Final Design Report
Pyrolysis Feeder

BREE 495: Engineering Design 3
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Abstract- Biomass is a well-known source of renewable energy and the process of gasification has been developed in order to optimize its use. Our project consists of developing an efficient feeding system that accommodates our client criteria’s and constraints, which revolve around a bottom fed gasifier. In fact, the biomass is inserted from the bottom, and moves against the force of gravity, which means the combustion process occurs within the base of the system. Therefore, the proposed design consists of an inclined screw feeding system, which conveys biomass in an upwards motion. The feeder includes features such as optimal screw parameters and proper air control. Our carefully designed system would ultimately be connected to a gasifier, which will convert the inserted biomass into syngas and the outcome would be used in different applications, such as supplying heat to a greenhouse.

1. Introduction

1.1 Objective

The client wishes to develop a new gasification system, in which the combustion occurs within the bottom of the bed; in other words, the combustion zone would be located at the lowest base of the gasifier. This system is also required to receive the feedstock from the bottom. In fact, the entrance of the material into the gasifier would be located below the grate, at the bottom point. From this location, combusted biomass would be diffused upwards and ash would fall down into an ash collector. Our task was to develop an efficient and cost-effective feeding system for the newly designed bottom-fed gasifier.

1.2 System Requirements

It is important to understand the design constraints as specified by the client, before any solutions are to be considered. Gasification is a sensitive process in which temperature and pressure variations need to be carefully monitored. In fact, temperature and pressure variations could potentially cause operational problems within the gasifier and hence influence the calorific value of the syngas through the reduction of CO and H\textsubscript{2} concentrations. Therefore, these factors also have to be considered for the feeding system, to ensure that the gasification process is not impacted from an unsuitable and inefficient conveyance. The following are the most important criteria and constraints to be considered:

- Uninterrupted feeding into combustion zone
- Material conveyed uniformly to the combustion zone
- Feedstock flexibility
- Densification of feedstock
- High reliability
- Low energy requirements
- Cost effective, i.e. low construction maintenance and operational costs
- Maximum feedstock intake of 1000 kg per day
- Material of the system should handle high temperatures ~ 150°C
- Sufficient pressure seal with minimal air intake
- Safe distance between combustion and feeding system
2. Proposed Design of Inclined Feeding System

2.1 Specifications and justification of proposed design

2.1.1 General components of a screw conveyor

Screw conveyors are widely used for transporting and/or elevating bulk materials at controlled and steady rates. In fact, screw feeding is the process of delivering bulk solid materials from one point to another over different feed rates. The standard unit, with variations in design, is suitable for solving a variety of bulk material handling problems. Screw conveyors vary in size from 75 to 400 mm in diameter and from less than 1 m to more than 30 m in length (Zareiforoush, Komarizadeh, Alizadeh & Masoomi, 2010).

Figure 1: Screw Conveyor Components (Source: "Screw Conveyor Components & Design")

The major screw conveyor components are the screw casing and the rotating screw. In fact, the screw rotates, allowing particles to make their way across the system while moving in a helical path. Figure 1, seen above, is a CAD drawing which displays a typical screw conveyor, along with its general components. This section provides an overview of the designation of each number on this figure. Generally, a screw conveyor includes a screw (1) mounted on a pipe, enclosed within a casing called the trough (18). The shaft is driven at one end by a motor and supported at the other end with a bearing. Two end bearings can be seen in the system above (10), each mounted on an end plate (12) and a shaft seal (11). The end plate, or trough end (12), supports the conveyor drive shaft (2) and end (tail) shaft (4). It may be furnished with a choice of bearings or thrust bearings, as shown in this case. The thrust bearing holds the rotating conveyor screw in position. Shaft seals (11) are used in the trough ends to prevent leakage into or out of
the trough. They also protect the trough’s end bearings from material leakage and the material being conveyed from the bearing lubricant. There is also an internal hanger bearing (7), fastened to a hanger (6) which is fixed to the covers (5). Hangers provide support, maintain alignment and serve as bearing surfaces. Moreover, hangers are used as an intermediate support between two sections of a conveyor screw. They help maintain alignment and provide a bearing surface for the coupling shaft. Couplings and shafts (drive and end shafts) connect and transmit the rotary motion to subsequent screw conveyors. In fact, the conveyor drive shaft (2) transmits the rotary motion from the drive unit to the conveyor screw, while the end (tail) shaft (4) supports the conveyor screw. Internal collars/bushings (13), coupling bolts (14) and bolt pads (15) serving as fixing/coupling mechanisms are largely used. Lastly, the trough is aligned and fastened to the floor or existing structures through support stands at intermediate locations, called supporting feet and saddles (9). Supporting feet provide the means of aligning and fastening the trough to the floor or existing structure at the trough joints. On the other hand, saddles are used to support the trough between the trough sections and fasten to the floor or existing structures. The whole system also accommodates an inlet (17) and a discharge (8), in which the inlet and discharge openings may be located wherever needed.

