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Original article

Simulation study of cutting sugarcane using fine sand abrasive waterjet

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ABSTRACT

Current rotary blade choppers for sugarcane harvesting have the disadvantage of becoming clogged with leaves/cane around the rotating blades causing them to hit the ground and rocks that result in rapid blade wear and tear. Dull blades require repeated cane cutting attempts causing damage to the cane and increasing the cutting force and energy requirements. Thus, the search for alternative, non-contact, cutting options such as waterjet (WJ) cutting has been undertaken. The results indicated that WJ cutting has potential but weaknesses have also been reported. Hence, this study explored the use of abrasive fine sand (AWJ) to overcome the weaknesses of the pure WJ cutting application. Using the Hoogstrate model and a MATLAB program, AWJ cutting simulation was performed using an orifice and nozzle diameter combination of 0.25 and 0.76 mm at 360 MPa water pressure, respectively, which produced a water flow rate of 1.6 L/min and a power input of 15 kW. Other parameters used in the test included: 80 mesh fine river sand abrasive materials, a specific cutting energy of 8.7×10^{-3} J/mm^3 and a fitted cutting efficiency of 0.35. The experimental results revealed that the system was able to cut sugarcane stalks completely at a much farther standoff distance by reducing the traverse speed. The study also showed that cutting sugarcane of 30 and 120 mm diameters would require a traverse speed of 4.4 km/h and 1.1 km/h, respectively. The results implied that limitations should be set for sugarcane thickness for the optimum traverse speed and a standoff distance should be set to no more than 210 mm with a minimum traverse speed of 0.6 km/h.

Introduction

Sugarcane harvesting involves cutting of the plant stalks at ground level. Traditional harvesting of sugarcane is done manually using hand cutters, which is quite laborious, time-consuming and expensive (Emerson, 2007). Burning the field before harvest is a common practice to make sugarcane cutting simpler and more efficient (Sangla and Suppadit, 2005). However, burning also contributes to gas and smoke emissions, which could be hazardous to human health and the environment (global warming), as well as causing soil and sugarcane deterioration (Eggleston et al., 2008; Ribeiro, 2008).

To simplify the harvesting process and to cope with the diminishing supply and increasing cost of labor, mechanical harvesters/cutters were developed (Iwai and Emerson, 2008). Harvesting of sugarcane involves cutting at the internode of the base stalk. The sugarcane stalk is divided into nodes and internodes, with the internodes being the softer part (Persson, 1987). Chopper harvesters, which utilize rotary blade cutters have been reported to not only maximize the quantity and quality of sugarcane production (Norris et al., 1998) but also to greatly reduce the burnt sugarcane labor requirements (Eggleston et al., 2008) and hasten the harvesting process (Iwai and Emerson, 2008).

To develop or design an appropriate mechanical sugarcane cutter, the physical and mechanical properties of sugarcane need to be taken into consideration. Yangyuen and Wongpichet (2006) reported that physical properties such as the cane length, stalk diameter, static friction coefficient between the sugarcane and mild steel surfaces, cross-sectional area and density are important in

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designing cane cutters. Moreover, data on the mechanical properties such as stress–strain curve, Young's modulus, toughness, modulus of rupture, energy of rupture, energy of fracture, hardness, shear strength, compressive strength and Poisson's ratio, which can be obtained through static or impact tests, are also required (Chang et al., 1982). All the above-mentioned properties though, depend on the plant species, variety, stalk diameter, maturity, moisture content, cellular structure, plant height, stalk-cutting direction and bending-plant knockdown (Shinners et al., 1987).

Taghijarah et al. (2011) reported that cutting sugarcane stalks (IRC99–01 variety) at an average moisture content of 75.27% wet basis (%w.b.) and average stalk diameter and area of 23.9 mm and 453 mm^2, respectively, required an average shear strength and specific energy of 3.64 MPa and 51.41 mJ/mm^2, respectively. Typical straight backward-forward-blade cutting of sugarcane requires an average specific cutting energy of 21.8 mJ/mm^2 (Mello and Harris, 2003). Taghinezhad et al. (2013) reported the average specific cutting energy requirements of 34.071 mJ/mm^2, 28.339 mJ/mm^2 and 16.297 mJ/mm^2 for sugarcane of low (0–10%), medium (10–50%) and high (50–75%) moisture content levels (%w.b.), respectively. Cutting sugarcane with an average stalk diameter of 21.7 mm at 90° and 45° orientations (parallel and at a 45° inclination to the cane cross section, respectively) at 15–20%w.b. levels yielded a mean specific internodal cutting energy of 10.02 mJ/mm^2 and 6.978 mJ/mm^2, respectively (Taghinezhad et al., 2012).

