Effect of Cylinder Rotation Speed and Teeth Density on Power Requirement and Specific Energy Consumption of Sago Rasping Machine

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***Abstract*— Rasping is the most frequently useful method to disintegrate or to break down the cellular structure of sago pith for mechanical processing. The objective of this study was to investigate the effect of cylinder rotation speed and teeth density on power requirement and specific energy consumption of cylinder type sago rasping machine. In addition, the performance of rasping machine in term of rasping capacity and product's amounts were also measured. In the experiment, five levels of cylinder rotation speed i.e. 745 rpm, 1490 rpm, 2235 rpm, 2980 rpm and 3725 rpm and three levels of teeth density i.e. 2.2 cm × 4 cm (D1), 2.2 cm × 3 cm (D2), and 2.2 cm × 2 cm (D3) were tested. A torque transducer (torque meter) was used to measure the rasping torque. The torque meter was calibrated before being used. In addition, a strain amplifier was used to amplify the output signal. The power requirement was then calculated. Results showed that the power requirement of the rasping machine increased as the rotating speed of cylinder increased. Likewise, the power required increased with increases of teeth density. The average level of power required at teeth density D1, D2, and D3 ranged from 0.45 to 1.62 kW, 0.46 to 1.62 kW, and 0.54 to 1.62 kW, respectively, when the cylinder rotation speed increased over the full range from 745 to 3725 rpm. The specific energy consumption increased with the increases of both cylinder rotation speed and teeth density. The specific energy consumption at D1, D2, and D3 ranged from 2.08 to 4.92 kW-h/ton, 2.67 to 6.53 kW-h/ton, and 3.01 to 9.11 kW-h/ton, respectively, over the range of cylinder speed tested. The lowest levels of power requirement and specific energy consumption were obtained at cylinder rotation speed of 745 rpm for all teeth density.**

***Index Term*-- sago rasping machine, cylinder type, power requirement, specific energy consumption, teeth density**

I. INTRODUCTION

Although Indonesia has the largest potential of sago (*Metroxylon sagu* Rottb.) in the world, unfortunately, the sago starch production and utilization is very low comparing with its potential. Millions of tons of the starch is not harvested and disappear every year. According to Samad [1], the utilization of sago palm resources in Indonesia is only about 0.1 % of its total potential. Meanwhile, Matanubun and Maturbong [2] predic that utilization of sago resources in West Papua, which has over 95 % of Indonesia's sago palm, is less than 5 % of its existing potential. Up to the present time, farmers in this region cut sago trees and process mainly for subsistence use and sell locally but they exploit only a very small amount compared with its potential. Consequently, a large number of mature sago palm are not harvested and lost every year. Meanwhile the current demand for sago starch, both for local and global markets, increases continuously. Currently, there has been no significant increase in sago starch production in West Papua. Unlike in Serawak, Malaysia, even though the sago potential was small, it was the world biggest exporter of sago starch with total export of 44,700 tons in 2007 [3, 4, 5]. Malaysian's annual sago export is around 47,000 tons [6, 7]. The sago industry in Malaysia (in the State of Serawak) is well established and has become one of the important industries contributing to export revenue [5].

A traditional method of sago starch extraction is now being used in most parts of West Papua and is mainly for subsistence [8, 9, 10]. It is well known that traditional method of sago starch processing was a time and labor intensive process. Consequently, sago starch production is very low, both in quantity and quality. Farmers in this area continue to use traditional systems to process sago starch because the lack of mechanical equipment. The industrial technology of processing starch and its derivatives from potato, cassava, maize, rice and wheat has developed very well. However, this is not the case with sago starch technology. There are only a few simple technologies besides traditional method.

The principles and methods of sago starch extraction are similar for both traditional and mechanical or commercial production, but differ only in the equipment which is used and the scale of operation. The main problem in increasing sago starch production in Papua is processing that is still carried out in a traditional method. The traditional method of sago starch extraction is very labor intensive and time consuming. The total time required to process one trunk of sago palm traditionally is 41 hours on average or 6 days of work. The most time consuming process is disintegration of pith (53.22% of the total time), followed by washing and screening the starch (38.92% of the total processing time) [11]. According to Girsang [12], the sago production capacity of traditional technology is estimated around 6 ton/year or 30 sago trees/year. The effort to increase sago starch production has being carried out by introducing mechanical equipment to the sago farmer.

