EFFECT OF VARIOUS OPERATIONAL AND DESIGN PARAMETERS ON THE PERFORMANCE OF A ROTARY FEEDING AND CUTTING SYSTEM

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ABSTRACT There has been extensive research completed in the area of biomass cutting, specifically, cutting plant material. However, there has been very little research completed with a focus on rotary feeding and cutting system (RFCS). A RFCS is a hybrid cutter which employs characteristics of both a sickle type cutter and a precision type cutter. With limited data available on the factors that affect the performance of a RFCS it has been assumed that the factors that affect the cutting performance of a sickle type cutter or a precision type cutter have the same influence on the performance of a RFCS. To validate these assumptions laboratory tests were conducted to investigate the effect of counter-knife sharpness, rotor speed, and throughput on the specific energy required to process barley straw. It was concluded that the only statistically significant factor (p 0.05) was counter-knife sharpness. The specific energy requirements to process barley straw at an average moisture content of 13 % wet basis was 0.39±0.16** for a sharp counter-knife and 0.74±0.08** for a dull counter-knife.

Keywords: Rotary feeding and cutting system (RFCS), Specific energy, barley straw, sharpness, throughput, rotor speed

INTRODUCTION It is important for the readers to note that there has been a certain level of censorship applied to this article (due to the proprietary kind of information protection from Industry). Thus some of the results presented in the article will be given without units, some of the pictures will be purposely presented out of focus and the levels of rotor speed examined will not be quantified.

Optimized farm machinery is very important because it increases the efficiency of the equipment. Having efficient equipment is desirable for a farmer because it will increase their productivity resulting in greater potential for marginal returns. Companies that produce equipment want to ensure that they are producing efficient equipment as they will be able to gain, maintain market share and be highly competitive. The equipment that was studied during this project was the rotary feeding and cutting system (RFCS). The
RFCS is an optional accessory on the round balers and large square balers produced by Case New Holland (CNH). The system is utilized to cut the forage (or straw) material entering the baler in order to achieve a desired mean particle length, increased crop density, and to facilitate the grinding operation inside a total mixed ration.

The RFCS used on the round baler is equipped with up to 15 counter-knives. If all 15 counter-knives are installed the crop will be cut to a length of approximately 66 mm before it is baled. Any combination of counter-knives can be used to achieve the desired mean particle length in various crops. Figure 1 shows the RFCS in the large square baler. The RFCS found in the round baler is very similar to the system in the large square baler.

Figure 1 The rotor of the RFCS is shown on the left and the counter-knives are shown on the right (adapted from cnh.com).

The use of the RFCS results in denser and heavier bales due to a shorter mean particle length. There is an advantage to reducing the mean particle length of a bale for both straw and silage bales. When dealing with silage it is advantageous to reduce the amount of air pockets in the bale as it aids in the fermentation process. The shorter length of straw results in easier spreading of the bale, and increases its absorbency. Regardless of the crop being baled the use of the RFCS increases the bale density, which results in fewer bales per field and fewer bales transported to storage.

There has been extensive research done on the mechanics of cutting plant material. The three most common mechanisms studied are the reciprocating cutter, rotary cutters fed parallel to the cutter axis and rotary cutters fed perpendicular to the cutter axis. The RFCS is a unique form of a rotary cutter fed perpendicular to the cutter axis. The RFCS has been largely accepted in industry however the lack of published research on the performance of these cutters has brought into question their performance. The objective of this study was to determine the effect of the counter-knife sharpness, rotor speed, and throughput on the specific energy requirements to process barley straw.
MATERIALS AND METHODS

Material The material that was used throughout this experiment was obtained from the University of Saskatchewan. The barley straw had all been processed with a conventional combine and subsequently baled into round bales. The moisture content of the straw at the time of processing was 13% wet basis. Moisture content was determined according to ASAE Standard S358.2 (ASAE, 1996) where 50 g samples were dried in a convection oven at 103°C for 24 h. Moisture was determined in triplicates and expressed in percent wet basis (% w.b.).

