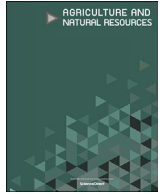


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Original article

## 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  $8.7 \times 10^{-3}$  J/mm<sup>3</sup> 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.

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## 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

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steel surfaces, cross-sectional area and density are important in 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<sup>2</sup>, respectively, required an average shear strength and specific energy of 3.64 MPa and 51.41 mJ/mm<sup>2</sup>, respectively. Typical straight backward-forward-blade cutting of sugarcane requires an average specific cutting energy of 21.8 mJ/mm<sup>2</sup> (Mello and Harris, 2003). Taghinezhad et al. (2013) reported the average specific cutting energy requirements of 34.071 mJ/mm<sup>2</sup>, 28.339 mJ/mm<sup>2</sup> and 16.297 mJ/mm<sup>2</sup> 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<sup>2</sup> and 6.978 mJ/mm<sup>2</sup>, 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):

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

where  $\rho_0 = 1000 \text{ kg/m}^3$ , which is the density of ambient water, and  $p$  is the water pressure (measured in mega pascals).  $E_0 = 2135 \text{ MPa}$  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):

$$\dot{q} = c_d A_0 v_j \quad (2)$$

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

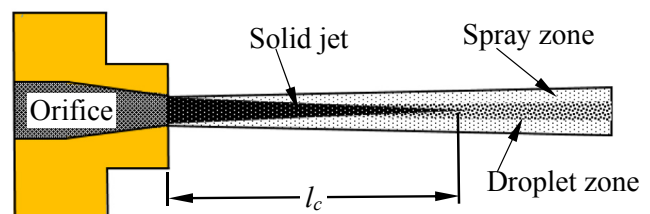


Fig. 1. Jet structure on the orifice or nozzle outlet where  $l_c$  is the jet length. Source: Modified from: Mohamed (2004).

is applicable for any orifice diameter in the range 0.152 mm–0.584 mm and any orifice outlet pressure in the range 105 MPa–240 MPa and is expressed as Equation (3). He reports his equation has 8% accuracy.

$$c_d = 0.785 - 0.00014p - 0.197d_0 \quad (3)$$

where  $d_0$  is the orifice diameter measured in millimeters and  $p$  is the water pressure measured in mega pascals.

The actual waterjet power  $P_j$  (measured in watts) at the orifice outlet can be determined from Equation (4):

$$P_j = \frac{1}{2} \dot{m}_w v_j^2 = \frac{1}{2} c_d \rho_0 A_0 v_j^3 \quad (4)$$

where  $\dot{m}_w = \rho_0 \dot{q}$ , which is the mass flow rate of water measured in kilograms per second.

#### Abrasive waterjet cutting parameters

In the abrasive waterjet cutting method, the jet at the outlet of the orifice is a mixture of abrasive particles and water. The mixture flows from the mixing chamber and passes through the focus tube of the nozzle. A typical AWJ nozzle is illustrated in Fig. 2.

The velocity of the abrasive particles  $v_{awj}$  depends on the waterjet velocity at the orifice outlet  $v_j$ , both measured in meters per second, the water mass flow rate  $\dot{m}_w$  and the abrasive mass flow rate  $\dot{m}_a$  both measured in kilograms per second. The velocity of the abrasive particles can be determined by momentum conservation (Hashish, 1989) as expressed in Equation (5):

$$v_{awj} = \eta \frac{v_j}{1 + \dot{m}_a / \dot{m}_w} \quad (5)$$

where  $\eta$  is the dimensionless momentum transfer efficiency.

The momentum transfer efficiency  $\eta$  was introduced by Hoogstrate (2000) as Equation (6):

$$\eta = c_1 - c_2 R \quad (6)$$

where  $c_1$  and  $c_2$  are constants obtained by experiment with typical values of 1 and 1.6, respectively, for a 0.8 mm nozzle diameter using #150 Barton garnet abrasive particles and  $R$  is the abrasive load ratio.