Rasping is the third step in sago starch processing after the trunk was felled down and debarked. Once the bark is removed, the pith is split into pieces up to 10 cm square called batons or billets. The pieces are fed onto the rasping machine end-on direction, the correct direction for optimal rasping. Rasping or grating is the most common method to break down the cellular structure of sago pith for mechanical processing. Rasping is aimed to disintegrate the cellular structure of the pith. By doing so, the starch granules which exist in the cells is freed or loosen, thus it is able to suspend into water during extraction process. Sago palms produce starch inside pith cells. It can not be washed out unless the cells are ruptured in some way. The subsequent process i.e. starch separation depends on the proportion of starch cells that are ruptured. Whatever type of rasping machine is used, it is important not to press the pith too forcefully onto the rasping surface, as will seriously reduce the efficiency of the machine. In extreme cases it could overload the motor or the engine. Furthermore, forcing material onto the rasper will result in coarser repos, fewer cells will be ruptured and as a result more starch will be lost in the sago pith waste.

There are two type of rasping machine commonly used in sago starch processing i.e. (a) Cylindrical rasping machine and (b) Disc rasping machine. The functional component of cylindrical rasping machine is a rotating cylinder/drum with an abrasive surface, while the disc one is a rotating disc with abrasive surface. In previous researches, a prototype of cylinder type sago rasping machine was developed. Functionally, it worked properly but it still has some drawbacks, hence it needs to be improved further in order to achieve a higher level of performance. The objective of this research is to investigate the effect of cylinder's teeth density and cylinder rotation speed on rasping performance, with the focused on rasping power requirement and specific power consumption.

II. MATERIALS AND METHODS

A. Construction of Cylinder Type Sago Rasping Machine

The cylinder type sago rasping machine consists of 4 main components, i.e. (1) a rotating cylinder with sharp teeth on its circumference surface enclosed in a housing made of 2 mm thick stainless steel sheet. The cylinder of 168 mm diameter and 220 mm length was made of 5 mm thick steel pipe (2) a single phase electric motor (2 hp, 1490 rpm, 220 Volt) was used as power driver of the machine. The electric motor was attached to the main frame in such a way that the power could be easily transmitted to the cylinder (3) a rotor shaft of the cylinder unit is an important component, which transmits the required power to disintegrate or to break down the sago pith in to small pieces called repos. The rotor shaft of 1 inch diameter was made of stainless steel rod. The rotor shaft was fixed to the cylinder and mounted on ball bearings to obtain low-friction rotation. The length of the rotor shaft was extended at one side of the cylinder so as to attach a pulley by means of which power was transmitted from the motor to the cylinder. Two A-section V- belt was used to transmit the power directly from the motor to the cylinder. (4) Main frame was made of equal angle steel bar having a cross section of 50 mm×50 mm×5 mm. In addition, it is equipped with cylinder's cover and feeding hopper component both made of plat steel with 2 mm in thickness. It had a rectangular shape. The frame was welded to provide rigidity to the whole unit and support to other parts of the machine which were also mounted on the frame. Because of its high rotation speed in the rasping process, it can cause very nasty wound, thus for safety they must be enclosed so that operator cannot get injured. Therefore, it is equipped with cylinder's cover and feeding component both made of plat steel with 2 mm in thickness. It is also equipped with a torque meter to measure the torque requirement and tachometer to measure the cylinder speed (Fig.1).

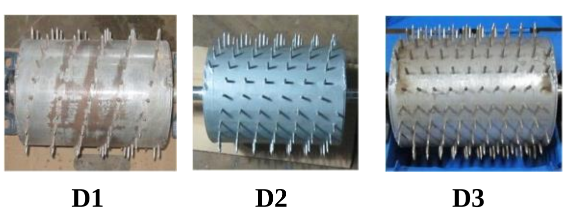
Note: (1) Cylinder, (2) Tachometer sensor, (3) Connecting cable to the torque sensor interface, (4) Electric motor, (5) Torque meter, (6) Driven pulley, (7) V-belt, (8) Driver pulley, (9) Main frame.

Fig. 1. Construction of cylinder type sago rasping machine equipped with torque meter

B. Experimental conditions and procedures

The more finely the pith is rasped, the more starch can be extracted in the subsequent rinsing process. Therefore, in order to free as much starch as possible, the pith must be disintegrated as finest as possible. Functional component of this machine is a rotating cylinder covered with sharp teeth on its circumference surface. The cylinder's teeth are made of high carbon stainless steel rod (SS 201) which is 4 mm in diameter and 20 mm in length. The function of the cylinder was to disintegrate or break down sago pith into small particles, so that starch in the pith can be freed in subsequent steps.

