STALK BIOMASS SHREDDER INVESTIGATION

Eriks Kronbergs, **Mareks Smits**
Latvia University of Agriculture
Eriks.Kronbergs@llu.lv; Mareks.Smits@llu.lv

Abstract. The target of EU is to double the share of the Renewable Energy Sources in gross inland consumption up to 12.0% by 2010. Mainly heat and electricity energy production from dry solid biomass is planned using it as solid biofuel. For solid biofuel production, biomass size reduction processes precede compacting. The article presents investigation of cereal straw and common reed biomass mechanical and cutting properties which determinate shredder design. The cutting properties of two types cutting knives with edge angles 20º and 90º were compared. The differences were not sufficient in the specific energy values for single flattened reed stalk cutting (average difference is approximately 2.4 $kJ \cdot m^{-2}$ for the two types of knives). The calculated maximum angle between cutterbar knives and counter knives for common reed stalk cutting is 19.2° and 23° for reed canary grass stalks accordingly. The results of experiments show mean value of angle of nip $\beta = 17.7° \pm 0.2°$. The difference between the calculated value and value determinated experimentally is only 1.5°, and mainly depends on individual friction properties of reeds.

Key words: biomass size reduction, shredder design.

Introduction

The 2003 reform of the EU Common agricultural policy means that income support for farmers is not linked to the crops produced. As a result, farmers can respond freely to increasing demand for energy crops. This reform also introduced a special "energy crop payment" under which a premium of €45 per hectare [1] is available for the production of energy crops. The reform stimulates farmers to grow more energy crops, including short rotation coppice and other perennial crops. Energy crop growing have to improve soil stability, fertility and quality of all ecosystem. There are others resources of bioenergy as agricultural residues and peat. More than 230 million tones of peat are available for solid biofuel production. Peat can be used as additive for manufacturing of briquettes, because it improves density of herbaceous material briquettes. Solid biofuel production from herbaceous biomass and peat compositions in rural area and energy crop growing create new unconventional busyness for country people. There is possibility in Latvia to provide for the use of approximately 0.92 million ha of the unused now agricultural land and its sustainable development for energy crop growing.

Biomass properties cause necessity of appropriate mechanization equipment for biomass conditioning for solid biofuel production. Dry vegetation materials contain stalks as the main part of biomass. Therefore biomass conditioning mainly includes stalk material flattening, cutting and compacting. The article presents investigation of common reed biomass mechanical and cutting properties which determinate shredder design for size reduction before compacting.

Materials and methods

Experimentally earlier [2] had been stated values of wheat stalk (with moisture content ~ 10%) ultimate tensile ($118.7 \pm 8.63\ N \cdot mm^{-2}$) and shear ($8.47 \pm 0.56\ N \cdot mm^{-2}$) strength, modulus of elasticity (13.1 ± 1.34 GPa) and shear modulus (0.643 ± 0.043 GPa) in order to find methods for mechanical conversion with minimal energy consumption. Similar values for switchgrass [3] (with the same moisture content) ultimate tensile ($\sim 120\ N \cdot mm^{-2}$) and shear ($\sim 18\ N \cdot mm^{-2}$) strength had been stated. The energy crop reed canary grass stalks (stems) are more useful with delayed harvesting for solid biofuel production [4], than leaf blades, therefore mainly stalk material cutting properties have to be investigated for shredder design. Experimental investigation of common reed stalk conditioning properties as flattening and cutting can characterize maximum of energy consumption in these operations for all group of mentioned stalk materials because reeds have higher tensile strength ($\sim 200\ N \cdot mm^{-2}$) and accordingly another strength parameters.

Naturally herbaceous biomass is a material of low density ($20 - 60\ kg \cdot m^{-3}$) and not favorable for transportation on long distances. Straw baling can increase bulk density to $100 - 200\ kg \cdot m^{-3}$. This practice is usable for energy crop as reed canary grass (*Phalaris arundinacea*) compacting, which would be source for solid biofuel in future. For small scale biofuel production, as pellets and briquettes the acceptance of the small rectangular baler has come about because people like the size, shape and density of the bales. Bales are small enough to be stacked by hand and dense enough for efficient long distance hauling and inside storage. Technology of small square baling causes some orientation of straw stalks. This stalk orientation in bale has to be taken into account in designing of shredder cutterbar. Reed stalk cutting experiments have been carried out by means of Zwick material testing machine TC-FR2.5TN.D09. Zwick material testing machine has force measurement accuracy 0.1 N, displacement measurement accuracy 0.01 mm, maximal force measurement – 2.5 kN. Computer controls the Zwick material testing machine. The force and displacement measurement data were collected on the computer.

