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Torque-arm Method to Measure Specific Energy in Laboratory Scale Biomass Preprocessing Equipment

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Abstract. *Specific energy for comminution and mechanical processing of lignocellulosic feedstocks provides an economically important basis to compare equipment and to provide data for lifecycle analysis of complete systems. Measurement of specific energy during equipment design and development activities enables optimization of design parameters. Forest Concepts developed a torque-arm apparatus and LabView data acquisition method that has proven to be easily adapted for preprocessing equipment such as orbital sieves, flail debarkers, and comminution machinery. We provide a comparison of torque-based energy measurement versus electrical motor current based measurement to demonstrate the limitations of motor current methods.*

Keywords. *Biomass, forest, bioenergy, standards, specific energy, power consumption, energy measurement*

Introduction

As the need for renewable fuels grows, so does the number of research entities involved in developing feedstock supply chain, preprocessing, and conversion processes. A key step in a conversion processes is feedstock comminution to produce particle sizes appropriate for a specific conversion platform. In order to develop total economic characterization of processes one needs to know the specific energy applied to the material being processed. Additionally, measuring specific energy allows processing comparison across machinery types.

Traditionally, specific energy consumption of processing equipment has been measured indirectly either electrically as total current and voltage draw to the equipment's electric motor (Bitra, 2009), or in the case of liquid fuel driven systems, the total energy content of fuel consumed during the process (Bitra, 2009). A substantial drawback to this kind of energy measurement is the motor efficiencies, particularly the variance in motor efficiencies across loading ranges and / or RPM ranges. Alternatively, Bitra et al used a rotary torque sensor to measure true specific energy consumption (Bitra, 2009). However, rotary torque sensors are relatively expensive and must be carefully selected for the shaft sizes and loads being measured. This led the team at Forest Concepts to develop a simple, inexpensive method for more accurately measuring the true specific energy consumption of processing equipment utilizing a torque arm load restraint.

Safety Emphasis

All biomass processing equipment, including rotary comminution equipment, has inherent dangers and safety risks. Equipment must be operated by persons who are cognizant of the safety hazards and trained to operate the equipment in a safe manor.

Drive Sources

Electric Motors

Electric motors appear to be the most common mechanical drive source in laboratory biomass processing equipment. As mention earlier, the traditional method to determine a processes' energy consumption is to measure the current and voltage going to the motor. At the surface level current (i) * voltage (v) * motor power factor (pf) * [(if the motor is a 3 phase) √3 * 3] equals the motor watts (W) output (Nilsson, 2001). Subtract the recorded no load condition from the recorded loaded condition to get the process energy consumption. The problem, however, is that the efficiency and power factor vary substantially with motor loading. For example, a Leeson 5hp, 3ph AC motor (catalog No G131581.00) at full load has 87.5% efficiency and a 82.3% power factor. At ¼ load the motor has 82.4% efficiency and a 44.6% power factor. The efficiency and power factors, and thus total kW used, at each load level may not be linear and often is not published for a given motor. Therefore, the specific energy used in a process cannot be easily determined, and in some cases not determined at all with published information.

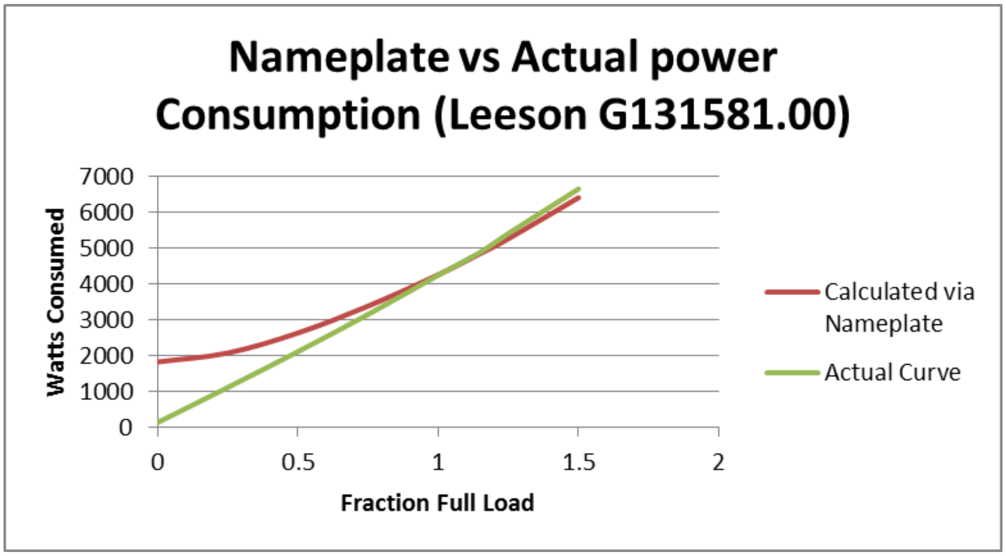

Figure 1. Power consumed by Leeson 3phase, 5hp electric motor, actual consumption and calculated using full load nameplate power factor consumption.