Hoogstrate (2000) introduced the abrasive waterjet cutting model in which the transformation energy from a pure waterjet to abrasive particles was determined using Equation (7):

$$P_{abr} = kP_j \quad (7)$$

where  $P_{abr}$  is the abrasive waterjet power and  $P_j$  is the actual waterjet power both measured in watts and  $k$  is the dimensionless power transfer efficiency as determined in Equation (8):

$$k = \eta^2 \frac{R}{(1 + R)^2} \quad (8)$$

where  $R$  is the abrasive load ratio between the abrasive mass flow rate and the water mass flow rate.

Oweinah (1989) studied the effect of the abrasive mass flow rate on the maximum depth of cut and the results obtained revealed that a 0.25 mm-diameter orifice is suitable for a nozzle of 0.8 or 1.2 mm diameter. Combining the above parameters and the abrasive mass flow rate of 7 g/s (420 g/min) produced the maximum cut depth. The cost of using an AWJ was estimated to be 70% of the total cutting cost (Hoogstrate et al., 2006). An  $R$  value of about 0.17 was found appropriate for an orifice/nozzle combination of 0.25/0.76 mm/mm (Chalmers, 1991). Using an orifice/nozzle combination of 0.25/0.9 mm/mm in a 100- $\mu$ m garnet-abrasive waterjet flowing at a rate of 300 g/min, with a water pressure of 300 MPa and a cutting speed of 1.67 mm/s to cut AlMgSi0.5, a ductile material, Ohlsen (1997) found that the maximum depth of cut was only 94–100% of the maximum that was obtained using 80–140  $\mu$ m abrasive particles.

The relationship between the power transfer efficiency and the abrasive load ratio, shown in Fig. 3, was plotted using the data from Hoogstrate (2000). However, the model was only applicable to ductile materials and not soft materials such as papers and plastics as these materials are unable to be cut by a pure waterjet nor by abrasive brittle materials composed of granite, marble and glass.

The material removal rate  $Q_{mat}$  (in cubic millimeters per second) of the work material was calculated using Equation (9):

$$Q_{mat} = \frac{\xi P_{abr}}{e_c} \quad (9)$$

where  $e_c$  is the specific cutting energy of the work material measured in joules per cubic millimeter and  $\xi$  is the cutting efficiency coefficient, also called the AWJ cutting efficiency. The  $e_c$  and  $\xi$  values are derived from experimental data.

Typically, the specific cutting energy requirements for aluminum and glass are 2.5 and 1.7 J/mm<sup>3</sup>, respectively. The relationship between the specific cutting energy ( $e_c$ ) measured in joules per cubic millimeter and the machinability number  $N_m$  is as depicted in Equation (10) (Hoogstrate, 2000):

$$e_c = \frac{611}{N_m} \quad (10)$$

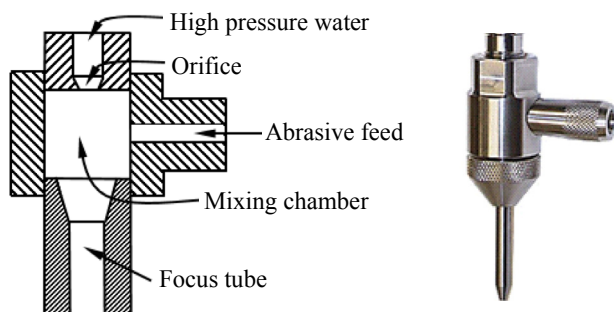


Fig. 2. Typical AWJ nozzle diagram and actual nozzle.

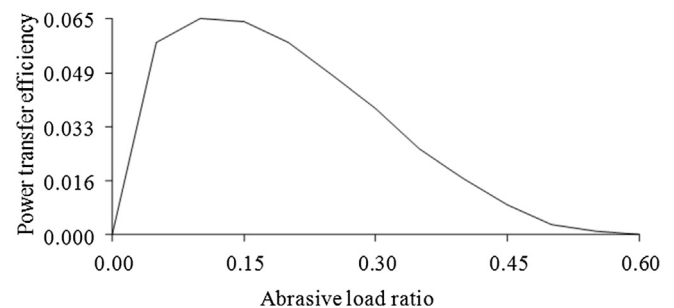


Fig. 3. Power transfer efficiency with respect to abrasive load ratio. Source: Modified from: Hoogstrate (2000).

where the machinability number for various materials can be obtained from the study of Zeng (2007). For example, the  $N_m$  values for stainless steel-grade 316, aluminum-6061 and limestone are to 82.5, 219.3 and 6156.4, respectively.