2.1.2 Description of the proposed design

In order to fulfill the upward conveyance desired by the client, the proposed design consists of an inclined screw feeding system. More precisely, it consists of a reversed L-shape feeder, as the inclined section of the system is directly followed by a vertical section (see figure 2). This vertical section conveys the feedstock uniformly, at a controlled rate, into the gasifier’s combustion zone. For safety reasons, a clearance of 6 inch, or 15.24 cm, between this zone and the auger was requested by the client. Moreover, the proposed system does not carry a discharge spout; instead, the discharge of the feedstock out of the feeding system is effectuated at the smooth transition zone between the vertical pipe of the system and the gasifier. An inclined screw feeder was selected, as the transition of the flow from the inclined section into the vertical section would be smoother and steadier.

Figure 2: Cross-sectional front view of the proposed design

The design of inclined screw feeders needs to take into account some modified parameters, such as the requirement of more HP due to both lifting the material and “reconvening” the material that falls back. A higher speed can also help overcome the tendency
of material to fall back (Source: "Screw Conveyor Components & Design", 2016). In addition, in order to suit our needs, the designed inclined screw feeder accommodated certain variations in the design, when compared to the standard unit. An important adjustment incorporated in our design was the elimination of hangers, as they were expected to create a “dead flow” area, which is emphasized within inclined screw conveyors. In fact, hangers were eliminated to ensure a better flow. Moreover, tighter clearance between the screw and the trough was required. Screw clearance is defined as the diametrical distance between the rotating flight and its stationary housing wall. Certain tests determined that increasing the screw clearance caused the volumetric capacity of the conveyors to be decreased. This may be due to a decrease in the active layer (the layer which is conveyed by the rotation of the auger) of the conveying grains as a result of increasing the distance between the screw rotating flight and conveyor housing (Zareiforoush, Komarizadeh, Alizadeh & Masoomi, 2010). The inefficiency in conveyance due to a large clearance is even more emphasized with inclined screw feeders, as materials have a larger tendency to fall back down. Furthermore, other aids in conveying feed for an inclined screw are the use of short pitch and tubular housings (smaller than the standard lengths), which will be described in depth in the following paper.

Moreover, the performance of a screw conveyor, which is characterized by its capacity, volumetric efficiency, and power requirements, is affected by the conveyor’s geometry and size, the properties of the material being conveyed, and the conveyor’s operating parameters such as the screw's rotational speed and the conveying angle (Zareiforoush, Komarizadeh, Alizadeh & Masoomi, 2010). If it is not designed in favor of the transported materials, potential problems include: surging and unsteady flow rates, inaccurate metering and dosing, inhomogeneity of the product, product degradation, excessive power draw, high start-up torques, high equipment wear and variable residence time and segregation (Owen, 2009). In fact, the efficient screw feeder design requires an in-depth knowledge of bulk solids and powder flow properties and characteristics, as the type of material being moved can have a significant effect on the size and type of conveyor needed. For this purpose, material classification and characteristics charts were used as guidance to select the proper conveyor components.

The system was designed to convey wood chips, as instructed by the client. The Screw Conveyor Corporation Catalogue and Engineering Manual was consulted to determine the necessary design data, i.e. the screw conveyor size and speed. According to this catalogue, wood chips are classified as the following:

- Weight: 10 - 30 lbs/ft³ (160.185 – 480.554 kg/m³)
- Material Class: 20 D 3 45 V Y
- Component Group: 2A-2B

The system is required to transport approximately 42 kg h⁻¹ of biomass and the chosen biomass for design calculations is wood chips with a bulk density of 481 kg m⁻³. Therefore, the required capacity for the system is 0.087 m³/hr⁻¹.

Knowing the material classification and the required capacity, which is 3.06 ft³/h (0.087 m³/h), the Capacity Chart (see Figure 3) was consulted in order to determine the conveyor size and speed, proceeded as the following:
1. The first letter and the last two numbers of the material class, hence D-45, indicating the Material Class Code, is associated with Non-Abrasive Materials.

2. Size can be determined by being at or less than maximum cubic feet per hour. As the capacity is very low, the smallest capacity available by the chart was selected, which corresponded to a screw diameter of 6 in (15.24 cm).

3. The exact conveyor speed is determined by dividing the required capacity in cubic feet per hour by cubic feet per hour at 1 revolution per minute.

Conveyor speed = \[\frac{3.061972222 \text{ ft}^3}{1.49} = 2.05 = 2 \text{ RPM}\]

The obtained value for the operating speed is therefore in conformance with the previously obtained value, and was verified with the client to meet the requirements, as the system would run continuously, at a very low and steady speed.