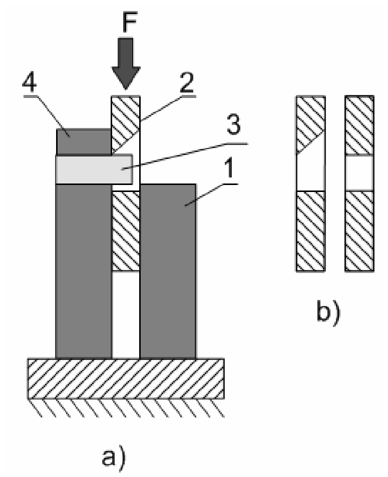

Fig. 1. **Flattened reed cutting device**

Energy consumption for reed stalk flattening and cutting has been investigated using the Zwick materials testing machine equipped with a cutting device (Fig. 1). Original cutting device has been designed for the Zwick material testing machine for flattened stalk material cutting.

The cutting device (Fig. 1a) consists of the die 1 with a gap and a turnable specimen fastening 4 and a rectangular prismatic punch with 5 mm thickness. Clearance between the punch and the gap is 0.02 mm from each side. Cutting using two types of knives – with edge angles 20º and 90º (Fig. 2b) had been investigated. Flattened reed stalks were used for cutting experiments. Displacement, stress and energy data were collected on the computer.

Specific cutting energy per area unit E_{scq} for reed stalk biomass can be calculated using equation:

$$E_{scq} = \frac{E_c}{A}, \tag{1}$$

where E_{scq} – specific cutting energy per area unit, $J \cdot m^{-2}$;
E_c – cutting energy, J;
A – cutting area, m^2.

The maximum angle β between cutterbar knives and counter knives during stalk cutting depends on coefficient of friction between the stalk and blades of knives:

$$\tan\frac{\beta}{2} = \mu . \tag{2}$$

Values of β can be obtained experimentally by means of simple scissor type device. Previously a stated value of coefficient of friction between common reeds stalks and steel sheet material is 0.17, but between reed stalks and rubber sheet material 0.3. For herbaceous stalk material shredder design feed rolls can be used as crushing (flattening) rolls. The relationship of required roll diameter D_r, to diameter of feed stalks D_f, and thickness of product particles D_p, is given [5] by:

$$\cos\frac{\alpha}{2} = \frac{D_r + D_p}{D_r + D_f}, \tag{3}$$

where α – angle of nip (the angle formed by the tangents to the roll faces at the points of contact with the particle.)

For the limiting case, when the stalk is just pulled into the rolls by friction:

$$\tan\frac{\alpha}{2} = \mu , \tag{4}$$

where μ – coefficient of friction between the stalk and the rolls.

Results and discussion

The calculation of flattening rolls for common reeds with average diameter $D_f = 8.5$ mm and thickness of product particles $D_p = 1.25$ mm results in $D_r = 350$ mm (steel rolls) and $D_r = 172$ mm (rubber rolls). For reed canary grass stalks with average diameter $D_f = 5$ mm and thickness of product particles $D_p = 1$ mm results in $D_r = 195$ mm (steel rolls) and $D_r = 95$ mm (rubber rolls). The calculated maximum angle between cutterbar knives and counter knives for common reed stalk cutting is 19.2° and 23° for reed canary grass stalks accordingly. This so named angle of nip had been stated for common reed stalks experimentally. The results of experiments show mean value of angle of nip $\beta = 17.7° \pm 0.2°$. The difference between the calculated value and value determinate experimentally is only 1.5° and mainly depends on individual friction properties of reeds.

Exchange of flattened und unflattened common reed cutting energy consumption during this process is shown in Fig. 2.