The use of a rotary blade contact-cutter/harvester caused clogging with leaves and canes in the harvester's rotating parts (Valco et al., 1989). Repeated cutting during harvest damages the stalk (Hu et al., 2011). Harvester knives hitting the ground or rocks results in rapid blade wear and thus need more cutting force and energy (Mello and Harris, 2003). An alternative non-contact cutting method using a waterjet has been used to cut sugarcane stalks under laboratory conditions by Valco et al. (1989). However, using a waterjet in a sugarcane field seems impractical because of the large standoff distance and energy requirements as well as the exceedingly high water flow rate (in excess of 7 L/min) needed.

To overcome the waterjet's weaknesses hindering its use in the field, this study was conducted using an abrasive waterjet (AWJ). The objective was to determine if an AWJ would be able to attain the necessary conditions where previously a waterjet had failed, for example, by using a lower water flow rate, lower energy requirement, larger cut depth and larger traverse speed. The AWJ tool parameters needing optimization to obtain the desired cutting performance include: suitable orifice and nozzle diameters, the required water pressure, appropriate waterjet force and power, the type and size of abrasive material, the optimum abrasive mass flow rate, sufficient cut depth, a suitable traverse speed, quality of surface cut, sufficient standoff distance and the physical dimensions of the material to be cut.

Materials and methods

The study was conducted in two major phases: 1) modeling the AWJ cutting process and 2) simulation of sugarcane stalk cutting by the AWJ.

Phase 1- modeling the abrasive waterjet cutting process

To simulate the cutting process by the waterjet and the abrasive waterjet, several parameters need to be defined and calculated and these are described as follows:

Waterjet cutting parameters

A pure waterjet (WJ) and an abrasive waterjet (AWJ) are extensively used in material cutting industries. Waterjet cutting is achieved by applying an ultrahigh pressure of about 300 MPa–900 MPa to force water into a small diameter orifice at an extremely high speed of about 300 m/s to 1000 m/s (Mohamed, 2004). The hydrostatic energy from the high water pressure is thus transformed to kinetic energy, enabling it to cut the material by erosion. This method is normally used for cutting soft materials such as meat, wood, vegetables, paper and plastic (Kulekci, 2002). With the abrasive waterjet, cutting is achieved through the combined impacts of the waterjet and the abrasive materials, which has been proven to perform better than the pure WJ cutting method (Lefevre et al., 2004). As a result, an AWJ is widely used for machining brittle and ductile materials such as aluminum, stainless steel, titanium, glass and composites (Akkurt et al., 2004). The waterjet at the outlet of an orifice can be categorized into three zones namely, the solid jet zone, the spray zone and the droplet zone (Fig. 1). The solid jet zone is responsible for producing a kerf with a narrower, deeper, more accurate and faster cutting speed than the other zones. Jet length (l_c) is defined as the region where the jet diameter is smaller than the nozzle diameter. The spray zone contains very small droplets of low energy that normally have no impact on the material to be cut (Mohamed, 2004).

The velocity of the waterjet at the outlet of the orifice, v_j (in meters per second) can be calculated by combining the density of compressible water and Bernoulli's equation (Susuzlu and Hoogstrate, 2006), as expressed in Equation (1):

$$v_j = \sqrt{\frac{2E_0}{\rho_0(n-1)}\left[\left(1+\frac{np}{E_0}\right)^{1-\frac{1}{n}} - 1\right]} \tag{1}$$

where $\rho_0 = 1000$ kg/m^3, which is the density of ambient water, and p is the water pressure (measured in mega pascals). $E_0 = 2135$ MPa and $n = 7.15$ are the experimental coefficients (Bridgman, 1970). The actual water flow rate $\dot{q}$ (in cubic meters per second) can be calculated using Equation (2) (Susuzlu et al., 2004):

$$\dot{q} = c_d A_0 v_j \tag{2}$$

where A_0 is the cross-sectional area of the orifice measured in square meters and c_d is the dimensionless coefficient of discharge. The coefficient of discharge, the contraction and the velocity coefficients are all derived from experimental data. Normally, the coefficient of discharge is in the range 0.6–0.8 for a sharp-edged sapphire orifice (Momber and Kovacevic, 1998). Hashish (1989) and Pi (2008) reported that the coefficient of discharge maybe reduced by increasing the water pressure or the orifice diameter. Hashish (2002) introduced a linear equation to calculate the coefficient of discharge for a sharp-edged sapphire orifice. His equation

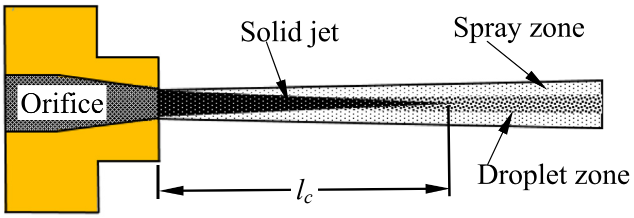

Fig. 1. Jet structure on the orifice or nozzle outlet where l_c is the jet length.
Source: Modified from: Mohamed (2004).