Moreover, upon consultation of the catalogue “Screw Conveyor Components & Design”, for component groups 2A-2B and for a screw conveyor diameter of 6in (15.24 cm), the
associated shaft diameter was determined to be 1 ½ in (3.81 cm). This parameter of the shaft is very important, as it shapes the design of several other components, such as the trough end, the end bearing, and the end seal. The design of these components is detailed further down in the report.

### 2.1.3 Auger

Screw feeding is the process of delivering bulk solid materials from one point to another. The screw rotates, allowing particles to make their way across the system while moving in a helical path. Once the screw conveyor receives the feedstock, the material is compressed in order to form a barrier to prevent backflow of gases and bed material (Cummer, 2002). The quantity of feed that can be displaced by the mechanism depends on the screw flight diameter, the shaft diameter, the distance of the pitch i.e. the distance between two neighbouring peaks, and eventually the angle of inclination of the system. Indeed, inclined screw conveyors require a reduced pitch to overcome the inefficiency of the helix of the screw flight, at the particular operating angle. Thus, by altering these parameters screw conveyors have versatility to condition powders and bulk solids.

a. **Shaftless vs Shafted**

First of all, the possibility of having a screw with a shaft or without a shaft needs to be considered. The main difference between these two models of screw conveyors lies in the screw/spiral configuration. A shafted screw has a center pipe that supports the screw flight, whereas the shaftless screw conveyor does not require such a pipe. The shaftless screw conveyor is normally used for the handling of sewage sludge, pulp and wood chips. In other words, it is used to handle sticky and sluggish bulk materials, in order to allow the flow movement of the material. Shaftless screw conveyors are also known for their low RPM values and their ability to enable higher material loading through the conveyor. Another advantage involves the way it minimises problems of jamming and build up. Lastly, when using a shaftless screw, the use of hanger bearings or internal bearings can be avoided; hence, maintenance is reduced, along with the overall cost. On the other hand, shafted screw conveyors are easier to use and have better efficiency for conveying a variety of bulk material. This type of screw conveyor is driven at one end by a gearbox and/or a motor and on the other end by a bearing to support the screw (S2S Industries, 2016). Indeed, this type of screw conveyor is mainly used when the material is considered easier to convey. Thus, with the use of an inclined screw feeder, a shafted screw would be ideal as it prevents the backflow of the material (KWS, 2016), in opposed to shaftless screw, in which material has a greater tendency fall back.

b. **Pitch and Flight**

The Kase Conveyors Company presents many of the different types of screw conveyors that currently exist. The differences arise from the unique pitch and flight type combination. For our purposed design, three choices were retained:

1. Short/half pitch, single flight
2. Variable pitch, single flight
3. Tapered, standard pitch, single flight

First of, the short/half pitch-single flight is represented with a reduced pitch of 2/3 or ½ of the standard screw diameter. This configuration is ideal for inclined and vertical screw conveyors. A shorter pitch is also associated with a better handling of free-flowing/fluid material. These are also recommended for their high mixing degree and high filling fraction of the screw. Next, the variable pitch-single flight is a pitch that increases throughout the length of the screw. This configuration allows for a smoother and more uniform movement of the material. The third option was the tapered-standard pitch, single flight, where the flight increases from 2/3 of the diameter to its full value along the screw, generally used for lumpy materials.

Finally, in choosing the right configuration, the ratio between the pitch and the screw, along with the dimension of the feed channel must be considered. These values are recommended to be greater than 0.25 when considering the ratio between the pitch and the screw and at least two times the feed’s dimensions for the feed channel. In fact, a short pitch screw flight, as well as a higher screw speed are required in order to obtain a cleaner upwards movement of the biomass (Kase Custom Conveyor, 2016). Because of the high costs and complexity associated with the second and third options, the standard, single flight screw, with a reduced pitch (1/2 pitch) was chosen. Standard pitch screws usually have a pitch equal to the outer diameter of the helical blade.

In regards to the flight Construction Style, there are 4 models to consider:

1. Helicoid Flighting
2. Sectional Flighting
3. Ribbon Flighting
4. Cut Flighting
5. Cut and Fold Flighting

A helicoid flighting consists of a continuous and symmetrical helix that extends all throughout the shaft. The sectional flighting is similar to the helicoid flighting, however the helix is formed from a steel plate, in which there is a significant difference between the lead and the pitch. The ribbon flights are commonly used to handle sticky material and their design differs from the others, as the helix is much thinner. Finally, the cut flighting was also considered, this model is represented with notches cut in the periphery of the screw (Continental, 1966). For simplicity and cost-effectiveness, a helicoid flighting was chosen as the main auger component. The flight thickness of the auger system varies in size, depending on different factors of the auger and its use. Diameters of 3/16, ¼, ⅜ and ½ inches are available for purchase (Continental, 1966). In order to reach a better feedstock compression throughout the screw, a larger thickness of flighting, i.e. ⅜ in, was selected.

