes two stabilizers that alleviate the scale subject to heavy vibration; a Fabreeka pad located under the module will assist in stabilizing the system. Also included is the IND560 terminal. It is the most versatile terminal available and offers a heavy wash down rating, can interface with the compression weigh module with ease, and can communicate directly with multiple interfaces, which is necessary to control the rest of the biomass compactor (image 5.)

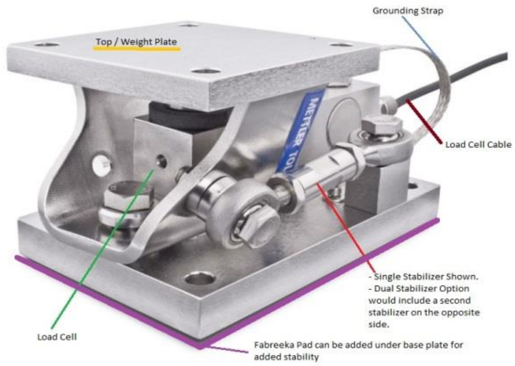

Image 5 – weighing module

The first actuator in this subsystem, attached to the door, closes the door in one second. It applies 16 pounds at a pressure of 64 psi; it has a 12 inch stroke and a bore of 9/16 inches. The second actuator is the piston inside the chamber that moves the biomass; this time requirement was eight-tenths of a second. It also has a 12 inch stroke, but it has a three inch bore; it apples 665 pounds at 94 psi. The supports are used to isolate the weigh module from as much machine vibration as possible; they also support the actuators and door system.

To ensure the correct dimensions and material had been selected, free body diagrams for each part were created. These drawings helped to find the equilibrium equations and then all the forces acting on each body. Last, these drawings were transcribed into ANSYS, a 3D force analysis software, to find the deflection and stress at any point of the body. The information that ANSYS provided was the last step in the material and dimension decision.

Flywheel

In order to determine the construction of the flywheel drive mechanism, the forces present must first be understood. The motion of the flywheel can be most accurately modeled as a piston-crankshaft mechanism. The image below (image 6) displays the geometry and coordinate axis of the system, r is the radius of the flywheel to the connector rod and L represents the connector rod which connects the wheel to the piston rod. Equations were then found that can be used to determine the forces acting along the respective axis given the design geometries.

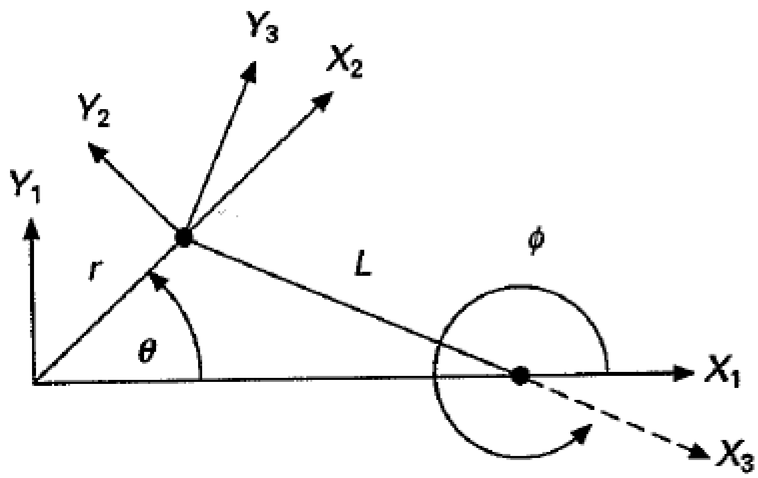

Image 6 - geometry and coordinate axis of flywheel system

Using the material property data obtained by the testing team, a force curve can be determined. The below curve (image 7) displays the pressure required to compress the biomass as a function of density. The amount of biomass in the chamber and the position of the piston face are known at all times so the density can be calculated and the equation used to accurately predict the amount of pressure required. Since the curve is the required pressure, it can be applied to any size or shape of brick to determine the amount of force required. This force is used as F_{x1} and is the driving parameter of all other forces in the system.