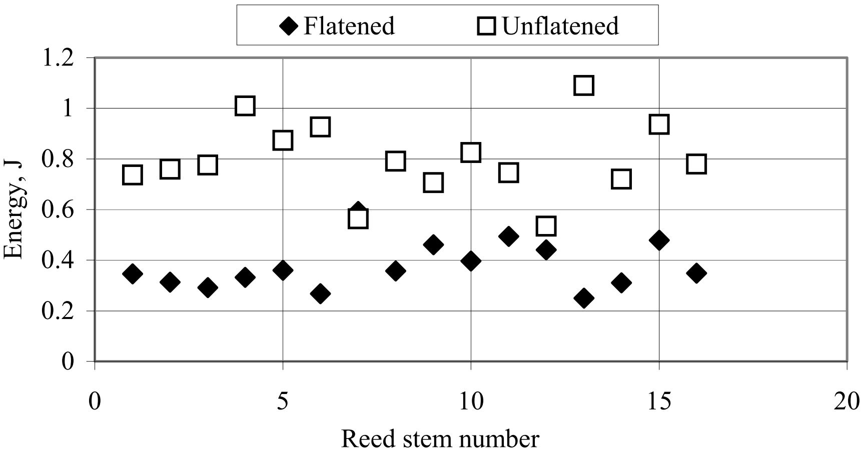

Fig. 2. **Reed stem cutting energy**

From force – displacement diagrams energy consumption for cutting was calculated. Average energy consumption 0.8 J has been stated for unflattened single reed stalk cutting. But average energy consumption for flattened reed cutting is 0.38 J. The difference between flattened and unflattened reed stem cutting energy consumption is 0.42 J. From previous flattening experiments it is stated that flattening energy consumption for reed stem with length 6 cm is 0.2 J. Therefore more economically is to use of flattened reed stems for cutting. It is simpler also for technology, because reed stem transportting can be realized with drive rolls. Cutting energy consumption for two types of knives and flattened reed stem stacks had been stated. For cutting two and three layer stack of flattened reed stalks the knife with edge angle 90º shows twice more energy consumption than knife with edge angle 20º. The differences were not sufficient in the specific energy values for single flattened reed stalk cutting (average difference is approximately 2.4 $kJ \cdot m^{-2}$ for the two types of knives). Therefore for reed stalk stack cutting more favorable will be usage of single reed stalk layers and chopping with cutter which edge angle is 90º. If cutter edge angle is smaller, then cutter edge stays edgeless faster. Sharpening of shredder knives can be serious problem during maintenance. There is possibility of choice during design process. If easy maintenance is preferred, then simple shape of cutter knife edge has to be used. The similar problem is for the choice of shape of cutter counter knives and it has to be solved accordingly. Specific cutting energy per area unit E_{scq} for reed stalk biomass is not significantly changing in dependence of punch orientation angle according cross section of specimen (Fig. 3). E_{scq} value varies in 8 – 16 $kJ \cdot m^{-2}$, depending of stalk strength.

Specific cutting energy per mass unit E_{sc} for stalk material can be calculated using equation:

$$E_{sc} = \frac{E_{scq}}{\rho}, \tag{5}$$

where E_{sc} – specific cutting energy per mass unit, $J \cdot m \cdot kg^{-1}$;
ρ – reed stalk material density, $kg \cdot m^{-3}$.

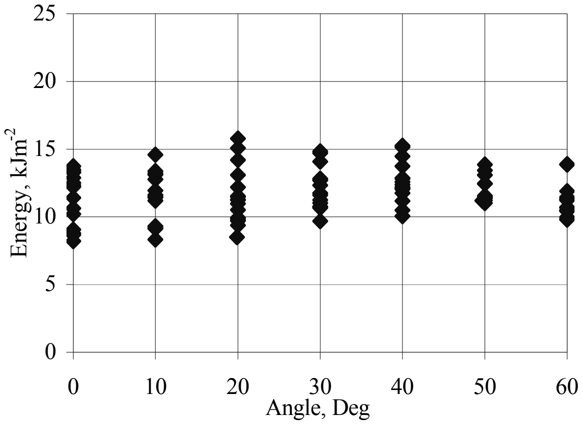

Fig. 3. **Reed stalk specific cutting energy**

Reed stalk material density varies from 500 – 700 kg·m^{-3}. According equation (2) for average density 600 kg·m^{-3} calculated specific cutting energy per mass unit E_{sc} = 13.3 – 27 J·m·kg^{-1}. The value of E_{sc} = 38 J·m·kg^{-1} can be found for alfalfa stalk material [6] cutting energy requirement calculations. These specific cutting energy values are the same order and can be used for calculations in cutting equipment design process. The cutting (chopping) energy E_c for stalk biomass unit (kg) is calculated using equation [7]:

$$E_c = \frac{E_{sc}}{L_c}, \tag{6}$$

where E_{sc} – specific cutting energy per unit mass, J·m·kg^{-1};
L_c – length of stalk cut, m;
E_c – cutting energy per unit mass, J·kg^{-1}.

