

Development and Evaluation of Straw Chopping System for Fluidized Bed Gasifiers

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-----ABSTRACT-----

A straw chopping system, designed to provide continuous flow of straw to a fluidized bed gasifier, was constructed and evaluated. The system consists of a frame, a revolving chute, a cutting drum, a depth of cut controlling mechanism, a concave, an output hopper and a power unit. The performance characteristics (rotational speed, feed rate, depth of cut, length of cut and the energy required for chopping of straw) were determined. The chopping of straw was achieved with low energy consumption due to the proper design of the input hopper in that provided a uniform cutting of straw from the bale, the design of the input cutting mechanism with adjustable depth of cut and the correct sizing of the output hopper to provide an efficient removal of uniformly chopped straw. Both the depth of cut and the cutting speed significantly affected the length of straw, the straw feed rate and the power required for cutting the straw. Decreasing the depth of cut and/or increasing the cutting speed increased the straw feed rate while increasing the depth of cut and/or increasing the cutting speed increased the power consumption and decreased the straw length. The feed rate for chopping straw ranged from 1.48 to 10.52 kg/min, the power consumption ranged from 1.76 to 7.76 hp and straw length ranged from 14.49 to 18.85 mm, depending upon the depth of cut and cutting speed used. The unit power (hp.h/t) improved with increases in the cutting speed due to increases in the feed rate. The energy of cut was less than 0.2% of the energy content of the straw. The sieve analysis of the sample indicated that 85-90% of the samples were collected in the sieves 2 (2.38 mm). The remaining 10-15% had a straw length of 0.59-2.38 mm.

KEYWORDS: Biomass, cereal straw, chopping, feeding, continuous flow, fluidized bed, gasification.

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I. INTRODUCTION

Cereal straw, the most abundantly available agricultural crop residue is an excellent fuel for thermochemical conversion (combustion and/or gasification) with relatively low ash content(5%) and high energy content (17.4 gigajoules/tonnes) (Jenkins et al., 1998). However, the problem often encountered during straw use stems mainly from its poor physical form and low bulk density (40-50 kg/m³) (Tabil et al., 2011). Straw is collected and transported in small bales (46 cm x 48 cm x 70 cm), large cube bales (1.8 m length) or large round bales (1.8 m length x 1.8 m diameter). The direct combustion of the small and large bales has lower energy recovery efficiency. Dense smoke and particulate emissions are always associated with this type of operation (Natalapati et al., 2007). Slag formation occurs as a result of high temperature (1200-1400°C) which also causes deterioration of the metal after burner and firebrick lining (Gilbe et al., 2008). In order to maximize the utilization factor and to address these problems, a fluidized bed gasification system utilizing biomass materials has been developed and used successfully (Sadaka et al., 2002).

However, the gasification system requires a continuous flow of chopped straw that is consistent in length. Straw, being a highly pliable material, represents difficult conditions in cutting operation and can easily bind up the cuttings edges and stall out the power source. Thus, the chief objective of chopping baled straw is to reduce the material to a length that can be handled by a screw feeder. A theoretical cut of 1.5 to 2.0 cm is usually fine enough for gasification purpose (Brigidewater, 1995; Werther et al., 2000). Kargbo et al. (2009) reported that the large sized agricultural feed stock causes fuel conversion efficiency problems such as incomplete combustion of biomass. Particle size of the biomass also influences the heat transfer. Jenkins et al. (1998) stated that smaller sized biomass materials are thermally thin and it heats up rapidly, while coarser and

larger particles are thermally thick and heats up very slowly. Thompson et al. (2003) reported that the chopped straw (≤ 1.9 cm) was not physically separated and the contact surface area and the mass are increased due to chopping of straw. Mani et al. (2004) reported that particle size reduction increases the total surface area, pore size of the material and the number of contact points and reduces the cellulose crystallinity which is required for the thermochemical conversion of feedstock during gasification.

The theoretical length of cut (the amount of advance of the feed mechanism between the cuts of successive knives) and energy requirement for the size reduction are affected by the cutting speed, the initial particles size, moisture content, material properties, feed rate of the material, the diameter of the holes in the concave and the knives - concave clearance (Ghaly, 1973; Tavakoli et al., 2009). Tavakoli et al. (2009) studied the effects of drum speed, screen size and number of blades on each flange on the power requirement for the size reduction of wheat straw. They reported that the power requirement increased with increases in the drum speed (from 500 to 800 rpm) and decreases in screen size (from 4 cm to 2.5 cm) and number of blades (from 8 to 4) in each flange. The power requirement for the size reduction of wheat straw ranged between 0.985-5.377 kW and the average power requirement was 2.763 kW. Ghaly (1973) studied the effects of rotational speed and concave - hole diameter on the length of straw and the energy of cut. Concaves having hole diameters ranging from 22 mm to 45 mm and rotational speeds ranging from 500 to 1200 rpm (2100 to 5000 m/min) were investigated. The length of straw varied from 2.5 to 6.0 cm. The energy of cut (hp-h/t) remained constant. Increasing the hole diameter and decreasing the speed increased the length of straw. However, speed higher than 900 rpm did not significantly reduce the length of straw.

The aims of this study were to: (a) design, construct and evaluate a straw chopping system that will chop baled straw (small bale) and transfer chopped material to the fuel feeding unit and (b) to study the effects of speed and depth of cut on the feed rate, the cutting energy and length of straw.

II. DEVELOPMENT OF STRAW CHOPPING SYSTEM

The straw chopping system (Figure 1) was designed for chopping (small bales of straw). The system consisted of: (a) a frame, which is used to raise the chopping drum and the hopper to a level where the chopped straw could be easily transported to the straw feeding unit, and provide mounting support for the power supply and the power transmission system, (b) a revolving chute, which is used for the temporary storage and feeding of baled straw to the cutting drum, (c) a cutting unit, which consists of a cutting drum with rotating blades, a casing, a concave and a hopper (d) a power supply and (e) a power transmission system, which consists of various belts and pulleys.