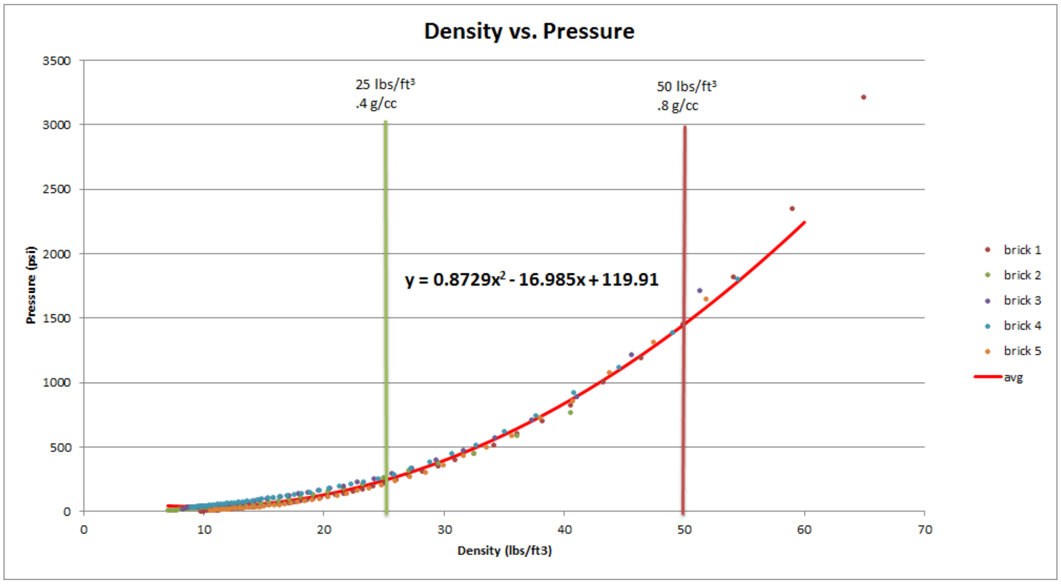

Image 7-density vs. pressure

The flywheel rotates at 36 rpm, which allows 3 strokes per brick: the first stroke to do the initial compression, the second to solidify the compression, and the third to eject the brick from the chamber. Each stroke takes 1.66 seconds. By using the required force as F_{x1} and using previously found equations, the stress in the piston rod can be determined. The highest forces happen during the first 180° of rotation and are the main focus of attention. A full sized machine with a cantilevered piston arm would see a maximum of 1,460 ksi of stress due to compression and bending. By adding a rail and carriage to provide the vertical support the bending moment can be eliminated to reduce the maximum stress in the piston rod to 23 ksi.

The material selected is 1018 cold rolled steel; it has a tensile strength of 54 ksi. When taking into account various fatigue factors: C_{load} =.7, C_{size} =.812, C_{surf} =.938, C_{temp} =1, C_{reliab} =.897, it brings the tensile strength down to 18.5 ksi. This gives a factor of safety of .80 in respect to infinite life for the piston rod. However the piston will be loaded in compression so failure is highly unlikely to occur.

In designing the axle for the flywheel it was decided to use a two wheel system that would symmetrically support the load in order to minimize the bending moments present. The torque however is only applied from one side in order to simplify the construction. The graph below (image 8) displays the stress in the wheel axle compared to wheel position. This is the total combined shear and torsional stresses. The maximum stress observed is 21 ksi at maximum stroke position.

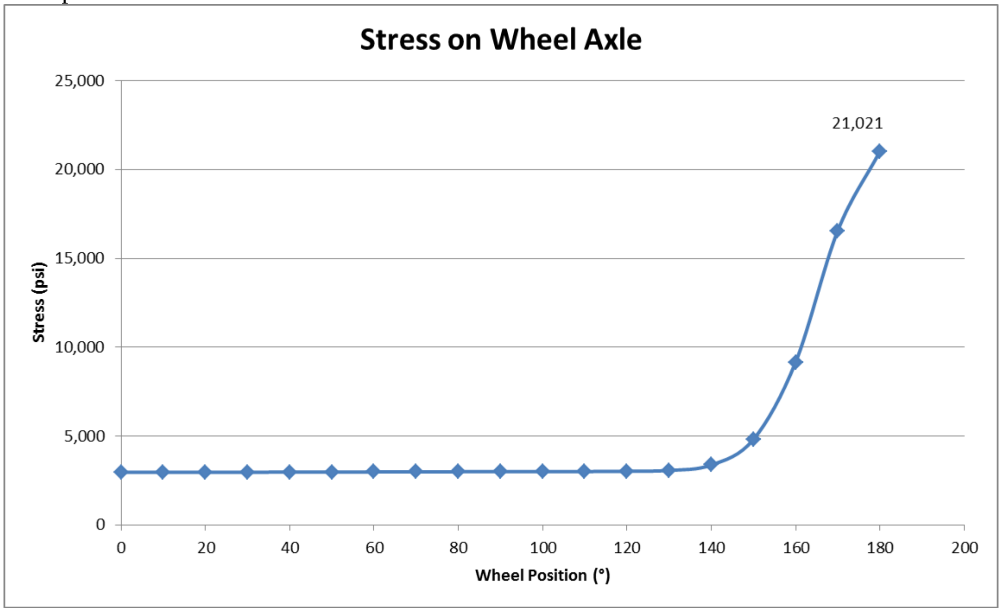

Image 8-stress vs position

Compression Chamber

The compression chamber is designed to utilize a two stage compression system. The first stage of compression is vertical, pushing the loose biomass down from where it enters the chamber into the lower portion and providing minor compressive forces. The initial compression plate is moved by a pair of high speed electric actuators. When the compression plate reaches its lowest point it is locked in place by a pair of pin bars moved by electric actuators. These pin bars will take any loads exerted on the initial compression plate due to the Poisson effect during the primary compression. After the initial compression plate is locked in place the primary compression piston extends and compresses the biomass up against the inside of the compression chamber door.