The different parameters of the auger are presented in figure 4. The shaft diameter of 1.5in, as well as the screw conveyor’s outer diameter of 6in, hence 2.25in on each side of the shaft, are
displayed. Moreover, the screw flighting thickness of 3/8in, or 0.38in, as well as the pitch of the auger, 3in, which is half of the conveyor’s diameter, are also shown.

![Figure 4: Design of screw with its different components](image)

### 2.1.4 Air control System at the Inlet

Imbalances in the gasification occur when pressure fluctuations take place during the reaction. One of the causes of such a problem is related to air entering the unit. In the current system, a vacuum was produced with the use of a venturi and an air compressor in order to attempt to eliminate fluctuations in the reactor during the combustion (Madadian et al., 2016). This could also be incorporated with the new system, however if high fluctuations continue to occur and lead to inefficient production, a means to further prevent this must be considered. One device commonly used for feeding solids to pneumatic systems is a rotary valve or rotary air lock (Woodcock & Mason, 1987). This motor driven device continuously feeds material from a hopper above the rotary airlock and directs it to the outlet below. Its function is to act as a seal between its inlet and outlet ports (Mace, n.d). If situated above the screw feeder, it can further prevent air leakage in and out of the feeding system, which could aid in stabilizing the pressure during combustion. Proper implementation of the device must be applied in order for the screw feeder to always be loaded at full capacity. The two main rotor forms are the open end or closed end. In the “open end” configuration the blades are welded to the rotating shaft whereas in the “close end” configuration the blades are welded to the shaft, however its blade ends form enclosed pockets. The open-end rotor, although less expensive, presents various disadvantages such as weakening of the rotor housing when used with more abrasive material and low rigidity when compared to the “close end” configuration (Woodcock & Mason, 1987).
2.1.5 **Screw Conveyor Drives**

Drive components of screw conveyors are available in a wide variety and are used in transmitting the necessary rotary motion to the screw. Integral or fractional horsepower motors can be coupled with many different types of gear reducers, which, in turn, are directly connected to the screw through a coupling, roller chain or V-belt (*Screw Conveyor Components & Design Catalogue*). Also, this catalogue demonstrates different drive arrangements available (see Figure 6).

![Figure 5: Rotary Airlock Sketch](image)

**Figure 5**: Rotary Airlock Sketch

![Figure 6](image)

**Figure 6**: Typical complete drive arrangements (Source: *Screw Conveyor Components & Design*)
In a “Direct Coupled In-line Drive”, the motor, reducer and conveyor drive shaft are mounted in-line and directly coupled together. It is typically supported by a drive base attached to the floor or the conveyor’s end plate. This is said to be the best configuration for longer component life of larger conveyors. In the second arrangement, “Screw Conveyor Drive”, the reducer is mounted on the trough end and has its own drive shaft, which is directly connected to the conveyor screw. The reducer includes integral thrust bearing and seal; hence, the separate drive shaft, end bearing, and seal are not required. The motor is connected via V-belt and may be mounted at the top, either side or below. In the third arrangement, “Shaft Mount Drive”, the layout is similar to the previous arrangement, however, the bearing, seal and drive shaft are not included with the reducer; instead, the reducer mounts onto the extended version of the standard conveyor drive shaft. This allows the use of a variety of bearings and seals. Lastly, in the “Helical Reducer with Chain & Sprockets” arrangement, the motor is assembled to the conveyor drive shaft through a chain drive. Usually, it is mounted to the side of the trough by means of an adapter plate. In the proposed design, the drive assembly, consisting of the output shaft, the conveyor thrust bearing, end seal and trough end, were designed as the “Direct Coupled In-Line Drive”, i.e. all these components were combined into one complete drive unit (See Figure 7).

Figure 7: Side view of the system, showing the drive assembly

The motor proposed for this design is a compact round-face DC-2 rpm gear motor. A gear motor is ultimately a motor mounted with a speed reducer in order to reduce the overall speed while increasing torque. In other words, a gear motor is a motor and a gearbox all in one system. This system was chosen in order to reduce cost and increase efficiency and simplicity of the process. The shaft of the motor would be connected to the shaft of the screw conveyor through a shaft coupling. A flexible shaft coupling is recommended, as a misalignment between
the shafts is accepted with these couplings. An Over-Torque-Prevention Vibration-Damping Flexible Shaft Coupling (McMaster, N.D) is suggested, as it serves as a safety mechanism as well. As mentioned, in time this system could also serve as an electrical safety mechanism. In fact, this type of coupling protects the power-transmission components from any damages. In case of over-torque conditions, the coupling will shear or tear, to sever connections between shafts. They are composed of steel hubs and a flexible neoprene center that not only compensates for misalignment, but also dampens vibration and shock loads. Moreover, another advantage of these couplings is the fact that they have no metal-on-metal contact, hence reducing noise and eliminating the need for lubrication. They are easily fastened to the shafts with two set screws, which bite into the shafts for a tight hold.