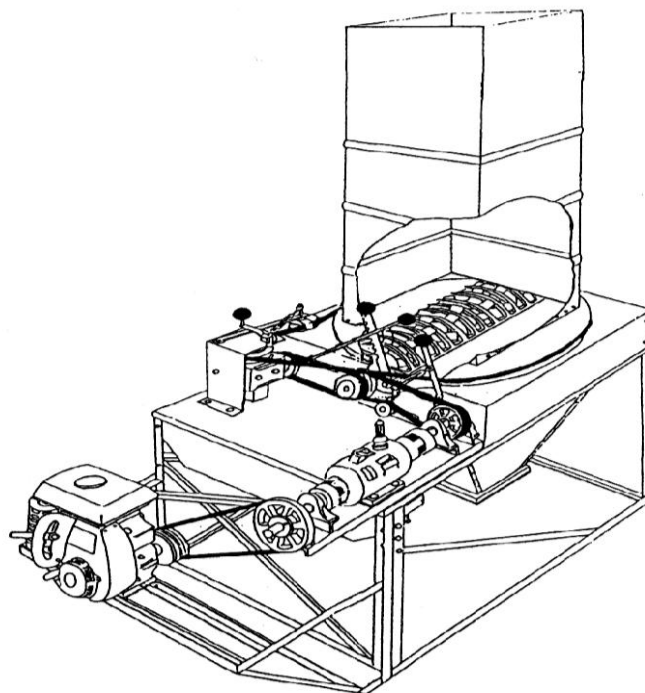


Figure 1. The Chopping system.

The Frame

The frame (Figure 2) was used to support the cutting drum and rigidly connect the power system with the cutting drum and chute. It was made of 50.8 mm mild steel angle iron arc welded together. The cross members of the frame were bolted together using 12.7 mm x 25.4 mm UNC hex head bolts and nuts. The frame consisted of three sections: (a) the primary section, (b) the secondary section (c) the torque meter section.

The primary section had a rectangular base of 1150 mm x 820 mm and a height of 1320 mm. Two cross braces were bolted onto the uprights of the sides with 19.7 mm x 40 mm hex head bolts and nuts at heights of 1067 mm to 330 mm. The primary section of the frame supported the cutting drum and revolving chute. The secondary section of the frame was an extension of the primary section made of a 650 mm x 820 mm horizontal rectangle bolted onto the vertical uprights at a height of 960 mm. Cross braces were bolted onto the outside of the rectangle section at a height of 50 mm. An additional section was used to support the torque meter sensor and the necessary couplings and bearings. This section was made of 75 mm wide x 35 mm deep channel iron and was supported on the outside by a mild steel square bar of 30 mm x 30 mm and on the inside by the upper edge of the primary section. The square bar was supported on the lower side by the secondary section of the frame.

The Revolving Chute

The chute (Figure 3) was made of a large open ended box with a cross-section of 420 mm x 520 mm and a height of 1520 mm. The box was constructed of 16 gauge galvanized steel. It was used to house 2 small bales of straw above the cutting drum. The two bales of straw in the chute created a downward force which kept the straw in contact with the cutting blades. A large circular plate of 4 mm thickness and 730 mm diameter was arc welded to the bottom of the box. The circular plate had a 40 mm wide flange welded underneath its outer edge.

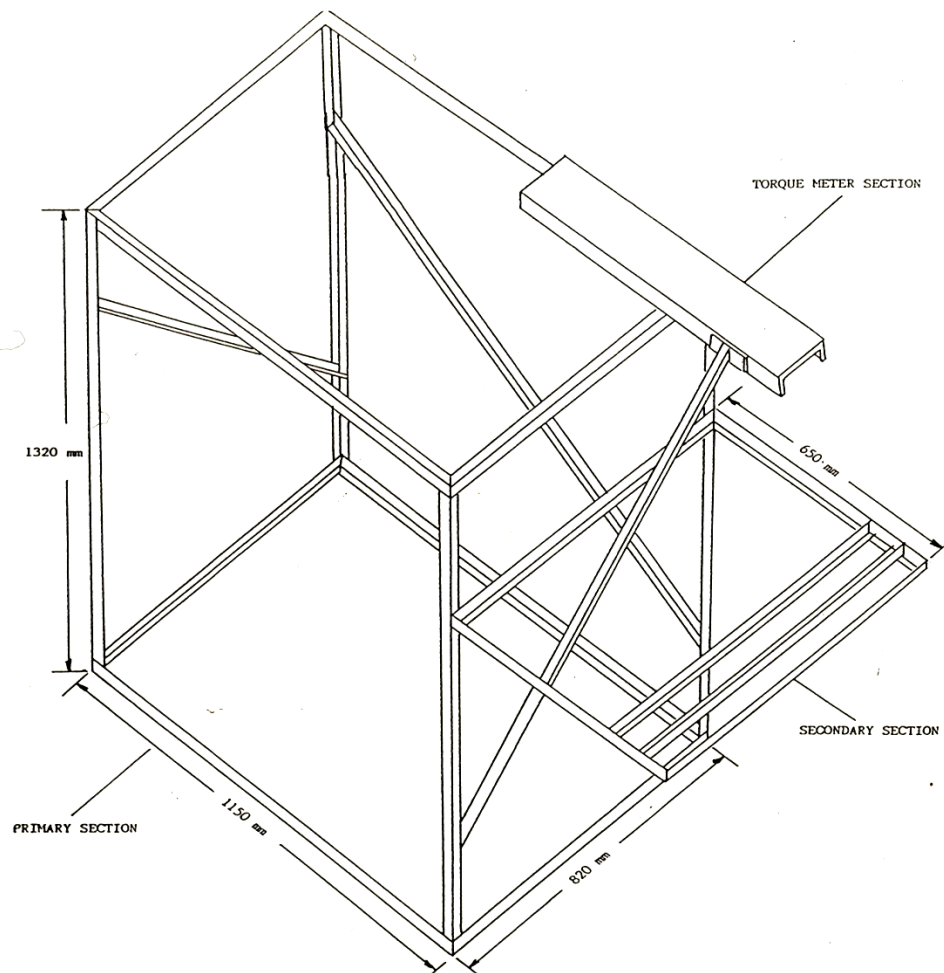
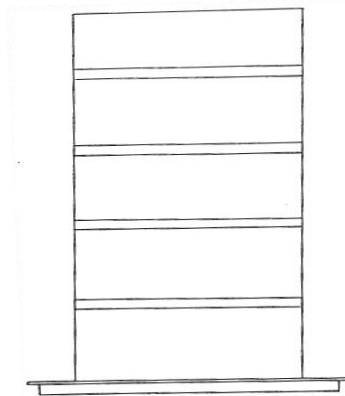
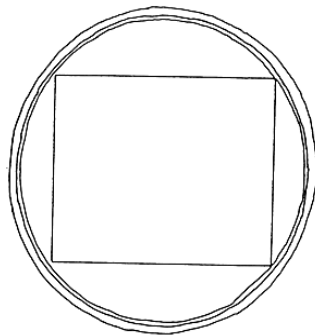


Figure 2. The frame.