The design process for the chamber was purely a statics problem, with the main limiting characteristic being the tensile strength of the chamber walls in the areas around the chamber door. The secondary limiting factor was in the availability of actuators for the initial compression plate. Since the plate would have to descend completely in under a second and the fastest actuators that could be found had a speed of nine inches per second that meant that the area the hay occupied after entering from the weigh chamber could be no taller than nine inches, not counting the five inch height of the compression piston track. The final design settled on was a 5 by 12 inch cross section piston track with a 36 by 12 inch by 9 inch tall space above the track for the hay to enter through and be compressed down by the initial compression plate. The wall thickness for this chamber design to not fail from tension in infinite life with a factor of safety of 1.2 using 1018 steel was determined to be a quarter of an inch.

System Summary

Overall, the system will have a footprint of approximately 13’ x 5’ and be 6’ tall and weigh around one ton. The amount of space needed for raw material, processing, packaging, and finished goods inventory is calculated as a function of days of inventory. For five days of inventory, 8280 square feet would be required. Power requirements for the machine are included in the energy calculator based on the actuators selected and availability of 240 V outlets. Cost and assumptions for shipping of material and finished goods are also included in the calculator and may be updated by the customer depending on where the system is implemented. Labor will also be calculated depending on the state of the raw material and the amount of data that needs to be collected in quality assurance at a particular stage of production.

Conclusions and Recommendations

The primary goal of this project was to develop an automated process to convert biomass into marketable compact bricks. The process needed to be safe, repeatable, capable of a high production rate, energy efficient, and cost efficient. The primary intention of the product is to be burned for fuel or used for animal feed.

Not including the cost of the machine or labor, the constant cost per brick is $0.87. At the selling cost of $1.50 proposed by the customer, this would be a 73% profit. However, the cost of heating oil would have to be at least $5.81 per gallon to make this option economically preferable to consumers. As current US heating oil costs hover below $4, the bricks would have to be sold at less than the desired price. While the cost of including additives necessary for feed bricks was not fully determined, it is likely that feed bricks would be more feasible because they would be more marketable at a profitable price.

Due to changes in project scope, some original aspects of the design study could use to be farther researched and improved. The team was not able to estimate how loud the machine would be and what level of ear protection would be necessary for the workers. At this time, the machine can handle bricks of different density (and hence selling weight) but not of different size. This could be improved by implementing separate exit doors for the biomass to be compressed against. Another opportunity in the flexibility of the system architecture would be making the machine easily portable.

Preliminary data gathered by the customer regarding the potential flywheel design and the properties of compacted biomass was successfully confirmed in this project. The high goal of a throughput of 720 bricks per hour was also achieved. Going forward, safety features should be reviewed depending on the environment the machine is in as well as the regulations relevant in that location. It is also recommended that focus be put on load cell accuracy. This includes minimizing vibration transferred to that area of the machine, as well as recording the weight of output bricks into an appropriate control chart.

Acknowledgements

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Works Cited

Beer, Ferdinand P. *Mechanics of Materials*. 5th ed. New York: McGraw-Hill Higher Education, 2009. Print.

Boedo, Stephen. "Practical tribological issues in big-end bearings." *Tribology and dynamics of engine and powertrain*. Ed. Homer Rahnejat. Oxford: Woodhead Publishing, 2010. 615-34. Print.

Boedo, Stephen, and J.F. Booker. "Transient dynamics of engine bearing systems." *Tribological Design of Machine Elements*. Amsterdam: Elsevier Science Publshers, 1989. 323-32. Print.

Budynas, Richard G., and J. Keith Nisbett. *Shigley's Mechancal Engineering Design*. 9th ed. N.p.: McGraw Hillq, 2011. Print.

Engineering ToolBox. N.p., n.d. Web. 1 Oct. 2013.

Granger. N.p., n.d. Web. 12 Sept. 2013.

Lanning, David N. "CROSS REFERENCE TO RELATED APPLICATION." *Engineered Tall Grass Biomass Baling System*. Forest Concepts, LLC, 2 Aug. 2011. Web. 21 Nov. 2013.

Lanning, David N. "Patent US8359974 - Method of Baling Switchgrass or Miscanthus at Optimum Highway Transport ... - Google Patents." *Google Books*. Forest Concepts, LLC, 29 Jan. 2013. Web. 21 Nov. 2013.

McMaster-Carr. N.p., n.d. Web. 12 Sept. 2013.

Wikipedia. N.p., n.d. Web. 30 Apr. 2013.