On the other hand, other devices such as shear pins and torque limiters could also be used as overload protection, to shut off power whenever the operation of the conveyor is stopped as a result of excessive material, foreign objects, excessively large lumps, etc. (Screw Conveyor Manual). However, as the over-torque prevention couplings could serve as a dual purpose, they would be the most cost-economical safety mechanism. When designing such complex systems, safety aspects have to be incorporated in the design. In a gasifier, the parameters that are carefully monitored include the temperature and pressure variations, through the sensors. Moreover, conveying material from one place to another, especially at an inclined angle, can turn out to be tricky, as material can jam within the system. Blockage occurs due to the overload of a material, creating an inefficient flow within the feeding system. When this occurs, the flow of the feedstock is interrupted along with the airflow inside the main reactor. This results in a destabilization in the combustion zone. In extreme cases, bridging could ultimately stop the whole gasification process.

The other components seen on Figure 7, apart from the motor and the coupling, are the through end, the shaft seal and the end shaft bearing. With the selection of a clearance of 0.2 in (0.51 cm) on each side between the casing and the auger, along with the determined shaft diameter value (1.5in), the appropriate dimensions for the trough end, the end bearing and the end seal were determined from catalogues. Firstly, the design of the trough end was achieved through consultation of the Martin Sprocket & Gear catalogue. This manufacturer offers different designs of trough ends, available for different purposes (see Figure 8). In our case, an outside tubular trough end with feet is recommended. This type of trough ends is used to support the end bearing where trough support is required. Drilling for bronze bearing or flanged ball bearing is said to be the standard (Martins Sprocket & Gear catalogue).
For a conveyor diameter of 6 in (15.24 cm) and a shaft diameter of 1 ½ in (3.81 cm), the following dimensions were retained from the catalogue (see Table 1 and Figure 9).

Table 1: Dimensions corresponding to the designated letters on Figure 5

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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1 ½</td>
<td>5.06</td>
<td>5.62</td>
<td>3.69</td>
<td>8.12</td>
<td>1</td>
<td>1.75</td>
<td>0.25</td>
<td>10.12</td>
<td>0.37</td>
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</tr>
</tbody>
</table>
The Screw Conveyor Components & Design catalogue was further used for the shaft seals’ design. Using a standard plate seal, the following dimensions were obtained (see Table 2 and Figure 10):

<table>
<thead>
<tr>
<th>Shaft Diameter (in)</th>
<th>B (in)</th>
<th>C (in)</th>
<th>D (in)</th>
<th>Bolts (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ½</td>
<td>5.37</td>
<td>4.12</td>
<td>4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A flange-mounted roller bearing was selected as the end bearing to be incorporated with the trough end and the shaft seal. These bearings are designed for combined thrust and radial loading. It does not allow for expansion and is typically located at the drive end of a conveyor. The following dimensions were applied (See Table 3 and Figure 11):
Table 3: Dimensions corresponding to the designated letters on Figure 11

<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ½</td>
<td>3.37</td>
<td>5.37</td>
<td>2.97</td>
<td>4.12</td>
<td>0.12</td>
<td>1.19</td>
<td>4.19</td>
<td>3.19</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 11: End Bearing Design (Source: Screw Conveyor Components & Design catalogue)

2.1.6 Bearings

There are many types of bearings available on the market for different purposes and applications. They vary in size, shape, utility, material and price. The main purpose of a bearing is to enable rotational movement and reduce the friction of a rotating object with its surroundings. In the case of a feeding system for a gasifier, a bearing will be needed at both ends of the auger. As referred to by the client, the speed of the screw will be as low as 2 rpm, thus the end bearing could be negligible, however for optimum conditions a swivel bearing would be installed.

Long screw conveyors require a centre shaft support bearing (hanger bearing) to limit the deflection of the spiral. For the system, a centre shaft support bearing does not need to be incorporated as the overall conveying distance is short, i.e. only 1m. However, end bearings will be necessary.

For the feeding system, a swivel and a thrust bearing are considered in the design. Thus, the supporting thrust bearing will be on the lower end at the beginning of the shaft. The main function of a thrust bearing is to manage loads and provide high-shock-load resistance (The Timken Company, 2016). As for the swivel bearing this would be mounted on the outside surface of the casing, on an additional perpendicular plaque to support the bearing.
2.1.7 Casing

For inclined screw feeding, the type of casings that are usually recommended are tubular troughs or shrouded troughs. These casings aim to closely surround the screw and prevent the feedstock from falling back down the auger (Screw Conveyor Components & Design, 2013). The two existing forms of tube troughs are solid tube trough and formed flange tube trough. Although the latter allows dismantling of the trough, the former is more economical and can still be dismantled at a trough end.