Test stand The test stand shown in Figure 2 was used to determine the effect of the counter-knife sharpness, rotor speed, and throughput on the specific energy requirements to process barley straw. The test stand is a replicate of the full size system that is found on the round baler. The only difference between the RFCS found on a baler and the test stand is the width or number of counter-knives. The test stand can have up to 5 counter-knives while the system on the baler has up to 15 counter-knives. Both the conveyor that fed the RFCS and the rotor of the RFCS was driven by hydraulic motors.

![Figure 2 RFCS test stand used to determine the effect of counter-knife sharpness, rotor speed, and throughput, on the specific energy to process barley straw.](image)

Experimental design As previously identified the objective of this experiment was to determine the effect of counter-knife sharpness, rotor speed, and throughput on the specific energy required to process barley straw. Thus the factors of the experiment were counter-knife sharpness with two levels sharp and dull, rotor speed with three levels low, medium and high, and throughput with three levels 2.5, 3.75 and 5.0 kg/s.

The counter-knife sharpness was determined by measuring the width of the leading edge of the counter-knife. The sharpness of each counter-knife used in the test stand was measured in triplicate at three locations on the leading edge of the counter-knife before and after the trials were completed. The measurements were taken before and after to ensure that there was not a significant change in the sharpness over the duration of the trials. A Q-Imaging 01-GO-3-CLR-10 (10 Bit color camera) was used in conjunction with an Ancansco 076850 stereoscope to take pictures of the leading edge of the counter-knives. The program used to take pictures of and measure the width of the counter-knife leading edge was Q Capture Pro version 6.0.0.412. For a counter-knife to be considered sharp the edge width needed to be 0.13±0.05 mm and to be considered dull the edge width needed to be 0.63±0.07 mm.
The rotor speed was determined by using an optical tachometer. The speed of the rotor was adjusted by a bypass type pressure compensated flow control valve.

The throughput during the trials was determined by placing a known mass of material on the conveyor which had at a constant velocity. The rotational speed of the conveyor motor was measured with an optical tachometer and set with a bypass type pressure compensated flow control valve. The rotational speed of the conveyor motor was set so that the velocity of the conveyor belt was constant. Thus varying levels of throughput were achieved by adjusting the mass density (mass per length of conveyor) of material placed on the conveyor at the start of each trial. The mass of material was quantified using a digital scale and it was spread uniformly over the length of the conveyor.

A split-plot experiment design was used to minimize the number of times the counter-knives needed to be changed in the test stand. By using equation 1 the number of replicates that needed to be completed was 3 based on the coefficient of variation of preliminary test results and a 15% of average allowable variation.

The number of replicates can be decided according to ASTM D 3108 (ASTM 1992c). The sample size can be calculated from:

$$N = \frac{(tv)^2}{A^2}$$  

where:

- $N$ is sample size,
- $t$ is the value of student’s $t$ for a two sided limit at 95% probability level and infinite degrees of freedom, 1.96 (for population)
- $v$ is an estimate of the coefficient of variation, CV, and
- $A$ is 15% of average, the value for allowable variation.

**Specific energy** Specific energy is the energy required by the RFCS to process the material at a given throughput. The power consumed by the rotor of the RFCS was measured during the trials and subsequently integrated to determine the energy consumed during the trial. The specific energy was calculated by dividing the energy consumed during the trial by the average throughput of the trial.

Since the rotor was driven by a hydraulic motor the power consumed by the motor was calculated by measuring the flow of oil through the motor and the pressure drop of the oil across the motor. A Pamapo Mark V-1/2-SB flow meter was used to measure the oil flow
through the motor and Stellar Technology GT 1600-5000G-233 pressure transducers were used to measure the pressure drop across the motor. The signal from the flow meter and pressure transducers were connected to a Validyne MC 170-X signal conditioner/amplifier. The signals from the Validyne were connected to a national instrument data logger NI-DAQ 6015. The three signals from the Validyne were logged at a rate of 10 kHz during all trials.

The pressure transducers and flow meter were both calibrated in the fluid power laboratory at the University of Saskatchewan. The pressure transducers were calibrated with a dead weight tester. The flow meter was calibrated by connecting it in series with a linear actuator traveling at a known constant velocity. The calibration process was completed using the same signal conditioner/amplifier and data logger that was used to during the experimental trials.