Liquid Fuel Engines

Liquid fuel engines, such as gasoline and diesel engines also power biomass processing equipment, though less frequently at a laboratory scale. A typical method for determining the energy used in a process seems to be determining the volume or mass of fuel (f) used and multiplying by the standard energy content (ec) of that fuel. (Yancey, 2009) While this will yield approximate energy consumption, the data does not lend itself to translating the process into other drive methods. Engine efficiencies are typically low, and vary under loading and rpm like electric motors do. Published efficiency curves are virtually nonexistent.

The Torque Arm Method

The torque arm measuring apparatus resists a rotational load with an instrumented linear force transducer. The method is applicable to parallel shaft drive systems, i.e. a motor drives a belt which in turn drives the processing equipment. Typically both the motor and the process are fixed to a rigid frame, resisting the rotation of the motor. We will describe the method assuming a torque arm is on the motor side of the drive system. Our method mounts the motor to a bearing mounted swing, where the swing is free to rotate co-axially with the motor output. Mathematically perfect alignment between swing and motor axis is not necessary, but practicality in maintaining pulley tension suggests a degree of alignment necessary. An arm of known length protrudes from the swing perpendicular to the motor output axis. A linear force transducer support attaches (preferably perpendicular) to the arm and to a rigid machine frame. Torque calculation error proportionally increases with angle measurement error as the angle between the sensor axis and arm axis digresses from 90 degrees. I.e. 1% error in angle measurement creates more error in the torque calculation at 30 degrees than does 1% error at 90 degrees. The effective lever arm length is the distance from the center of the swing pivot to the force transducer axis. Neglecting the bearing friction, the entire resistance to motor spinning is withstood by the linear force transducer. Utilizing the geometric relationship between the effective torque arm length, the load cell axis angle to the effective torque arm, and the load cell output one can determine the torque output of the motor. Power and therefore energy consumption can be calculated knowing the RPM of the motor. Alternatively the load end of the system can be mounted to a torque arm swing using the same techniques. Figure 2 below shows and example setup diagram.

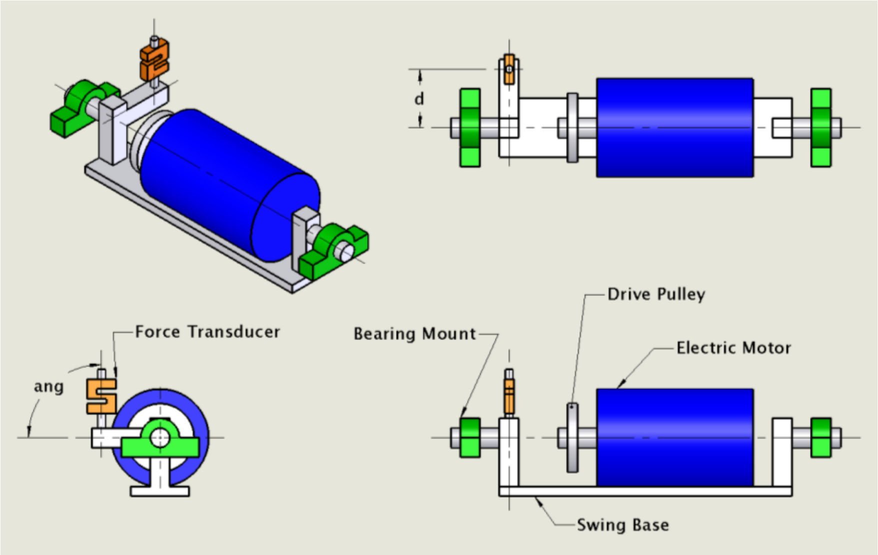

Figure 2. Torque arm method example diagram.