Moreover, for inclined feeding, a tighter clearance between the screw and trough, i.e. the distance between the outer edge of the screw blade and internal surface of the casing, must be chosen (Screw Conveyor Components & Design, 2013). This is particularly important for granular materials including wood chips.

![Figure 12: Casing of the screw feeding system](image)

2.1.8 Inclination

Inclined screw feeders allow for an elevation of the feedstock, however, the screw feeder’s capacity will change with different angles of inclination. In fact, the higher the angle of inclination the smaller the capacity of the feeder. If a standard screw feeder is inclined upwards by 15°, it will carry 75% of its horizontal capacity (Catalog and Engineering Manual, 2010). Another consideration to take into account with inclined feeding is that they have a greater horsepower requirement, when compared to horizontal feeding. Therefore, a lower angle of inclination is proven to be more efficient. With the appropriate modifications mentioned in previous sections, such as tubular trough, short pitch and tight clearance, capacity losses could be decreased.
2.2 Cost Estimation

A cost analysis of the feeder components was undertaken in order to determine the overall cost of the system, which excludes the assembly and manufacturing costs. The majority of the components were found on the McMaster online manufacturing website, except for the rotary airlock. The rotary airlock was found at Wenzhou Longva Light Industrial Machinery Co., Ltd., along with its corresponding motor. All of these components respect the dimensions presented earlier. Finally, the overall cost for this system was set at 1960.95$, which respects the budget that was defined by the client.

<table>
<thead>
<tr>
<th>Feeder Components</th>
<th>Price ($)</th>
</tr>
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<tbody>
<tr>
<td>Auger</td>
<td>62.68</td>
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<tr>
<td>Motor</td>
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</tr>
<tr>
<td>Coupling</td>
<td>88.34</td>
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<tr>
<td>Casing</td>
<td>720.78</td>
</tr>
<tr>
<td>Bearings &amp; Seals &amp; Trough End</td>
<td>92.60 + 111.9 + 72.23</td>
</tr>
<tr>
<td>Rotary airlock*</td>
<td>500</td>
</tr>
<tr>
<td>Support</td>
<td>200</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1960.95$</td>
</tr>
</tbody>
</table>

Prices were taken from McMaster online manufacturer
* Rotary Airlock from Wenzhou Longva Light Industrial Machinery Co., Ltd.

3. Prototyping

3.1 Prototype Components

In order to understand and evaluate the different components of the feeding system, the following device was built (figure 13). The purpose of the prototype is to test certain factors, such as the proper feed capacity that can be inserted into the system and the appropriate angle of inclination. The prototype is also used to demonstrate the way the feed moves up the inclined auger and makes it way to the base of the gasifier. The following will describe the main components of the feeding system.
Auger

The auger (figure 14) was designed by using a PVC pipe and plastic cardboard to create the screw. The PVC shaft has an outside diameter of 7/8in (2.22cm) and a length of 20.87in (53cm), while the screw diameter is 3in (7.62cm) and the pitch is approximately 1.20in (3.05cm). The helical shape was made by cutting 3inch diameter circles from the plastic cardboard and by using hot glue to strategically glue each piece together. The auger begins at point 1 and stops at point 2, as shown on figure 13. Since it extends on the right side of the inlet, feedstock that falls behind can easily be picked up by the auger and pushed upwards.

Casing

The casing is made out of a rolled up clear plastic sheet (D) as seen in the figure below, and is connected to an inlet and an outlet. Both connections are made out of PVC plastic. The inlet, known as a T section (A), has a diameter of 3in (7.62cm), as does the outlet (B), called the elbow. The outlet has a certain curvature, allowing the material to move upwards in a smoother motion. The plastic casing was connected to both ends by the use of hot glue and black electric tape.
**Motor & Shaft**

The motor is a 12 V DC motor with 15 rpm, considered as being a high torque motor. The shaft is connected to the motor and auger through a half inch copper adaptor (E). The connector contains aluminium inside the end that is connecting the motor, in order to fill the space within the piece. The copper adaptor is fixed to the auger by a screw and the motor is strapped down on a piece of wood support with plastic straps. There is an on/off switch (F) located under the motor, which is powered by the electric grid, through electric wires, as shown in the figure below.
Wood support

A 3/8-inch (0.95cm) compressed wood platform, with a length of 22.64in (57.5cm) and a width of 6.9in (17.5cm), was used to provide support to the entire unit (G). The system sits on a 0.30in (0.76cm) thick wood base, which is connected to the bottom wood support by 2 hinges, that allow the change in elevation (I). The inlet and outlet rest on a wood piece, which was connected to the base with wood glue and plastic straps. The motor also sets on 2 smaller piece of wood (J) in order to be at the same elevation as the auger. There are also two wood columns 18.9 x 1.78 x 0.6 inches (48 x 4.5 x 1.5 cm), one located on each side of the device, with holes indicating the different possible angles, ranging from 15 to 45 degrees. A cylindrical shaped wood piece of 0.4in (1cm) in diameter is used to set the unit on the desired angle as seen on the bottom of point K. Furthermore, the wood piece seen in point H is used as a resting point for the unit. Small pieces of rubber were added on the H piece, in order to soften the contact between both wood pieces. Each wood piece included in the design was smoothened with sand paper and joined together by the use of wood glue.