The parameters studied for evaluating rasping power requirement and specific energy consumption were cylinder's teeth density and rotation speed of the cylinder. The cylinder rotation speed consists of 5 levels i.e. 745 rpm, 1490 rpm, 2235 rpm, 2980 rpm, and 3725 rpm, equivalent to peripheral velocities of 6.55 m/s, 13.10 m/s, 19.66 m/s, 26.21 m/s and 32.76 m/s respectively. Adjusting cylinder rotation speed was done by changing the ratio of driver pulley (pulley on motor's shaft) to driven pulley (pulley on cylinder's shaft). Therefore, there are five different ratios of driver to driven pulleys that are used in this experiment, each corresponding to the intended rotation speed of the cylinder. They are: (a) 3 inch : 6 inch, (b) 3 inch : 3 inch, (c) 4 inch : 3 inch, (d) 6 inch : 3 inch and (e) 10 inch : 4 inch. On the cylinder surface, holes were made using electric drill, and then the teeth were firmly embedded in the cylinder. In addition, to prevent the teeth from falling away, the teeth were welded on the cylinder surface. There were three cylinders, each with different teeth densities, they are teeth density 1 (D1) was set at 4 cm × 2.2 cm apart (the distance between adjacent teeth was 4 cm and between the teeth axes was 2.2 cm), teeth density 2 (D2) was 3 cm ×2.2 cm apart, and teeth density 3 (D3) was 2 cm × 2.2 cm apart (Figure 2 and 3). Each cylinder was tested to five different rotation speed, therefore there were 15 experimental conditions (independent variables) for testing. In the experiment, testing for each condition was repeated five times and the data were recorded.



Note: **D1**: the distance between adjacent teeth was 4 cm and between the teeth axes was 2.2 cm, 4 teeth, **D2**: the distance between adjacent teeth was 3 cm and between the teeth axes was 2.2 cm, **D3**: the distance between adjacent teeth was 2 cm and between the teeth axes was 2.2 cm.,

Fig. 2. Three cylinders with different teeth density

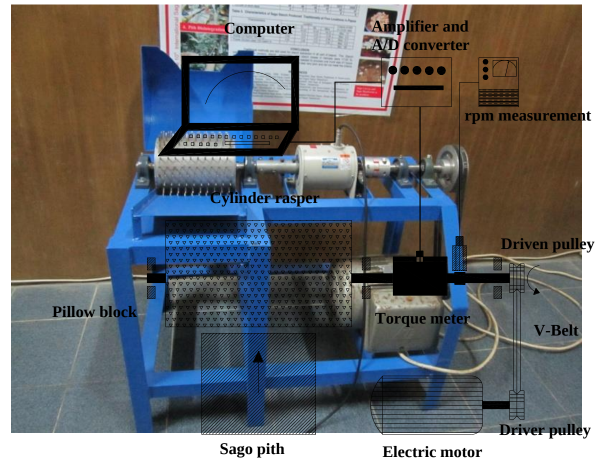


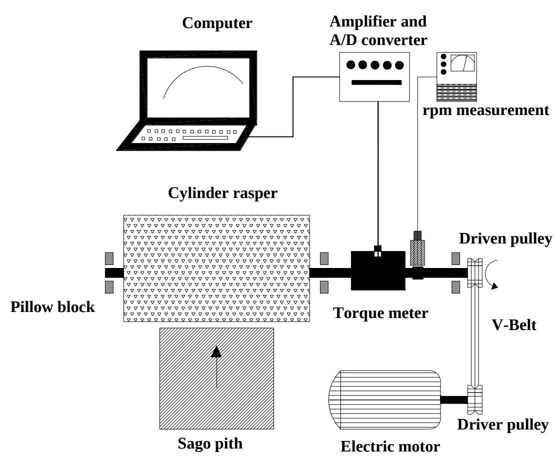
Fig. 3. The cylinder was assembled on the frame and ready for testing

C. Rasping power requirement

To calculate the power requirement for rasping, the rasping machine was equipped with torque meter (KYOWA TYPE TP-5KMCB, capacity 50 Nm) as shown in Figure 1. The torque meter was calibrated before being used. In addition, a strain amplifier was used to amplify the output signal. The experimental device setting for torque measurement is shown in Figure 4. The power requirement was then calculated using equation (1).

$$P = \frac{\pi T n}{30} \quad (1)$$

Where P is power requirement (W); T is rasping torque requirement (N・m); n is cylinder rotation speed (rpm)



Note: The data of rasping torque was recorded and then convert into power requirement using equation (1) and specific energy consumption (SEC) using equation (4)

Fig. 4. Experimental setting and instruments for torque measurement

D. Rasping capacity (product's amount/hour)

The mature sago palm trees which are ready for harvest were felled using a chainsaw. The felled sago palm trunk is then cut into shorter logs about 100 cm in length to facilitate transportation to the laboratory. The first stage in the extraction of starch is to separate the bark from the log. The bark is removed before rasping, because the bark does not contain starch and is also very hard such that it would quickly damage the cylinder's teeth. Once the bark is removed, the pith is split into pieces suitable for the rasping process. The pieces are then fed manually onto the feeding plate and pushed gently to rotating cylinder (Figure 5). The pieces are fed onto cylinder end-on direction. The rasped pith called *repos* [13, 14, 15] is then collected and weighed (Figure 6). Rasping capacity is calculated according to equation (2):

$$Rc = \frac{W_R}{t} \qquad (2)$$

Where R_C is rasping capacity (ton/h); w_R is weight of rasped pith/repos (ton); t is time required (hour).