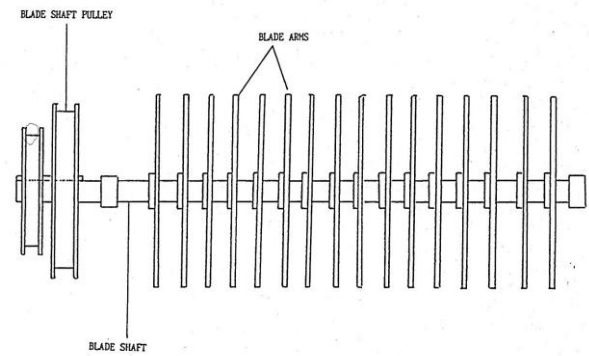


(a) Side View

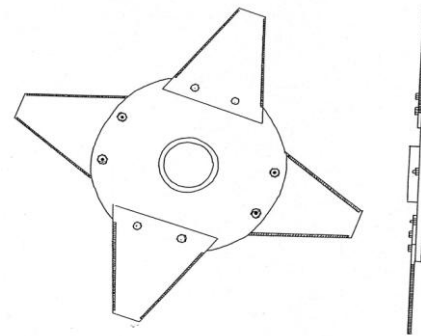


(b) Bottom View

Figure 3. The revolving chute.



(a) The blade shaft



(b) The blade

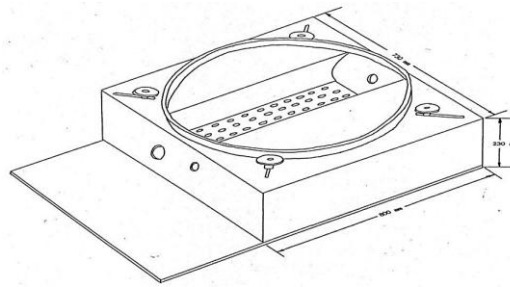
Figure 4. The cutting unit.

The Cutting Unit

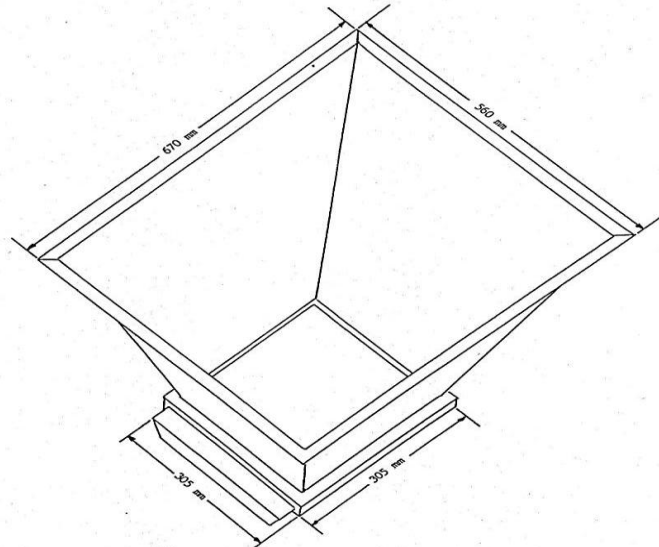
A solid round bar of 30 mm diameter and 840 mm length was used to support 16 cutting blades (Figure 4a). The shaft was supported by a slip bearing at each end. The first blade arm was located 180 mm from the driven end of the blade shaft, with the other 15 arms located at 35 mm intervals. The arms were arc welded onto the shaft whereas the blades were connected to the arms by 12.7 mm x 20.0 mm hex head bolts and nuts (Figure 4b). The arms were made of mild steel circular plates of 5 mm thick and 140 mm diameter. The blades were made of high tensile steel and were 80 mm long, 80 mm wide at the base and 20 mm wide at the tip. A driven pulley of a 135 mm diameter was fastened to the blade shaft by a 5 mm x 5 mm key. A drive pulley of 100 mm diameter was mounted outboard of the blade shaft driven pulley and was used to supply power to the revolving chute. The drive pulley was fastened to the blade shaft by a 5 mm x 5 mm key.

The casing of the cutting drum (Figure 5a) was a 230 mm high x 800 mm wide x 730 mm long mild steel box with two small rectangular openings on the upper surface was 250 mm x 670 mm. It was centered in a circular ring of 700 mm diameter and 35 mm height. A wide teflon strip was connected to the circular ring with 18 flush mount 10 mm x 15 mm machine screws. The opening on the lower surface was 250 mm x 670 mm. A concave having 12 mm diameter holes was connected to the casing under the cutting drum. The knives—concave clearance was 25 mm at the front and 12 mm at the back. A large galvanized sheet metal hopper was connected to the bottom of the cutting drum casing. The hopper (Figure 5b) was 670 mm x 560 mm at the top and 305 mm x 305 mm at the bottom with a height of 340 mm. A sliding door (305 mm x 360 mm) located at the bottom of the hopper was used to empty the hopper.

The theoretical length of cut was varied by the movement of a restricting grate in relation to the blades. The restricting grate (Figure 6) consisted of 16 prongs welded to an end bar. Each prong was 295 mm long, 10 mm wide and 10 mm thick. The prongs formed an arc around the rotating blades. A notched arm connected directly to the end bar of the arced grate was used to allow more or less straw to come in contact with the blades.



(a) The cutting drum



(b) The hopper

Figure 5. The casing of the cutting drum.