3.2 Prototype considerations & testing

Physical Design

In order to determine the most efficient screw feeding system, a series of tests were performed on the prototype. For example, the prototype was initially constructed with an inlet similar to the elbow outtake B seen on figure 13. However, it was quickly discovered that the auger was not close enough to the inserted feedstock to begin the movement. In fact, the feed had to be manually pushed towards the auger, which defeats the purpose of the design. Therefore, a t-section inlet was put in place, which easily maneuvered the material. The outlet was also modified in order to ensure that, once enough feedstock accumulated at the top, the continuous feeding would allow the material to push itself upwards, until it reached an appropriate height. At first, the outlet had a smaller curvature, which created a greater distance for the material to travel and therefore required more time for the material to reach the top of the system. Therefore, the greater curvature allowed for a smoother and easier rise for the material once it reached the end of the auger.

Feedstock

Many different types of feedstock were tested for the prototype. The first material that was tested were wood chips. The main issue related to the prototype’s design is the fact that the space between the casing and the auger was too large, therefore, wood chips would get stuck in between, affecting the auger’s overall flow. The large scale model, however, is designed to be capable of taking in wood chips. The next material that was tested was rice. Rice flowed much smoother than the wood chips, however the size of the material was too small, and therefore required a high load in order to push itself upwards once the outlet was reached. The most efficient feedstock was found to be chickpeas. The material’s round shape allowed it to smoothly flow through the auger without getting stuck between the casing. The feedstock was also heavy enough to properly push itself towards the combustion zone. However, due to its weight, an
overload would cause too much stress on the motor, therefore the material had to be added in moderation.

**Angle of Inclination**

The most effective test involved loading the auger with a 60-gram capacity and running the motor for a minute and 30 seconds. The purpose of the test was to see how much material would make its way to the end of the auger, when the angle varied from 15 to 45 degrees. It was shown that as the angle increased, the final weight of the material decreased, which means it became more difficult for the material to move across the auger. In fact, in order for the other angles to achieve the same results as the 15-degree angle, more power would have to be supplied to the system. Evidently, the most efficient angle is the smallest one within the range, which is $15^\circ$, as seen in the following table:

<table>
<thead>
<tr>
<th>Angle of Inclination ($^\circ$)</th>
<th>Weight of material (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>43</td>
</tr>
<tr>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>25</td>
<td>30</td>
</tr>
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<td>30</td>
<td>29</td>
</tr>
<tr>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>45</td>
<td>13</td>
</tr>
</tbody>
</table>

**4. Testing**

**4.1 Analysis of the possible failure modes**

The development of the feeding system for the gasification process has various risks that need to be considered. In fact, there are multiple ways in which the system can fail, whether the issues are coming from the auger itself, or anything linked to its movement. First off, there is a possibility of jamming in the feeder; in other words, too much feed is inserted into the system, causing an overload on the auger, which results in its malfunction. This issue can also be linked to a glitch in the sensor, causing its failure to regulate the biomass intake. Next, the motor can experience some technical difficulties, resulting in its failure, which will also affect the performance of the auger. Another issue related to the feeding system is having a high air intake, which can affect the gasification process, thereby creating an inefficient production of syngas. The potential failures of each component, along with their effects on the whole system will be analysed using the “bottom to top” and “top to bottom” concepts.
4.1.1 Bottom to top

The bottom to top analysis is in regards to the components of the system that comprise the whole feeding system. The main components of the feeding system are thereby; the auger, the motor, the shear bolts and the air compressor mechanism. The failure mode of each component is therefore studied.

- Auger: The auger system conveys the feedstock all the way to the gasifier’s entrance. Therefore, the auger can suffer through bridging, where there is an excess input of biomass causing a stress on the component, resulting in its stoppage. The auger can also fail if the motor ceases to function. A non-mechanical failure would be its inability to convey the material up the feeding system. The auger is the component that is driving the biomass into the gasifier, therefore, its failure would result in the failure of the entire unit to fulfill its duties.

- Motor: The motor is the main driver of the auger. It can suffer through different mechanical failures. Failures can arise from a transient voltage or a voltage imbalance. The motor can also suffer from a mechanical misalignment or an operational overload, causing it to overheat and malfunction. The failure of the motor would indeed stop the gasification process, however would not require the system to be rebuilt. The motor would be replaced and connected to the linked components.