The AWJ cutting efficiency depends on various parameters such as the traverse speed, abrasive size, water pressure and abrasive load ratio. However, the AWJ cutting efficiency has a linear relationship with the traverse speed over a defined narrow range (Hoogstrate, 2000). A typical AWJ cutting efficiency is in the range 0.4–0.6 (Pi, 2008).

By assuming that the cutting width is uniform throughout the cut depth (which is equal to the focusing tube diameter  $d_f$  measured in millimeters) and assuming that the waterjet energy has no effect on the material being cut, the maximum cut depth,  $h_{max}$  (measured in millimeters) can then be predicted using Hoogstrate's model, expressed in Equation (11) (Hoogstrate, 2000):

$$h_{max} = \xi \left( v_f \right) \frac{P_{abr}}{e_c d_f v_f} \quad (11)$$

where  $e_c$  is the specific cutting energy measured in joules per cubic millimeter,  $P_{abr}$  is the abrasive waterjet power measured in joules per second and  $v_f$  is the traverse velocity measured in millimeters per second.

#### Specific cutting energy of sugarcane

The specific cutting energy presented in Equation (11) can be calculated using Equation (12):

$$e_c = \frac{Fv}{tdv} = \frac{F}{1000td} \quad (12)$$

where  $F$  is the cutting force measured in newtons,  $v$  is the cutter velocity measured in millimeters per second,  $t$  is the cutter thickness and  $d$  is the sugarcane stalk diameter both measured in millimeters. It is defined as the ratio of the energy required for cutting to the volume of material removal and it is determined by dividing the cutting power by the sugarcane removal rate. By assuming that the sugarcane removal thickness is equal to the cutter thickness, the specific cutting energy in joules per cubic millimeter can thus be simplified as is shown in Equation (12). The schematic diagram of sugarcane cutting is shown in Fig. 4.

The results of other studies conducted on sugarcane cutting energy requirements all indicated that the cutting force or specific cutting energy requirements depend on the sugarcane and knife edge characteristics. Typical values of the specific cutting energy

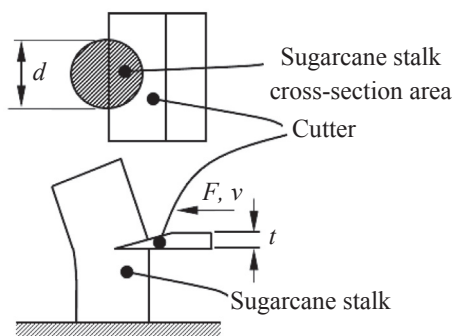


Fig. 4. Schematic diagram of sugarcane cutting, where  $F$  is the cutting force measured in newtons,  $v$  is the cutter velocity measured in millimeters per second,  $t$  is the cutter thickness and  $d$  is the sugarcane stalk diameter both measured in millimeters.

requirement ranged from 6.978  $\text{mJ}/\text{mm}^2$  to 51.41  $\text{mJ}/\text{mm}^2$ . Cutting sugarcane of 50–75%w.b. with an average diameter of 21.8 mm using a commercial sugarcane cutting edge with a single slant angle of 30° and a 60° notch angle, Taghinezhad et al. (2013) found that the peak cutting force was at 602 N. Using 602 N as the cutting force of a cutter thickness ( $t$ ) of 3.175 mm, on sugarcane diameter ( $d$ ) of 21.8 mm in Equation (12), the specific cutting energy for sugarcane was found to be equal to  $8.7 \times 10^{-3} \text{ J}/\text{mm}^3$ .