The motor output torque is calculated using the equation:

$$f * d * \sin(ang) = T \qquad \text{equation 1.}$$

where:

f = linear force transducer force output (N)

d = effective torque arm length (m)

ang = angle between effective torque arm and linear force transducer (deg)

*see Figure 2 for variable locations

Force Transducer Selection

The force transducer should be selected such that as much of the full load range is used as possible. This method yields greater output resolution as the load uses a greater portion of the transducer's electrical output. In other words, there is more electrical output per force input, helping differentiate the load from electrical noise. However, care must be taken to not over load the transducer. We have found that for laboratory biomass processing equipment that will receive an unknown motor loading a safety factor of 3 applied to the motor's full load torque to be sufficient. Refer to the previous 5hp motor example; the full load torque is 15 ft*lb, while the break down torque is 48.6 ft*lb, approximately 3 times the full load torque. If it is known that the loading will not exceed full load torque, a smaller safety factor may be used. Therefore, the equation to determine force transducer size is:

$(SF * T) / (d * \sin(ang)) = f_{cap}$ equation 2.

where:

SF = design safety factor

T = motor output full load torque (N*m)

d = effective torque arm length (m)

ang = angle between effective torque arm and linear force transducer (deg)

f_{cap} = force transducer capacity (N)

Motor output torque can be calculated using the equation:

$(kW * 9550) / rpm = T$ equation 3.

where:

T = motor output full load torque (N*m)

kW = motor full load power rating

rpm = revolutions per minute of output shaft / drive pulley

Note that the rpm of the output shaft is the rpm of the drive pulley that the swing arm base rotates about. Therefore, if a 1750 rpm motor has a gearbox attached that outputs 541 rpm and the gearbox assembly is attached to the swing arm frame, the torque calculations the use the 541 rpm value.

Example Setup

We have used this energy measurement method on a number of machines, comparing the output with the traditional electrical measurement method. Figure 3 shows an example of motor mounted to the swing. Figure 4 shows an example of the alternate position of the processing head mounted to the swing.

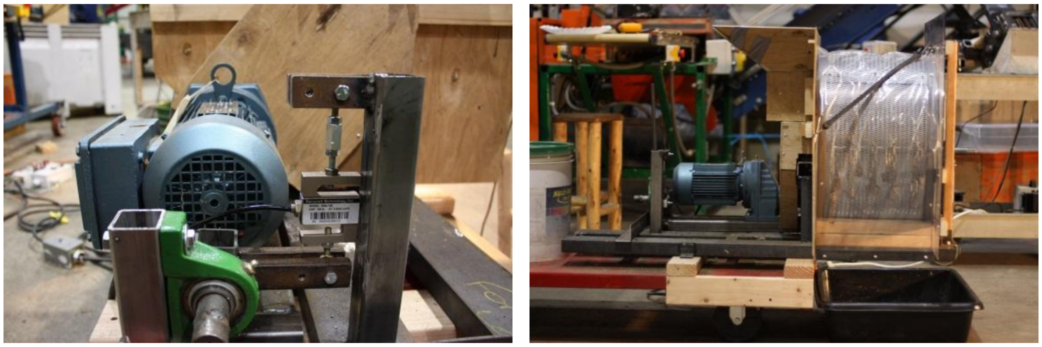

Figure 3. Motor mount swing, torque arm, and force transducer mounted on the motor side of the drive system.

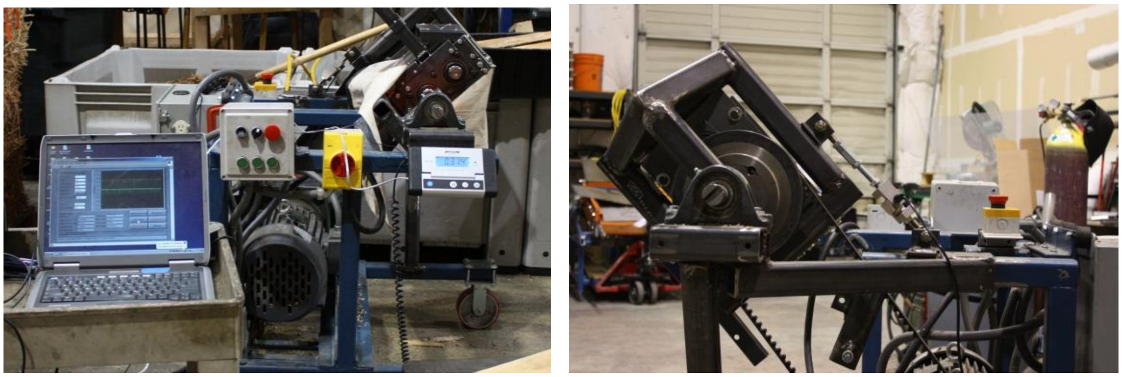

Figure 4. Processing head mount swing, torque arm, and force transducer mounted on the processing head side of the drive system.