- Rotary Airlock: The main role of the air valve in this unit is to limit the air intake in the system, by forming a seal in the opening whenever feed is not being conveyed. Thus, operational and mechanical failures are possible. Incorporating an airlock rotary valve into this system could be challenging, because of the continuous feeding system, hence constant entry of air. Moreover, the feeder is directly connected to the gasifier where gas exchange is constantly occurring. An inappropriate installation could directly affect the minimization of air intake, hence operational failure down the road, affecting the whole gasification process. This rotary airlock also includes a motor to drive the valves, therefore a failure in the motor in itself could affect the rotary airlock and thus the system would not be considered as airtight and could eventually cause damages to the gasification process.

4.1.2 Top to bottom

Considering the fact that the system was designed in order to prevent bridging from occurring, a disastrous system failure would include the reproduction of this initial issue (see figure 17). Bridging of the biomass would cause the failure of the auger, which in turn, would interrupt the whole gasification process. This failure mode has in fact multiple causes, such as material overload, or the use of a very dense material. The worst-case scenario would then involve the auger failing to uplift the material going against gravity into the gasifier, which is the whole purpose of this design. Deflection can also be experienced due to the screw weight. Deflection is rarely a problem; however, it should be held to a minimum in order to increase the useful life of the screw. Excessive end angle can significantly reduce shaft and bearing life. Moreover, as the spiral rotates, it is subject to cyclic fatigue. Therefore, it is important to
maximize the end bearing (and hanger bearing) and shaft seal life, as well as minimize cyclic fatigue on the screw conveyor drive connections, to straighten the screw spiral assembly after fabrication.

![Diagram](image)

Figure 17: General top to bottom failure system of the screw feeder

5. **Optimization**

One means of achieving compression of feedstock within a screw feeding system is by tapering the feed channel (Dai & Grace, 2008). This would form a plug of material which acts as a barrier in order to prevent gas backflow from the reactor. Dai and Grace (2008) tested different tapered and extended sections with a screw feeding system that transported different materials such as wood shavings and wood pellets. Their results for torque requirements deviated from the model predictions for the performance of wood chips in a tapered casing. Both lengths of 0.15m and 0.3m were tested with a diameter change of 1.4cm and screw rotational speed of around 40 rpm. Blockages occurred with both lengths, however since the rotational speed is only 2 rpm in the new feeding system, different results would be expected. Longer choke sections and tapered sections although predicted to result in a better seal, have a higher risk of blockage and increase the torque requirements (Dai & Grace, 2008).

Standard screw feeders are manufactured with a uniform pitch, however designing a screw with a decreasing pitch can also aid in generating a plug of material. Uniform pitch screws do not feed against pressure gradients and therefore, the formation of a plug with a decreasing pitch screw can act as a pressure seal preventing pressure leakages between the feeder casing and reactor (Woodcock & Mason, 1987). Since the new feeding system has a vertical section, the plug could jam when trying to move within this section. In order to try and avoid this problem, recommendations from manufactures could aid in designing a decreasing pitch screw where the material in the plug is not greatly compressed, which would allow the conveying of the material into the vertical part.
6. Conclusion

To conclude, the goal of the research was to design and prototype an inclined screw feeding system that would serve as the main feeder for a gasification process. Many criteria and constraints had to be respected in order to fulfill the client’s needs. Having continuous feeding at low speed, a maximum intake of 1000 kg per day and stable pressure throughout the system were the most essential ones to consider. Indeed, many components had to be understood, in order to increase the efficiency of the process. As presented, a prototype was built to demonstrate the functionality of the feeder when conveying biomass/feedstock upwards in an incline motion. Various tests were also performed to determine the most effective angle of inclination, which was shown to be 15°. However, such as in any system there were certain flaws, which required future optimization that were considered and presented to the client for future recommendations.

7. Acknowledgements

The team would like to acknowledge all the individuals who sacrificed a tremendous amount of time and energy to help us during our research process. A special thank you to our mentor Dr. Mark Lefsrud for providing useful information and guidance in order for us to achieve our design goal, Professor Grant Clark for his constant support and advice. And finally, a big thank you to Edris Madadian and Dr. Abdolhamid Akbarzadeh Shafaroudi for their cooperation and shared knowledge on the topic. This project would not have been possible without the help of each and everyone.

8. Competition Entered

The competition we will be entering is within the ASABE organization: The AGCO National Student Competition. This competition is designed for students in an environmental/ agricultural related field in order for them to present their innovative design project to a group of professionals.
9. References

AGCO National Student Design Competition: Deadline April 27th, 2016

http://www.screwconveyor.com/assets/1/7/Engineering_Catalog_1-2010.pdf