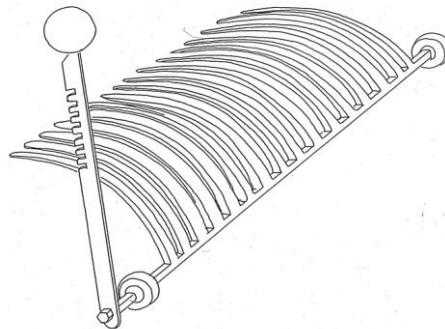


Figure 6. The Restricting Grate.

The Torque Meter

A torque meter sensor (Inter technology 1105 - 10K, Toronto, Ontario, Canada) was utilized to measure the torque output of the engine (Figure 7). The signal from the sensor was transmitted to a dial (Vishay Instruments Bridge Amp meter) to give a scale reading. The sensor was rigidly mounted on the channel section iron with four 14.3 mm x 45 mm hex head nuts and bolts. Two couplings (Lovejoy L110 I.500) were used to connect the torque meter sensor shaft to the torque meter input and output shafts. The two couplings were connected to the torque meter sensor input and output shafts with two 5 mm x 5 mm keys. The torque meter input and out shafts were supported by 2 non expansion, 2 bolt pillow blocks each. The pillow blocks were bolted onto 41 mm horizontal angle iron support using two 14.3 mm x 50.4 mm UNC hex head bolts and nuts. The horizontal angle iron support was arc welded onto the channel section of the frame. The pulley on the output shaft (Figure 7b) had a 100 mm diameter while the diameter of the pulley on the input shaft (Figure 7c) was varied to provide various blade shaft rotational speeds.

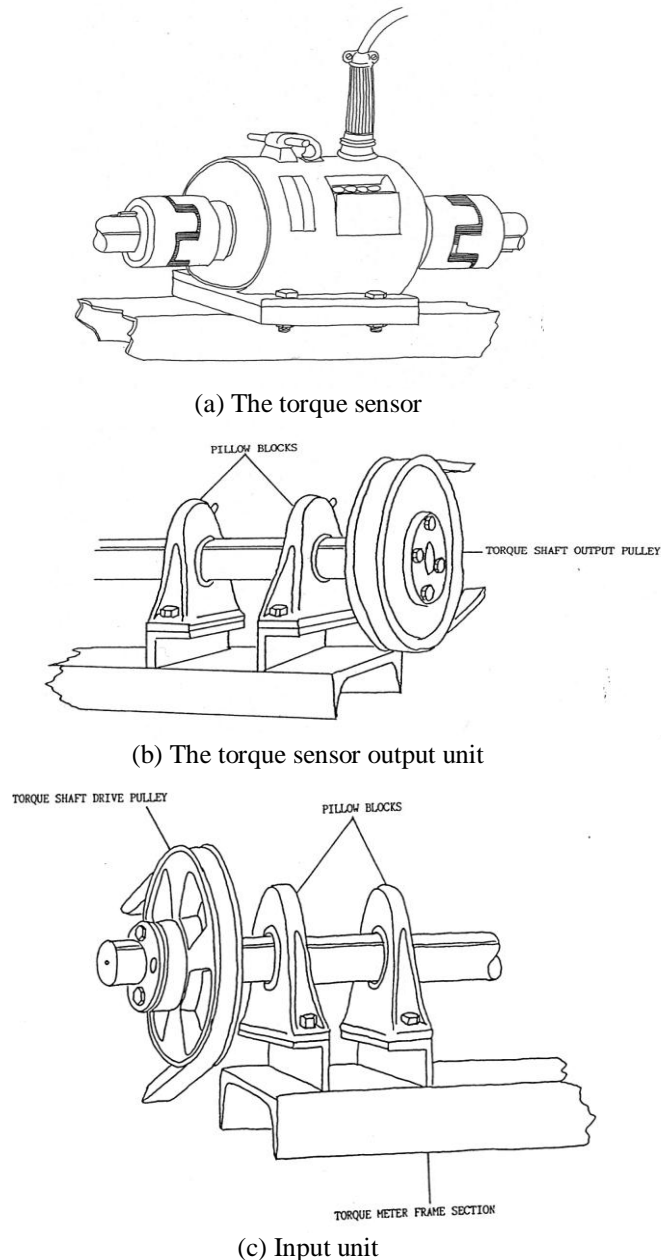


Figure 7. Torque meter system.

The Power System

The power unit was used to rotate the blades and the revolving chute. An 8 hp, 4-stroke, single cylinder gasoline engine was used as a power supply. The engine was mounted on a moveable platform on the secondary frame section. It was fastened onto the platform with 20 mm x 45 mm hex head nuts and bolts. A 115 mm diameter pulley with a 15 mm deep groove was connected to the 25 mm diameter output shaft of the engine. A 5 mm x 5 mm key prevented the pulley from rotating on the shaft. A 450 mm rubber belt was used to connect the engine pulley to the pulley on the torque meter input shaft. Another 760 mm rubber belt was used to connect the pulley on the torque meter output shaft to the pulley on the blade shaft. An engaging/disengaging mechanism made of 90 in diameter idler pulley and lever arm was used to engage and tighten the belt around the pulleys of the blade and torque meter shafts (Figure 8).

A 910 mm belt was used to connect the outboard pulley on the blade shaft to a small input pulley on the transfer case of the chute which was used to change the plane of motion from vertical to horizontal. The transfer case consisted of an input pulley, a gear set and an output pulley (Figure 9). The gear set consists of two bevel gears which operated at a 90° angle, with the vertical gear connected to the pulley and the horizontal gear

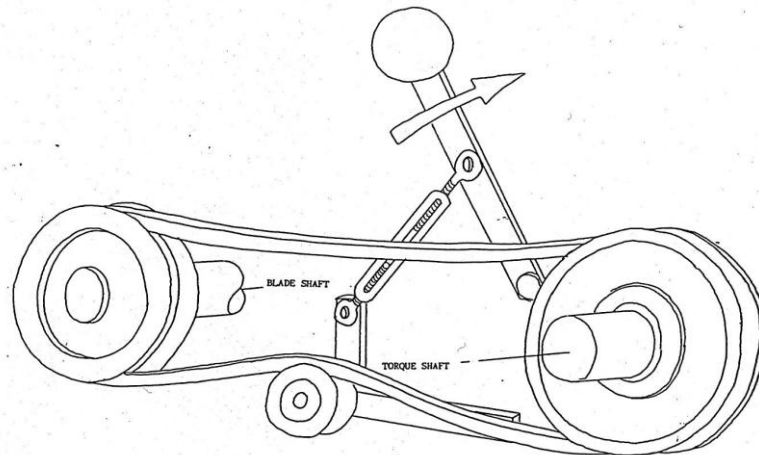


Figure 8. The blade shaft engaging mechanism.