The load cell output, excitation voltage, electrical current and voltage were all recorded into NI LabView program at 960 samples per second. 960 S/s allows for 16 points per period on the 60Hz electrical, enough to be reasonably close to catching the electrical peaks. All data was captured using a Measurement Computing USB-1616HS DAQ board.

Figure 5. Data logging system: Measurement Computing USB-1616HS DAQ board, Laptop running LabView with custom vi, power supply, and electrical power scaling box (scales line voltage to acceptable DAQ input voltage).

As mentioned earlier, the electrical power was computed using the equation for a 3 phase motor:

$$i * v * pf * \sqrt{3} * 3 = W \qquad \text{equation 4.}$$

where:

i = measured electrical current in a single leg, (a)

v = measured electrical voltage, leg to leg, i.e. 460v, (v)

pf = motor power factor

W = electrical power (W)

Or for a single phase motor:

$$i * v * pf = W \qquad \text{equation 5.}$$

where:

i = measured electrical current, (a)

v = measured electrical voltage, i.e. 230v, (v)

pf = motor power factor

W = electrical power (W)

Torque arm based power was computed using the equation:

$$(T * rpm) / 9.55 = W \qquad \text{equation 6.}$$

where:

T = measured torque (N*m) (load cell output * lever arm)

rpm = rotations per minute of shaft that the torque arm is set about

Results

The resulting data from the experiments clearly shows the value of the torque arme method. Figure 6 below shows a 10hp machine operating with no load. The load cell output was zeroed before starting the machine to correct for gravity acting on the machinery head. Notice that the electrical based load is substantially higher than the torque based load. This is due to the drop in efficiency and power factor under small load conditions.

Ordinarily, one would subtract the no load energy usage from the full load energy usage to correct for machine drive train efficiencies. This chart suggests that one is losing 3000 Watts (4 hp) to drive train loses. The toque based measurement suggests that there is very little drive train loss.

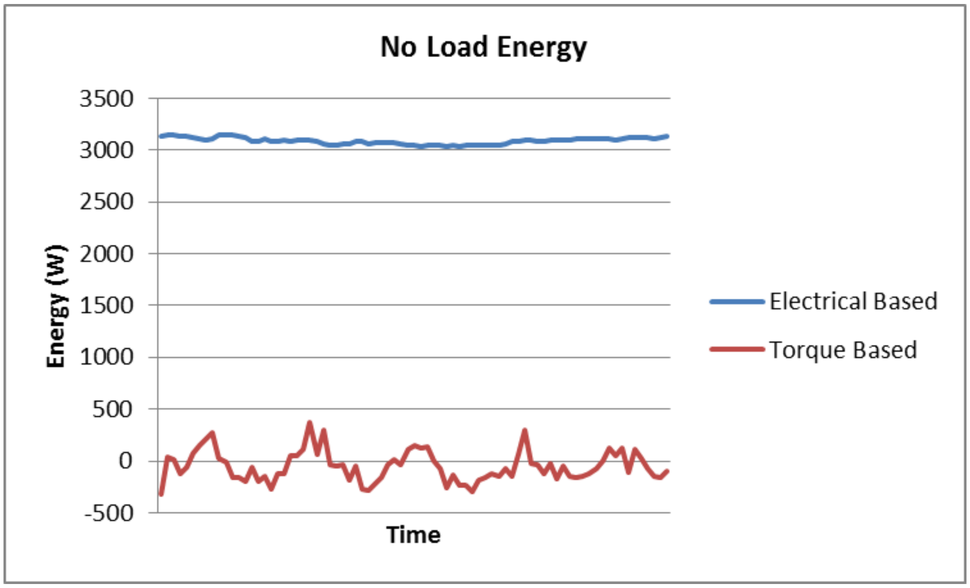

Figure 6. Torque arm based power consumption vs. electrical based power consumption in a no load condition.

Figure 7 below shows the same machine under a full load condition. Notice how the electrical and torque based loading rise to the same energy usage. At the full load range the nameplate motor efficiencies and power factors are correct, and thus our energy consumption equation is valid.