The mean specific cutting energy of sugarcane stalks at low (0–10%), medium (10–50%) and high (50–75%) levels of moisture content were 34.071  $\text{mJ}/\text{mm}^2$ , 28.339  $\text{mJ}/\text{mm}^2$  and 16.297  $\text{mJ}/\text{mm}^2$ , respectively (Taghinezhad et al., 2013). With high levels of moisture content, a decrease in the moisture content from 78% to 46% produced a 16.7% decrease in the specific shearing energy of sugarcane (Hemmatian et al., 2012). However, a decrease in the moisture content from high to medium levels produced a 73.89% increase in the specific energy (Taghinezhad et al., 2013).

#### Fitting abrasive waterjet cutting efficiency

Using the data of Lefevre et al. (2004) with AWJ cutting of stainless steel (INOX), the AWJ cutting efficiency fit was tested. The AWJ system parameters in the study included: water pressure of 350 MPa and 600 MPa, an orifice diameter of 0.25 mm, a nozzle diameter of 1.10 mm and an 80 mesh Australian garnet mass flow rate of 320 g/min. The specific cutting energy for stainless steel was 7.46  $\text{J}/\text{mm}^3$  (Zeng, 1992; Pi, 2008). The traverse speed ranged between 0.6 mm/min and 130 mm/min and between 1 mm/min and 320 mm/min for water pressures of 350 MPa and 600 MPa, respectively. The traverse speeds tested produced a cut depth of 200 mm–10 mm. Assuming that the jet stream in the distant positions from the nozzle exit is spread into a conical volume, then the cutting efficiency fitted the 3rd order polynomial of the “polyfit” command on MATLAB. Moreover, to ensure fit accuracy of the AWJ cutting efficiency, the AWJ cutting simulations of traverse speeds were compared with those of the AWJ manufacturer's cutting data for aluminum and stainless steel.

#### Phase 2- simulation of the sugarcane stalk cutting using an abrasive waterjet

##### Abrasive materials

In this study, 80 mesh fine river sand was used as an alternative to garnet, a commonly used abrasive in the industry. To ensure that the abrasive materials used in the study were comparable to garnet, performance tests of garnet and fine river sands on cutting a 5 mm steel plate were conducted and the kerfs produced by the respective abrasive materials were compared.

##### Sugarcane cutting simulation using an abrasive waterjet

The major advantages of using an AWJ in sugarcane fields are: a low water flow rate, a low energy requirement, a large cut depth and a high traverse speed. The water flow rate determines the amount of water that a harvester should carry. For example, a harvester with continuous water injection working for 8 h a day at a water flow rate of 3.2 L/min would need to carry 1536 L per day. However, if the water injection could be controlled to flow periodically instead of continuously, then the water requirement would be reduced which means that much less water would be needed to be carried by the harvester. Likewise, a typical hydraulic motor for conventional base cutters requires a 50 hp motor to rotate the base cutters in the range 1000 revolutions per minute to 1500 revolutions per minute (Payton, 1980). In the AWJ system, the energy required to generate the necessary water pressure needed could be assumed to be less. The cut depth affects cutting

**Table 1**  
Water flow rates and the energy levels of AWJ relative to WJ.

	Actual water flow rate (L/min)	Power input (kW)
WJ of Valco	3.2	36.4
AWJ	1.6	15.0

performance—with typical sugarcane field distances at 460 mm (Valco et al., 1989), a cut depth of 230 mm was feasible using a two-nozzle WJ system. Using a similar system for an AWJ, it could also be presumed a deeper cut depth might be achievable. Although a greater traverse speed implies higher cutting efficiency, the damage caused by the rapid cutting of sugarcane stalks cutting needs further attention. The tests made on AWJ sugarcane cutting in this study were based on a maximum traverse speed of 0.36 km/h.