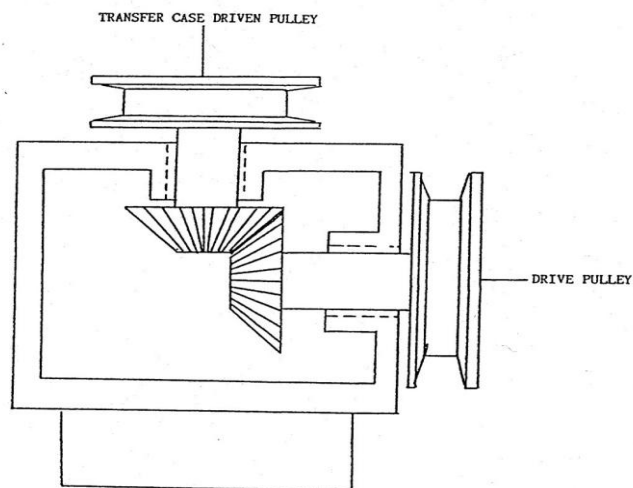


Figure 9. The transfer case.

connected to the output pulley. To rotate the revolving chute, a 2800 mm rubber belt was used to connect the flange of the revolving chute and the small output pulley on the transfer case.

A clutch system (Figure 10) consisting of a 90 mm diameter idler pulley and an engaging/disengaging arm, allowed the starting and stopping of the revolving chute. Four idler wheels (Figure 11) made out of hardened rubber were bolted to the top of the casing to keep the revolving chute in line with of the circular ring on the top of the cutting drum. The idler wheels were fastened using 20 mm x 75 mm hex head bolts and nuts. A belt guide was added to each bolt to prevent the belt from running off the edge of the plate. Each guide was made of a 60 mm x 25 mm mild steel piece of 3 mm thickness, bent 90° to form two 30 mm x 25 mm rectangles. One side of the guide was mounted on the bolt under the idler wheel and the other side was pointed up towards the centre of the lower surface of the idler wheel.

III. EVALUATION OF STRAW CHOPPER

Straw Collection

Monopol variety winter wheat straw was used in this study. The wheat straw was initially collected in the form of small bales (0.46 m x 0.48 m x 0.70 m) from a field on the Dyke View Farms situated at site at Port Williams, Nova Scotia. To maintain a uniform straw composition, straw was collected during the same harvesting season and from the same field. The straw bales were placed in a drying system and dried by blowing warm air (35°C) before they were chopped, in order to obtain a consistent moisture content of the feedstock.

Experimental Design

Seven blade rotational speed (800, 1000, 1250, 1400, 1750, 2000 and 2500 rpm) were investigated.

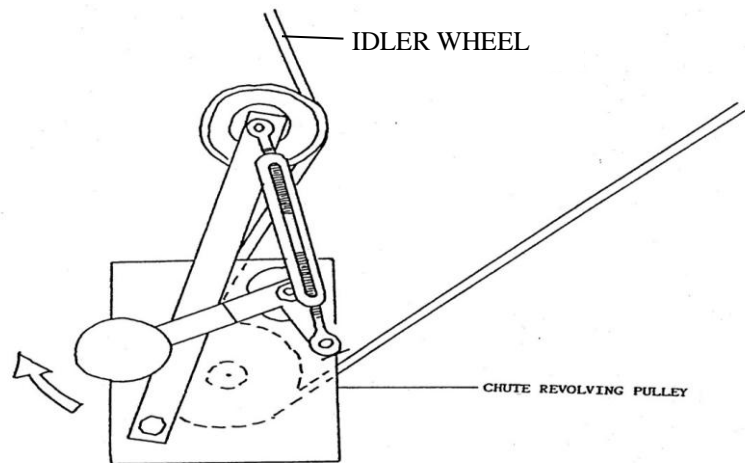


Figure 10. The revolving chute engaging mechanism.

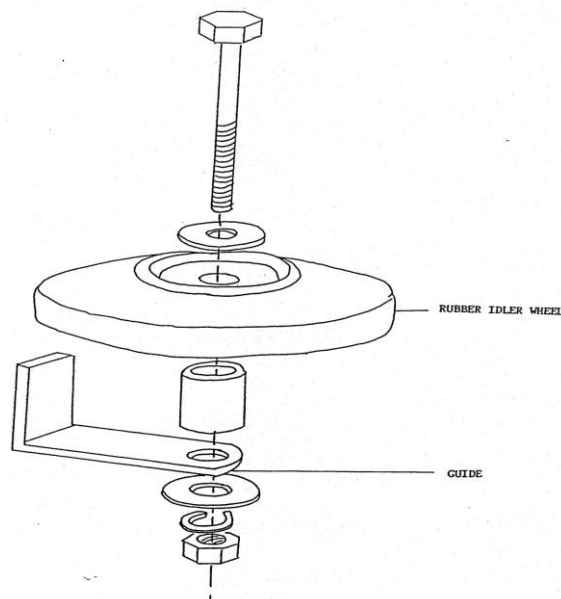


Figure 11. The idler wheel.

This allowed a cutting velocity in the range of 12.56 to 39.25 m/s. For each blade speed, 7 theoretical lengths of cut (3.9, 8.2, 12.1, 16.7, 21.8, 27.0 and 32.0 mm) were carried out. Three replicates were carried out for each length of cut - blade speed combination. This resulted in 147 experimental runs.