Energy consumtion for common reed cutting (average specific cutting energy per mass unit E_{sc} = 20 J·m·kg^{-1}) according formula (6) illustrates Fig. 4.

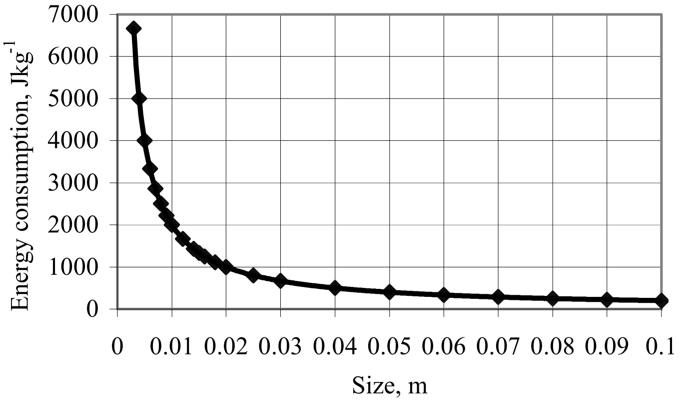

Fig. 4. **Energy consumption for common reed cutting**

Reed stalk material particle size reduction during cutting (shredding) process increases energy consumption very significantly. Wheat straw and switchgrass grinding perfomance investigation [8] shows the same order values of energy consumption per mass unit. The grinds from hammer mill with screen size of 3.2 mm had a large size distribution with a geometric mean particle diameter 0.64 mm for wheat straw and 0.46 mm for switchgrass grinds. Corresponding energy consumption for grinding is 11.36 kW·h·t^{-1} (40.9 kJ·kg^{-1}) for wheat straw and 23.84 kW·h·t^{-1} (85.8 kJ·kg^{-1}) for switchgrass. The calculation of energy consumption for common reed cutting to sizes 0.64 and 0.46 mm is giving results 31.25 kJ·kg^{-1} and 43.48 kJ·kg^{-1}. Taking into account that common reeds have higher values of ultimate tensile and shear strength, this theoretical calculation, without energy losses from friction during shredding process, is giving feasible results. The shredder cutterbar have to be designed with friction energy losses decreased to minimum. This aim can be realised by reducing tfe area of cutterbar knives moving into stalk biomass, and minimizing biomass pressure on cutterbar. With these conditions taken into account common reed specific cutting energy per mass unit $E_{sc} = 13.3 - 27$ J·m·kg^{-1} can be used for shredder cutting energy consumption calculation. Developments of new technologiesfor solid biofuel production from biomass have to create new equipment for this purpose with friction energy losses minimized. There is also a possibility to cut down energy consumption for stalk material shredding by increasing the size of particles for compacting. Peat usage as additive improves densification properties of such increased size stalk material particles. The burning performance of stalk material biomass fuel if we use peat additive is improved also. If only wood chips or herbaceous biomass are burned, the sulphur content is low [9] and chlorides are formed. The chlorides then tend to condense on heat transfer surfaces of the steam boiler, slowing down the heat transfer and causing the risk of high temperature corrosion. If the sulphur content of the fuel is increased, e.g. by blending peat with chips or herbaceous biomass, sulphates are formed instead of chlorides. There is an advantage of using peat with woody or herbaceous biomass, because the formation of chlorides during combustion process is avoided.

Conclusions

1. For small scale biofuel production usage of square bales with size 0.36×0.5×0.8 m is preferable.
2. The calculation of flattening rolls for common reeds results in $D_r = 350$ mm (steel rolls) and $D_r = 172$ mm (rubber rolls).
3. For reed canary grass stalks the calculation of flattening rolls results in $D_r = 195$ mm (steel rolls) and $D_r = 95$ mm (rubber rolls).
4. The difference between the calculated value of angle of nip ($\beta = 19.2°$ for common reeds) and value, determinated experimentally ($\beta = 17.7° \pm 0.2°$), is only 1.5° and mainly depends on individual friction properties of reeds.
5. Usage of single reed stalk layers for shredding with cutter which edge angle is 90º for shredder easy maintenance is preferred.
6. Increasing the size of stalk material particles for compacting cuts down energy consumption for stalk material shredding.
7. There is a double advantage of using peat with herbaceous biomass for briquetting, because peat addition improves densification properties of increased size stalk material particles and the formation of chlorides during combustion process is avoided.

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