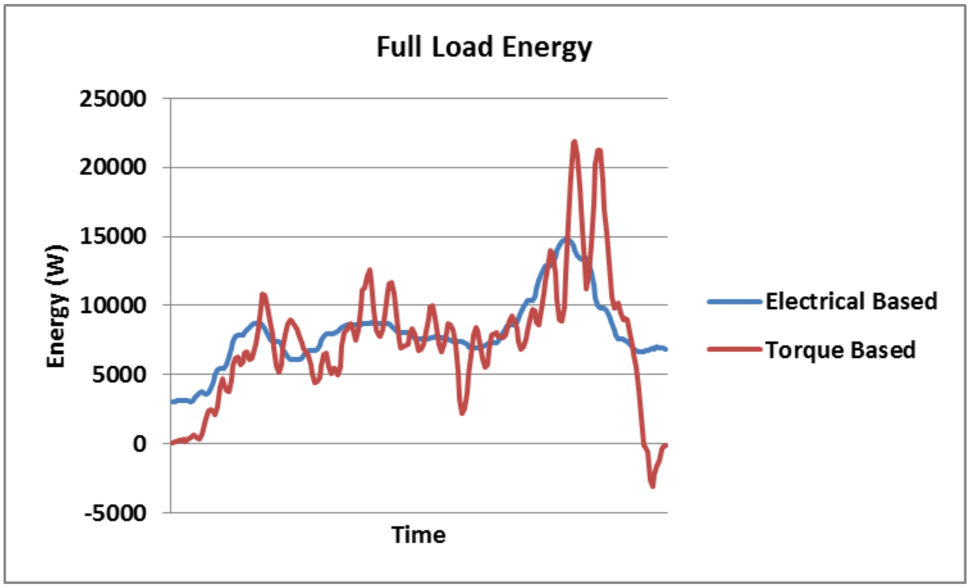

Figure 7. Torque arm based power consumption vs. electrical based power consumption in a full load condition

Figure 8 below shows the same machine with a partial load condition. Again, notice that the electrical based energy is substantially higher than the torque based. This condition is particularly relevant to the challenge of determining specific energy usage for comminution equipment. Often during lab experiments one is not working at full motor load, and thus the standard energy equation is not strictly valid. Utilizing the torque arm method, specific energy calculations can be achieved through out the motor loading range.

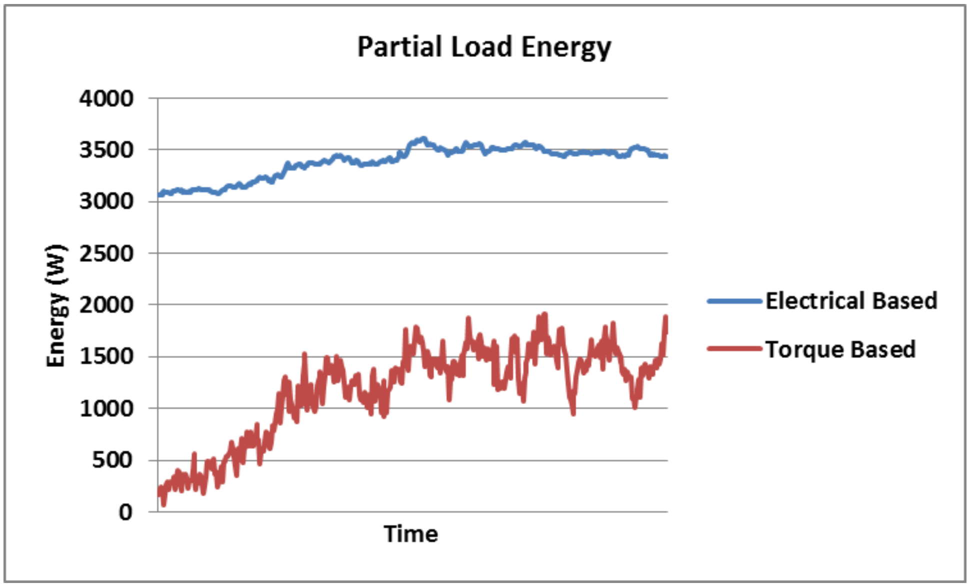

Figure 8. Torque arm based power consumption vs. electrical based power consumption in a partial load condition

Conclusions

The torque arm measuring method is useful for determining specific energy consumption of many biomass processing equipment types. The simple method can be adapted to many machinery configurations.

There are, however, a couple of drawbacks to this method. First, existing machines must be modified so that either the processing mechanism or the motor can rotate about the drive shafts. Secondly, as can be seen in the charts above, the output from the load cell can be noisy as it is very sensitive to the variations in the processed material resistance. Smoothing techniques will generally need be applied to the output.

It is suggested that future researchers use the torque arm or similar methods for determining specific process energy independent of motor loading. Energy consumption comparisons across process types will be more meaningful as the driver load inefficiencies will be accurately removed energy consumption data.

Acknowledgements

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