Testing Protocol

Two bales of straw were placed in the revolving chute and the baling wires were removed. The pulley of the torque meter input shaft was changed to give the required blade shaft speed. The engine output pulley was connected to the torque meter input pulley with the rubber belt. The belt tension was adjusted by moving the engine mounting platform. The depth of cut controlling lever arm was then placed on the selected notch. The blade shaft pulley was disengaged using the engaging/disengaging mechanism. The engine was turned on and the throttle was opened to increase the engine speed to 300 rpm. The blade shaft pulley and revolving chute were engaged by moving their respective engaging arms. The blade shaft rotational speed was fine tuned using the engine throttle. The hopper door was closed and the stopwatch was started. A large extra heavy duty trial plastic bag, labelled with the blade speed, the notch number and the trial number was then placed under the hopper. The hopper door was reopened and the experimental run lasted 2 minutes. Ten readings each were taken of the blade shaft speed, the torque meter input shaft speed and the torque meter sensor scale during the 2 minute period of each experimental run.

The blade shaft pulley was then disengaged and the chute refilled with two bales. The notch selection lever arm was then moved up one notch and the test procedure was repeated. The torque meter input shaft pulley was changed and the above procedure was repeated. The weight of the trial bag was recorded for feed rate computation. A sample of the output chopped straw was retained and the rest of the straw was disposed off. The test was repeated three times for all notches.

Straw Analysis

Samples of the chopped straw were collected randomly for sieve analysis to determine the size distribution (length, width and weight fractions) of straw particles. An electrical sieve shaker (Hoskin Scientific Limited, Burnaby, British Columbia, Canada), driven by a 0.25 hp (0.19 KW) electric motor was used. The motor runs at 1725 rpm (115 volts, 5.8 A and 60 Hz). The shaker contained six standard sieves and a bottom pan whose specifications are given in Table 1. The sieves were arranged according to the size of their openings. The bottom pan was placed under sieve No. 6 and designated sieve No. 7 with sieve No. 1 at the top, sieve No. 2 directly below it and so on until sieve No. 6. The system of sieves was placed onto the electrically operated sieve shaker. A sample of the chopped straw was weighed and put into sieve No. 1 which was then covered with the sieve lid. The shaker was operated for 30 minutes. The chopped straws, collected in each sieve, were then analyzed for weight, length and width distribution.

IV. RESULTS AND DISCUSSION

The performance characteristics of the straw chopping system were evaluated at various rotational speed and depths of cut (notch number). Both the feed rate and energy of cut were calculated. The length, width and weight of straw were determined.

Feed Rate

The straw chopper output (feed rate) was calculated at various depths of cut and cutting speeds. An analysis of variance was performed on the feed rate data using Minitab (Ver 16.2.2, Minitab Inc., Pennsylvania, USA). The results are shown in Table 2. Both the depth of cut and cutting speed had significant effects on the feed rate at the 0.001 level. There was also a significant interaction between the depth of cut and cutting speed at the 0.001 level. Tukey Test was also performed on the data to test the differences among the means as shown in Table 3. All the levels of the depth of cut were significantly different from each other at the 0.05 level. The highest average feed rate (5.52 kg/min) was achieved at 3.9 mm depth of cut. All the levels of the cutting speed were also significantly different from one another at the 0.05 level. The highest average feed rate (10.52 kg/min) was achieved at the cutting speed of 2500 rpm. The results showed that decreasing the depth of cut and/or increasing the cutting speed increased the feed rate. The values ranged from 1.48 to 10.52 kg/minute depending on the depth of cut and cutting speed used.

Elsaied et al. (2009) reported that feed rate increased linearly with increase in the drum speed, but the straw sizes decreased with increase in the drum speed and decreases in the moisture content of the material. Sudajan et al. (2003) and Sudajan et al. (2002) reported that when the drum speed was increased from 650 to 750 rpm the feed rate of the sunflower increased from 698 to 1058 kg/h, but when the drum speed was further increased to 800 rpm, the feed rate of the sunflower decreased to 965 kg/h. Vejasit and Salokhe (2004) reported that the feed rate played an important role in the rotational speed and capacity of the drum during threshing of soybean. They indicated that when the feed rate was increased the capacity of the drum increased with all rotational speeds and at different moisture content of the material. Emara (2000) and El-Behiry et al. (1997) reported that the straw sizes decreased with increasing drum speed and decreasing moisture content.

Table 1. Sieve specifications.

Sieve Number	Mesh Number	Size of Opening (mm)
1	4	4.7600
2	8	2.3800
3	14	1.4100
4	30	0.5950
5	50	0.2970
6	100	0.1490
7	Bottom Pan	Bottom Pan

Table 2. Analysis of variance of the feed rate data.

Source	DF	SS	MS	F	P>F
TOTAL	146	1515.77			
MODEL	48	1442.65	30.06	40.28	0.001
D	6	106.09	17.68	23.70	0.001
S	6	1183.20	197.20	264.29	0.001
D*S	36	153.36	4.26	5.71	0.001
ERROR	98	73.12	0.75		

D = Depth of cut (cm)

S= Speed (rpm)

 $R^2 = 0.95$

CV = 1.724%

Table 3. Mean values of feed rate as affected by the depth of cut and cutting speed.

Parameters	Level	N	Mean Feed Rate (kg/min)	Grouping
Depth of cut (mm)	3.9	21	5.52	A
	8.2	21	5.09	B
	16.7	21	4.68	C
	21.8	21	4.20	D
	27.0	21	3.85	E
	32.0	21	3.45	F
Speed (rpm)	800	21	1.48	A
	1000	21	2.37	B
	1250	21	3.43	C
	1400	21	4.80	D
	1750	21	5.53	E
	2000	21	6.94	F
	2500	21	10.52	G

Means with the same letters are not significantly different from one another at 0.05 level.