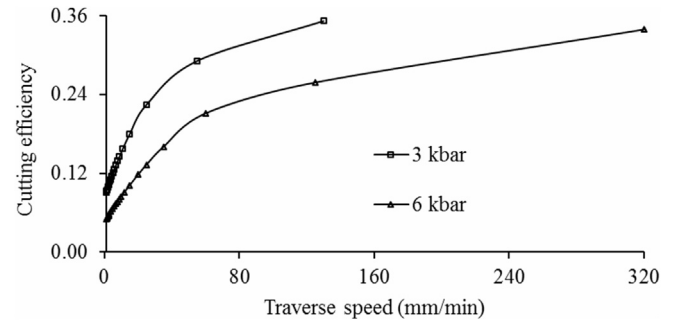
Sugarcane of 29 mm stalk diameter was used in both the pure and abrasive waterjet cutting tests. In the AWJ case, the ratio of orifice to nozzle diameters was set at 0.25 mm per 0.76 mm. The water pressure and flow rate were set at 360 MPa and 1.6 L/min, respectively. To find the optimum cutting condition, traverse speeds and standoff distance were varied from 600 mm/min to 6000 mm/min and from 3 mm to 180 mm, respectively. Because the maximum cutting energy for cutting sugarcane stalk was obtained at 90° stalk orientation (Taghinezhad et al., 2012), all tests in this study were made using the same orientation. Since the moisture content of sugarcane has substantial effects on the specific cutting energy, one end of the canes for testing was buried in moist soil to not only retain the moisture but also to keep them fresh longer.

The maximum traverse speed of the AWJ machine in the study (the speed of the harvester), was 6000 mm/min or 0.36 km/h. In the pure waterjet case, six trial tests were performed with standoff distances of 3 mm, 15 mm, 50 mm, 100 mm, 150 mm and 180 mm and traverse speeds of 600 mm/min, 1500 mm/min, 2500 mm/min, 3500 mm/min and 6000 mm/min, respectively. The total distance between the sugarcane and the nozzle was 209 mm.

Another six trial tests were conducted using a fixed standoff distance of 250 mm. Sugarcane with a 26 mm stalk diameter was subjected to AWJ cutting using varying traverse speed of 4000 mm/min, 3800 mm/min, 3700 mm/min, 3600 mm/min, 3500 mm/min and 3000 mm/min, respectively. The total distance between the sugarcane and the nozzle was 276 mm.

Using a fixed standoff distance of 180 mm, four stalks of sugarcane of 26 mm diameter were subjected to AWJ cutting by varying traverse speed to 3000 mm/min, 1000 mm/min, 500 mm/min and 250 mm/min. The total distance between the sugarcane and the nozzle was 284 mm.

Using the Hoogstrate model (Equation (11)), the maximum cut depth in the AWJ sugarcane cutting was predicted. The MATLAB



**Fig. 6.** Waterjet cutting efficiency versus traverse speed at different water pressure.

program was used to calculate the sugarcane AWJ cutting parameters using Equations (1)–(11). The dimensions of the parameters used were: water pressure of 360 MPa, orifice diameters of 0.25 mm, nozzle diameter of 0.76 mm, 80 mesh abrasive (fine sand) mass flow rate of 320 g/min and a sugarcane specific cutting energy of  $8.7 \times 10^{-3} \text{ J/mm}^3$ . The AWJ cutting efficiency was obtained from the data fit previously described.

*AWJ cutting calculations*

The power input (in watts) at the orifice inlet was determined using Equation (13):

$$P = (\pi/8)\rho_0 d_0^2 v^3 \tag{13}$$

where  $\rho_0$  is 1000 kg/m<sup>3</sup>  $d$  is the orifice diameter (in meters)  $p$  is the water pressure (in pascals) and  $v = \sqrt{2p/\rho_0}$  (in meters per second).

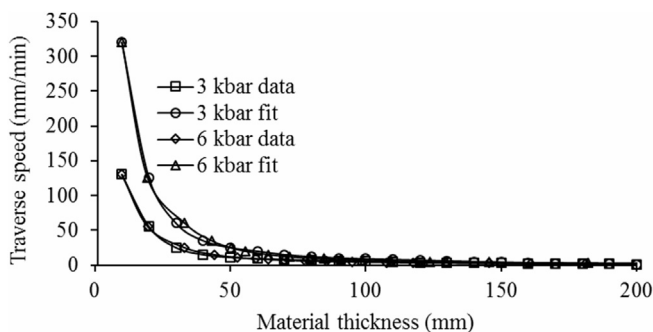
The calculation did not include the effects of compression or contraction, compressible velocity and water friction based on the orifice geometry. The actual water flow rate was determined using Equations (1)–(3).