To determine the energy consumed by the rotor the power curve was integrated using the following technique. A power curve, shown in Figure 3 was created based on a point by point multiplication of the pressure drop across the motor and the flow rate through the motor. The average energy required to process the material was determined by subtracting the baseline energy from the total energy. The total energy for each trial was determined by integrating the power curve using the trapezoidal method. The baseline energy for each trial was determined by integrating the baseline line, LBL, using the trapezoidal method.

The period that was logged for each trial did not start when the crop enters the RFCS and did not end when the crop exited the RFCS thus the period of integration was defined as follows. The period that was integrated starts at T1 and ends at T2 shown in Figure 3. In order to determine the time T1 and T2 the average and standard deviation of period A and B was determined for each trial. The start time T1 was defined for each trial as the point when the power exceeds the mean plus two standard deviations of period A. Similarly the end of the period T2 was defined for each trial as the point when the power was less than the mean plus two standard deviations of period B.

The baseline energy was approximated with the assumption that the change in the baseline energy from T1 to T2 was linear. In order to define the baseline line, LBL, two points were defined. The start of the line was defined at the time T1 and a power equal to the mean power of period A. The second point on the line was defined at time T2 and a power equal to the mean power of period B.
RESULTS AND DISCUSSION The specific energy requirements of the RFCS are given in Table 1. It is clear from Figure 4 that the counter-knife sharpness had a considerable effect on the specific energy requirements; however the differences between the different levels of rotor speed and throughput are not as pronounced. SPSS, a statistical software package, was used to determine what factors had a significant effect on the specific energy requirements. It was concluded that the only significant factor in the experiment was counter-knife sharpness at a 0.05 level. Thus the specific energy requirements, to process barley straw at an average moisture content of 13% w.b., for a sharp counter-knife was found to be 0.39±0.16** and for a dull counter-knife 0.74±0.08**.

There specific energy requirements of the trials with dull counter-knives at a low and medium rotor speed with a throughput of 5 kg/s are not given because the power requirements of the trials exceeded the available power of the test stand. The specific energy requirements of these trials are not known however it is reasonable to assume that the specific energy requirements exceed all other specific energy requirements of the experiment.
Table 1 Specific energy (S.E.) required to process barley straw at a throughput of 2.5, 3.75, and 5.0 kg/s with sharp and dull counter-knives and three levels of rotor speed.

<table>
<thead>
<tr>
<th>Throughput (kg/s)</th>
<th>Rotor Speed</th>
<th>Knife Sharpness</th>
<th>Average S.E. (N/A)</th>
<th>Standard Deviation of S.E. (N/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>Low</td>
<td>Sharp</td>
<td>0.364</td>
<td>0.080</td>
</tr>
<tr>
<td>3.75</td>
<td>Low</td>
<td>Sharp</td>
<td>0.315</td>
<td>0.056</td>
</tr>
<tr>
<td>5.0</td>
<td>Low</td>
<td>Sharp</td>
<td>0.353</td>
<td>0.037</td>
</tr>
<tr>
<td>2.5</td>
<td>Medium</td>
<td>Sharp</td>
<td>0.403</td>
<td>0.017</td>
</tr>
<tr>
<td>3.75</td>
<td>Medium</td>
<td>Sharp</td>
<td>0.321**</td>
<td>0.033**</td>
</tr>
<tr>
<td>5.0</td>
<td>Medium</td>
<td>Sharp</td>
<td>0.333</td>
<td>0.008</td>
</tr>
<tr>
<td>2.5</td>
<td>High</td>
<td>Sharp</td>
<td>0.293</td>
<td>0.042</td>
</tr>
<tr>
<td>3.75</td>
<td>High</td>
<td>Sharp</td>
<td>0.284</td>
<td>0.018</td>
</tr>
<tr>
<td>5.0</td>
<td>High</td>
<td>Sharp</td>
<td>0.380</td>
<td>0.176</td>
</tr>
<tr>
<td>2.5</td>
<td>Low</td>
<td>Dull</td>
<td>0.688</td>
<td>0.152</td>
</tr>
<tr>
<td>3.75</td>
<td>Low</td>
<td>Dull</td>
<td>0.756</td>
<td>0.054</td>
</tr>
<tr>
<td>5.0</td>
<td>Low</td>
<td>Dull</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>2.5</td>
<td>Medium</td>
<td>Dull</td>
<td>0.613</td>
<td>0.105</td>
</tr>
<tr>
<td>3.75</td>
<td>Medium</td>
<td>Dull</td>
<td>0.728</td>
<td>0.075</td>
</tr>
<tr>
<td>5.0</td>
<td>Medium</td>
<td>Dull</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>2.5</td>
<td>High</td>
<td>Dull</td>
<td>0.624</td>
<td>0.068</td>
</tr>
<tr>
<td>3.75</td>
<td>High</td>
<td>Dull</td>
<td>0.615</td>
<td>0.247</td>
</tr>
<tr>
<td>5.0</td>
<td>High</td>
<td>Dull</td>
<td>0.738</td>
<td>0.122</td>
</tr>
</tbody>
</table>