Energy of Cut

The effects of both the depth of cut and cutting speed on the energy of cut were investigated. An analysis of variance was performed on the energy data as shown in Table 4. Both the depth of cut and cutting speed had significant effects on the power required for cutting the straw at the 0.001 level. There was also a significant interaction between the depth of cut and cutting speed at the 0.001 level. Tukey Test was also performed on the data to test the differences among the means as shown in Table 5. The depths of cut 12.1, 16.7, 21.8 and 27.0 mm were not significantly different from each other at the 0.05 level. However, they were significantly different from the depths of cut 3.9, 8.2 and 32.0 mm at the 0.05 level. The highest power consumption (5.02 hp) was observed with the 16.7 mm depth of cut. The results showed that the energy consumption increased when the depth of cut was increased up to 16.7 mm and then decreased when the depth of cut was further increased (from 16.7 to 32 mm). The cutting speeds 1000, 1250 and 1400 rpm were not significantly different from each other at the 0.05 level. They were, however, significantly different from the speeds of 800, 1750, 2000 and 2500 rpm at the 0.05 level. The highest power consumption (7.76 hp) was observed at cutting speed of 2500 rpm. The power required for cutting the straw varied from a low of 3.69 hp to a high of 5.02 hp (36%) when the depth of cut was changed from 3.9 mm to 32.0 mm (720%) while the power required to cut the straw varied from a low of 1.76 hp to a high of 7.76 hp (340%) when the speed was changed from 800 rpm to 2500 rpm (212%). The unit power (hp.h/t) improved by increasing the speed due to increases in the feed rate. The energy of cut was less than 0.2% of the energy content of the straw.

Tavakoli et al. (2009) analyzed the power requirement for the particle size reduction of wheat straw on the basis of rotation speed of drum, screen size and number of blades. The results indicated that rotation speed of drum had significant effect on the energy consumption for cutting of wheat straw. When the rotation speed of the drum was increased from 400 to 800 rpm, the energy consumption increased from 1.506 to 5.144 kW and from 1.134 to 4.093 kW for screen sizes 2.5 and 4 cm, respectively. Increasing the rotation speed of drum increased the feed rate of the wheat straw which required greater power for size reduction of material when it passed through the threshing drum and screen. The energy required to cut straw increased with decreasing

Table 4. Analysis of variance of the horse power data.

Source	DF	SS	MS	F	P>F
TOTAL	146	647.36			
MODEL	48	568.74	11.49	14.77	0.001
D	6	30.19	5.03	6.27	0.001
S	6	447.54	74.59	92.97	0.001
L*S	36	91.01	2.53	3.15	0.001
ERROR	98	78.62	0.80		

D = Depth of cut (cm)

S= Speed (rpm)

R² = 0.88

CV = 20.30%

Table 5. Mean values of power consumption affected by the depth of cut and cutting speed.

Parameters	Level	N	Mean Power (hp)	Grouping
Depth of cut (mm)	3.9	21	3.69	A
	8.2	21	4.31	AB
	12.1	21	4.45	C
	16.7	21	5.02	C
	21.8	21	5.01	C
	27.0	21	4.45	C
	32.0	21	4.27	B
Speed (rpm)	800	21	1.76	A
	1000	21	2.97	B
	1250	21	3.87	B
	1400	21	4.58	B
	1750	21	4.89	C
	2000	21	5.07	D
	2500	21	7.76	E

Means with the same letters are not significantly different from one another at 0.05 level.

screen size. Eight blades in each flange provides much finer straw particles and decreases the amount of energy required to cut the straw when compared to that of using 4 blades on each flange.

Sieve Analysis

Samples were collected at the third trial of the 800 rpm and notch number 4 combination and sieve analysis was performed. The straw collected from each sieve was analyzed for weight, length and width. The results are shown in Table 6. The sample whose analyses are reported was collected having at the third trial speed of 800 rpm and notch number 4 (1.2). Most of the straw (85-90%) was collected in sieves 2, 3 and 4. In general, there were more variations in the length of straw collected in each sieve than in width of the straws. The following are descriptions of the straw collected in each sieve.

Sieve No. 1: The length of the straw collected in this sieve varied from 8 mm to 86 mm with an average length of 42.6 mm. Most of the straws was between 30 and 59 mm in length. The width of the straw varied from 1.5 mm to 7 mm with an average width of 3.8 mm. Most of the straw collected here were not sheared longitudinally and has nodes.

Sieve No. 2: The length of the straw collected in this sieve varied from 3 mm to 50 mm with an average length of 22.5 mm. Most of the straws were between 10 and 35 mm in length. The width of the straw varied from 1 mm to 4 mm with an average width of 2.6 mm. Most of the straws were about 3 mm in width. Most of the straws collected were halved longitudinally. Many nodes were found in this sieve but the nodes here differed from the nodes collected in sieve No. 1 in that they were smaller in width and the parts of the stalk connected to the nodes were relatively very short.

Table 6. The sieve opening size and straw weight, length and width distribution for a typical experimental run

Sieve Number	Opening Size (mm)	Weight		Length (mm)		Width (mm)	
		(g)	(%)	Range	Average	Range	Average
1	4.7600	1.82	2.90	30.0-59.0	42.6	3.0-5.0	3.8
2	2.3800	14.90	23.39	10.0-35.0	22.5	2.0-3.0	2.6
3	1.4100	22.30	35.01	3.0-19.0	13.3	1.5-2.0	1.7
4	0.5950	16.75	26.30	2.0-13.0	9.0	1.0	1.0
5	0.2990	4.81	7.55	1.1-5.0	2.0	0.2	0.2
6	0.1490	2.58	4.05	0.1-2.0	0.5	0.1	0.1
7	Bottom pan	0.53	0.80	dust	dust	dust	dust
		63.69	100.00				

Sieve No. 3: The length of the straw collected in this sieve varied from 3 mm to 38 mm with an average length of 13.3 mm. Most of the straws were between 3 and 19 mm in length. The width of the straw varied from 1 mm to 3 mm with an average width of 1.7 mm. Most of the straw was about 2 mm in width. Most of the straw resulted from about 3 times longitudinal shearing of the straw stem. No nodes were found.

Sieve No. 4: The length of the straw collected in this sieve varied from 2 mm to 19 mm with an average length of 9.0 mm. Most of the straws were between 2 and 13 mm in length. The width of the straw varied from about 1 mm in width. Most of the straw resulted from about 5 to 10 times longitudinal shearing of the straw stem.