**Results and discussion**

Table 1 presents the actual water flow rates and energy levels of the AWJ and the Valco WJ, respectively. The results showed that the AWJ did indeed perform better than the Valco WJ in terms of reducing the actual water flow rate and power input by 50 and 58.8%, respectively.

*Abrasive waterjet cutting simulation study*

Using the MATLAB program fitting for INOX stainless steel cutting of varied thickness and water pressure, the corresponding traverse speed was obtained (Fig. 5). The AWJ cutting efficiency



**Fig. 5.** Traverse speed versus the INOX thickness data fitting with the data generated by Lefevre et al. (2004).

**Table 2**  
Calculated traverse speed ( $v_f$ ) using Hoogstrate model versus KMT waterjet's introduced traverse speed.

Material type	Thickness (mm)	$d_0/d_f = 0.25/0.76 \text{ mm/mm}$ (orifice to nozzle diameter)		
		KMT waterjet traverse speed, $v_f$ (mm/min)	Cutting efficiency, $\xi(v_f)$	Calculated traverse speed using Hoogstrate's model, $v_f$ (mm/min)
Aluminum	5	595–855	0.17	610
	10	270–385	0.17	305
	20	120–175	0.17	150
Stainless steel	5	205–295	0.15	205
	10	95–135	0.15	105
	20	45–60	0.15	50



Fig. 7. Sugarcane cutting using a waterjet.

based on the data fittings against the traverse speed shows that the cutting efficiency and the traverse speed are directly related (Fig. 6). By increasing the water pressure from 3 kbar to 6 kbar, the traverse speed increased more at a higher water pressure for the same cutting efficiency which ranged from 0.05 to 0.35. A comparison between traverse speeds calculated using the Hoogstrate model for aluminum and stainless steel cutting and values provided by KMT Waterjet (2015) is presented in Table 2. MATLAB simulations were performed. The cutting parameters include the following: water pressure of 360 MPa, garnet abrasive (surface quality of medium to fine) mass flow rate of 250 g/min and an orifice/nozzle diameter of 0.25/0.76 mm/mm. The results show that aluminum required a cutting efficiency of 0.17 calculated using the Hoogstrate model to produce a traverse speed in the range of the introduced traverse speed while stainless steel required only 0.15 cutting efficiency to come up to a similar traverse speed.

Cutting sugarcane with a 29 mm stalk diameter at a traverse speed of 6000 mm/min and a standoff distance range of 3 mm–150 mm using a pure waterjet resulted in complete penetration of the stalk. However, under the same conditions but increasing the standoff distance further to 180 mm, the pure waterjet failed to cut the stalk completely (Fig. 7) while the AWJ achieved a complete penetration of the stalk. The test results revealed that the waterjet could cut sugarcane at a standoff distance of 150 mm and a traverse speed of 6000 mm/min. However, in the last tests, it was found that a waterjet with a standoff distance of 180 mm, a stalk diameter of 29 mm and a traverse speed of 6000 mm/min was able to penetrate 26 mm and 27 mm of the stalk only whereas the two tests conducted on sugarcane using AWJ with a garnet abrasive mass flow rate of 328 g/min was able to cut the stalk completely. The total cutting distance was 209 mm.

Steel has a specific cutting energy close to that of stainless steel. Testing the AWJ cutting on a 5 mm steel plate using garnet as the

abrasive material traversing at a speed of 200 mm/min showed complete penetration of the steel plate. The same result was achieved when garnet was substituted with fine sand as the abrasive material (Fig. 8). To test for the maximum standoff distance for the AWJ to achieve complete sugarcane stalk (26 mm diameter) penetration, the standoff distance was set to a maximum distance of 250 mm. The results indicated that it failed to achieve complete sugarcane stalk penetration. At traverse speeds of 4000 mm/min, 3800 mm/min, 3700 mm/min, 3,600 mm/min and 3500 mm/min, the AWJ was able to almost cut the stalk completely except for the skin. Complete penetration though was achieved when the traverse speed was reduced to 3000 mm/mm. The total cutting distance was 276 mm.