** Data is based on only two replicates
* Data is unavailable (only one trial was completed)

The results of this experiment, specifically the effect of counter-knife sharpness are in agreement with the conclusions drawn from previous research. Experiments completed comparing the effect of knife sharpness revealed that a knife with a 0.25 mm radius edge had double the force and energy requirements than a knife with 0.05 mm to 0.1 mm radius (Reznik, 1979). Studies by Tuck (1976-1978) on power requirements of mowers indicated that the specific cutting energy per unit field area was 1.5 kJ/m² for a sharp blade and 2.1 kJ/m² for a worn blade. Liljedahl et al., (1961) concluded that the energy requirements for a dull knife were twice that of a sharp knife when the clearance between shearing edges was small (0.05 mm) and three times as high for a larger clearance (0.41 mm). All of these studies have revealed the same trend; a dull knife requires more energy to cut material than a sharp knife. This can be physically explained by the fact that a very sharp knife causes localized cell failure and compression in the material, in contrast to a dull knife that will cause cell failure and compression over a greater area.
Figure 4 Specific energy required to process barley straw at three levels of throughput, rotor speed and two levels of counter-knife sharpness.

It is not a surprise that the throughput did not have a significant effect on the specific energy to process barley straw because specific energy is a function of throughput. If the data were reported in energy consumed (kJ) or power consumed (kW) per trial the effect of throughput would have been more pronounced and likely statistically significant. According to Persson (1987) typically there is a linear relationship between the total power requirement of a rotary mower and capacity. The increase in cutting power can be explained by the fact that a higher throughput, given the same cutting speed, the material layer thickness increases. As the thickness of material being cut increases the stress concentrations near the blade decreases resulting in increased amounts of pre-compression occurring before the material is cut.

The effect of rotor speed, which is proportional to the cutting speed, was not a significant factor in this experiment. This conclusion has also been observed in previous research. Springer et al., (1976) completed a comprehensive review of the research that had been published on the effect of various parameters on the performance of cutting devices and concluded that in general the energy changed very little through the range of quasi-static to 60 m/s for all devices. Chancellor (1957) examined the effect of cutting speed on the force and energy required to cut timothy at a moisture content of 54% wet basis. He concluded that there was very little change in cutting energy when the cutting speed was changed from 1.75 to 5.2 m/s.

**CONCLUSION** The objective of this study was to determine the effect of counter-knife sharpness, rotor speed and throughput on the specific energy required to process barley straw with a RFCS. It was found that the counter-knife sharpness was the only factor that had a statistically significant (p 0.05) effect on the specific energy requirements of the RFCS. Therefore, the rotor speed and throughput did not have a significant effect on the
specific energy requirements of the RFCS over a range of 2.5 to 5.0 kg/s. The specific energy requirements, to process barley straw at average moisture content of 13% w.b., for a sharp counter-knife was found to be 0.39±0.16** and for a dull counter-knife 0.74±0.08**.

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REFERENCES