Sieve No. 5: The length of the straw collected in this sieve varied from about 0.5 to 20 mm with an average length of 2.0 mm. Most of the straws were between 1 and 5 mm in length. The width of the straw varied from very minute particles to about 0.3 mm with an average width of about 0.2 mm. Most of the straws were about 0.2 mm in width. Most of the straw resulted from about 25 times longitudinal shearing of the straw stem.

Sieve No. 6: The length of the straw collected in this sieve varied from very tiny particles (about 0.1 mm) to 10 mm with an average length of 0.5 mm. Most of the straws were between 0.1 and 2 mm in length. The width of the straw varied of about 0.1 mm. Most of the straws were about 0.1 mm in width. Most of the straw resulted from about 50 times longitudinal shearing of the straw stem.

Sieve No. 7 (Bottom Pan): Fine fluffy dust with straw fibres of about 3 mm long and about 0.05 mm in width were collected in this pan. The dust (tiny particles, not fibres) made up most of the contents of this pan. The straw fibres might have resulted from about 100 times longitudinal shearing of the straw stem.

Straw Length

The weighed average of the length of the straw values of each sieve was determined. Analysis of variance was performed on the length of straw data as shown in Table 7. Both the depth of cut and cutting speed had significant effects on the length of straw at the 0.001 level. There was a significant interaction between the depth of cut and cutting speed at the 0.001 level. Tukey Test was also performed on the straw length data (Table 8) to test the differences among the means. The results indicate that the length of straw was not significantly affected by the depth of cut at the 0.05 level. The longest average length of straw (17.20 mm) was obtained at the 3.9 mm depth of cut and the shortest average length of straw (15.82 mm) was obtained at the 32.0 mm depth of cut. The speeds of 1250, 1400, 1750 and 2000 rpm were not significantly different from each other at the 0.05 level. They were, however, significantly different from the speeds of 800, 1000, 2000 and 2500 rpm at the 0.05 level. The longest average length of straw (18.85 mm) was obtained at the cutting speed of 800 rpm.

Adapa et al. (2011) and Adapa et al. (2010) studied the size reduction of barley, oat, canola and wheat straw using various screen sizes (1.6, 3.2, 6.4 and 30 mm) and calculated the geometric particle diameter or length, particle density and bulk density. The geometric mean particle length of the chopped straws ranged from 0.456 to 3.373 mm, 0.367 to 2.415 mm, 0.404 to 4.153 mm and 0.452 to 4.220 mm for barley, canola, oat and wheat straws. The average feed rate of the straw varied from 24 to 224 kg/h depending upon of the screen size. The results indicated that increase in screen size increased the geometric particle length, but decreased the bulk density, particle density and specific energy requirement

Mani et al. (2004) determined the mean particle size diameter of wheat, barley and corn straws and switch grass (having moisture content less than 10%) using various screen sizes (0.8, 1.6 and 3.2 mm). The

Table 7. Analysis of variance of the length of straw data.

Source	DF	SS	MS	F	P>F
TOTAL	146	647.36			
MODEL	48	568.74	11.49	14.77	0.001
D	6	30.19	5.03	6.27	0.001
S	6	447.54	74.59	92.97	0.001
D*S	36	91.01	2.53	3.15	0.001
ERROR	98	78.62	0.80		

D = Depth of cut (cm)

S= Speed (rpm)

R² = 0.72

CV = 8.89%

Table 7. Mean values of straw length as affected by the depth of cut and cutting speed.

Parameters	Level	N	Mean Straw Length (mm)	Grouping
Depth of cut(mm)	3.9	21	17.20	A
	8.2	21	16.87	A
	16.7	21	16.73	AB
	21.8	21	15.82	BC
	27.0	21	15.52	BC
	32.0	21	15.82	C
Speed (rpm)	800	21	18.85	A
	1000	21	17.95	B
	1250	21	16.57	C
	1400	21	16.17	C
	1750	21	16.07	C
	2000	21	14.94	D
	2500	21	14.19	D

Means with the same letters are not significantly different from one another at 0.05 level.

results indicated that the mean particle size diameter of wheat, barley, corn and switch grass ranged from 0.28 to 0.6 mm, from 0.32 to 0.69 mm, from 0.19 to 0.41 mm and from 0.25 to 0.46 mm, respectively. The particle size increased with increases in the screen size.

Chou et al. (2009) used a chopping system to cut air dried rice straws (ranging from 60 to 104 cm) into smaller sizes (10-5, 5-2 and <2 mm). The rice straws were cut by rotating blades while the straw is being smashed between the inner wall of the chamber and the rotating knife. The straw particles exit when they are smaller than the sieve. They indicated that the average feed rate increased as the rotation speed was increased. For the 10 mm length straw, the average feed rate increased from 2.3 to 2.5 kg/min as the rotation speed was increased from 620 to 980 rpm.

V. CONCLUSIONS

A straw chopping system, designed to provide continuous flow of straw to a fluidized bed gasifier, was constructed and evaluated. The system consists of a frame, a revolving chute, a cutting drum, a depth of cut controlling mechanism, a concave, an output hopper and a power unit. The performance characteristics (rotational speed, feed rate, depth of cut, length of cut and the energy required for chopping of straw) were determined. The chopping of straw was achieved with low energy consumption due to the proper design of the input hopper in that provided a uniform cutting of straw from the bale, the design of the input cutting mechanism with adjustable depth of cut and the correct sizing of the output hopper to provide an efficient removal of uniformly chopped straw. Both the depth of cut and the cutting speed significantly affected the length of straw, the straw feed rate and the power required for cutting the straw. Decreasing the depth of cut and/or increasing the cutting speed increased the straw feed rate while increasing the depth of cut and/or increasing the cutting speed increased the power consumption and decreased the straw length. The feed rate for chopping straw ranged from 1.48 to 10.52 kg/min, the power consumption ranged from 1.76 to 7.76 hp and straw length ranged from 14.49 to 18.85 mm, depending upon the depth of cut and cutting speed used. The unit power (hp.h/t) improved with increases in the cutting speed due to increases in the feed rate. The energy of cut was less than 0.2% of the energy content of the straw.

The sieve analysis of the sample indicated that 85-90% of the samples were collected in the sieves 2 (2.38 mm). The remaining 10-15% had a straw length of 0.59-2.38 mm.

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