Using a fixed standoff distance of 180 mm, four sugarcane stalks of 26 mm diameter were subjected to AWJ cutting using varying traverse speed from 3000 mm/min to 250 mm/min. The total cutting distance was 284 mm. At a traverse speed of 3000 mm/min, 1000 mm/min, 500 mm/min and 250 mm/min, one, two, three and four stalks, respectively, were completely cut. By lowering the traverse speed, a larger kerf width was produced, demonstrating the evident cutting power and sugarcane pith losses (Fig. 9).

MATLAB simulations were performed using the Hoogstrate model (Hoogstrate, 2000) to predict the traverse speed and cut depth in sugarcane cutting and selecting an AWJ cutting efficiency of 0.35 (based on the hardness of the stalk material in comparison to steel) and assuming that the kerf width is uniform throughout the depth of cut ( $h_{max}$ ) and is equal to the focus tube or nozzle diameter ( $d_f$ ). Tests were performed to determine a suitable nozzle diameter for a 0.25 mm orifice diameter.

Table 3 presents the results of the MATLAB simulation showing that the suitable nozzle diameter for a 0.25 mm orifice diameter was 0.76 mm based on the maximum traverse speed obtained for all cut depths tested. Large kerfs generally required a slower traverse speed but the last column of the table shows that the 0.75 mm-nozzle diameter resulted in a higher traverse speed than did the 1 mm-nozzle diameter producing the same kerfs size. The results also show an inverse relationship between the traverse speed and the thickness of the cut material. For example, a 30 mm sugarcane diameter requires a traverse speed of 4.4 km/h; whereas by doubling the sugarcane diameter to 60 mm, the traverse speed was simultaneously reduced by half to 2.2 km/h. A further doubling of the sugarcane thickness to 120 mm, resulted in the AWJ system's traverse speed being further halved to 1.1 km/h. The results imply that the findings can be used in designing an AWJ machine for sugarcane cutting harvesting by setting limitations on the sugarcane thickness to optimize the traverse speed and to set the standoff distance to no more than 210 mm for a minimum traverse speed of around 0.6 km/h.

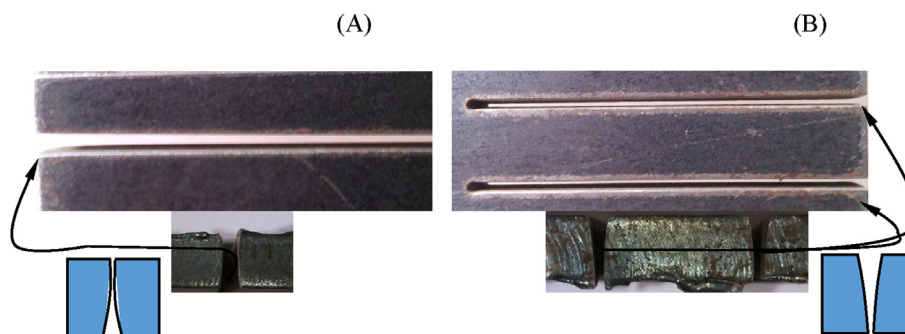


Fig. 8. Waterjet with abrasive cutting a 5 mm steel plate using: (A) garnet abrasive, where the kerf has V-reversed taper because the nozzle runs at low traverse speed; and (B) fine river sand, where the kerf has V-shaped taper because the nozzle runs at high traverse speed.



Fig. 9. Kerfs in the sugarcane stalk, positioned further from nozzle.

**Table 3**  
MATLAB simulation to obtain the suitable nozzle diameter for a 0.25 mm orifice diameter.

Cut depths, $h_{\max}$ (mm)	$d_f = 1.1$ mm	$d_f = 1$ mm	$d_f = 0.90$ mm	$d_f = 0.76$ mm	$d_f = 0.76$ mm
	$e_c = 0.0087 \times 1.1$	$e_c = 0.0087 \times 1$	$e_c = 0.0087 \times 0.9$	$e_c = 0.0087 \times 0.76$	$e_c = 0.0087 \times 1$
Traverse speed					
	$v_f$ (km/hr)	$v_f$ (km/hr)	$v_f$ (km/hr)	$v_f$ (km/hr)	$v_f$ (km/hr)
20	3.2	3.8	4.7	6.6	5.0
30	2.1	2.6	3.2	4.4	3.4
40	1.6	1.9	2.4	3.3	2.5
50	1.3	1.5	1.9	2.6	2.0
60	1.0	1.3	1.6	2.2	1.7
120	0.5	0.6	0.8	1.1	0.8
160	0.4	0.5	0.6	0.8	0.6
210	0.3	0.4	0.4	0.6	0.5

$d_f$  = focus tube diameter;  $e_c$  = specific cutting energy;  $v_f$  = traverse velocity.

#### Future practical possible abrasive waterjet application

Considering that the sugarcane distance in the field is about 420 mm, it would therefore be necessary for an AWJ harvester to have a V-shaped device to force the sugarcane stalks to stick together before the cutting process commenced.

Thus, with the maximum cut depth of 210 mm obtainable from this study, the AWJ should use two nozzles placed opposite each other for more efficient cutting capability. The water flow rate and abrasive mass flow rate of the AWJ with the two nozzles would be 3.2 L/min and 740 g/min, respectively. Assuming that a harvester works 8 h per day in the field, it would then need to carry 1536 L of water and 355.2 kg of abrasive sand per day for continuous AWJ operation. However, if sensors could be installed to automatically control water valves to open and close periodically as cutting was required, then the water flow would be minimized. A similar detection device maybe installed to regulate the mass flow of the sand, suggesting a reduction in the amount of water and sand load for the harvester.

Considering that water for use by the AWJ system needs pre-treatment such as softening, deionization and reverse osmosis, while the abrasive sand also needs sifting in an 80-mesh sieve and both materials are waste following the cutting operation, it would be both beneficial and interesting if a cost effective way of recycling them could be worked out.

A large traverse speed requirement implies that a large engine for the harvester is needed. A suitable selection of a pump for an AWJ based on this study is a 50 hp hydraulic pump with a maximum water flow rate of 3.6 L/min and a pressure range of 50–380 MPa (KMT Waterjet, 2015). This hydraulic pump for the AWJ sugarcane harvester would then be the same as that required to drive the base cutter of a conventional harvester.

#### Conclusion

Abrasive waterjet cutting simulation for sugarcane cutting was performed by investigating the relationship between WJ and AWJ

cutting parameters. Using an AWJ with an orifice diameter of 0.25 mm and water pressure 360 MPa, Valco WJ's cutting performance was improved by reducing the actual water flow rate and the power input down by 50% and 58.8%, respectively. The specific cutting energy selected was at  $8.7 \times 10^{-3}$  J/mm<sup>3</sup> with an equivalent cutting efficiency of 0.35. Selection was based on the fitted stainless steel (INOX) cutting data of Lefevre et al. (2004).

The traverse speed obtained using the Hoogstrate model for cutting aluminum and stainless steel with the respective cutting efficiencies of 0.17 and 0.15 were comparable to the introduced traverse speed given by the KMT Waterjet (2015). The aluminum and stainless steel cutting simulations obtained from the model's calculated traverse speeds were within the range of the introduced traverse speeds of the KMT waterjet, showing that the Hoogstrate model can reliably be used to predict cutting parameters for ductile materials.

The results of the sugarcane cutting experiment have shown that an AWJ has a greater cutting capability than a WJ. Substituting garnet abrasive materials with fine river sand was also proven to be feasible based on the 5 mm steel plate cutting test results. The test further showed that an AWJ was capable of cutting sugarcane stalks even at an increased standoff distance of 250 mm by reducing the AWJ traverse speed.

To explore the potential of an AWJ, further studies on the application of an AWJ will be needed, including for example, the application of electronic control to automatically regulate water and sand usage to reduce the water and sand load of the AWJ harvester. The possible use of a hot air jet should be considered in place of water as this option would not only be cheaper in raw materials but also would not require storage nor add to the machine load for the water and sand. The greater traverse speed of an AWJ for cutting also improves the cutting efficiency as well as saving energy.

#### Conflict of interest statement

The authors declare that there are no conflicts of interest.

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