(**a**) Ready harvested sago trunk was felled down, then cut into logs, **(b)** Debarking and splitting the log (**c**) Pieces of sago log called batten was ready to be rasped, (**d**) Sago log pieces is being rasping, (**e**) Rasped sago log/sago pith called *repos*, **(f)** Weighing the rasped pith.

Fig. 5. Rasping capacity test procedures

E. Specific energy consumption (SEC)

Specific energy consumption is defined as a ratio of energy used for producing a product [16]. SEC is calculated by dividing the amount of energy used with the amount of products. Generally it is formulated as equation (3):

$$SEC = \frac{Eu}{Pa} \qquad (3)$$

Where *SEC* is specific energy consumption, *Eu* is energy used, *Pa* is product's amounts.

Likewise, SEC in sago rasping machine is defined as the amount of energy per unit of production (kW-h/ton). It is obtained from the quotient of power requirement and rasping capacity (Equation 4):

$$SEC = \frac{P}{Rc} \qquad (4)$$

Where *SEC* is specific energy consumption (kW-h/ton), *P* is power requirement, *Rc* is rasping capacity.

III. RESULTS AND DISCUSSION

A. Power requirements of sago rasping machine

Torque requirements for sago rasping is measured using torque meter as shown in fig.4. Physical resistance that is taking place caused by sago pith during rasping process is converted into electrical signal by the sensor of torque meter. The electrical signal is then amplified and converted into digital signal by amplifier and A/D converter respectively. Finally, the magnitude of rasping torque is shown on the computer display, and in the same time the data are recorded and saved on the computer's hard disc. The obtained data of rasping torque then convert to the power requirements using equation (1).

The average power required at different teeth densities and cylinder rotation speeds is shown in Fig.6.

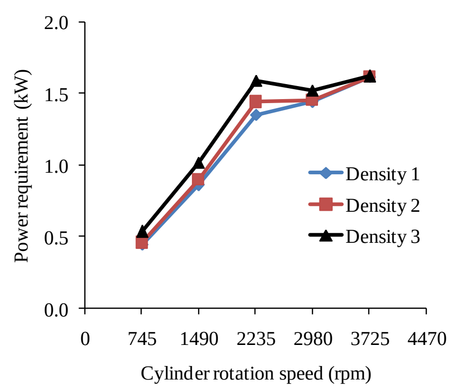


Fig. 6. Effect of teeth density and cylinder rotation speed on power requirement

Figure 6 shows that the rasping power requirement for all teeth density increased sharply with the increase of cylinder rotation speed from 745 rpm to 2235 rpm and then increased slightly when the speed was increased further up to 3725 rpm. The average levels of power required at teeth density D1, D2 and D3 ranged from 0.4 to 1.6 kW, 0.5 to 1.6 kW and 0.5 to 1.6 kW, respectively, when cylinder rotation speed increased over the full range from 745 t0 3725 rpm. It was observed from torque measurement that rasping torque requirement decreased as the cylinder rotation speed increased. Darma et al. [17] also found that rasping torque requirement to be inversely proportional to cylinder rotation speed. Rasping involves both cutting and crushing process. During rasping/cutting a cutting edge (teeth) penetrates into a material, overcoming its strength and thereby separating it. During rasping various deformations occur in the material, depending on the form of teeth edge and kinematics of the process. Since rasping velocity increases, the torque requirements decreased and the proportion of useful cutting work increases. The cutting process may be distinguished in two stages, the first stage involves preliminary compaction of the material until a pressure is reached at which the material under the edge yield, while the second stage concerns the motion of the edge in the material. With increase in cutting velocity, preliminary compaction decreases as a result of the material's inertia and plastic behavior, whereby the torque requirements of cutting are lowered [18]. However, unlike to the torque requirement which is inversely proportional to the cylinder rotation speed, on the other hand, power rasping requirement increased as the cylinder rotation speed increased. This is because cylinder rotation speed factor (***n*** as in Eq.1) is much more dominant in affecting power requirement (***P***) compared to the effect of torque (*T*). Consequently, even though the torque factor decreased with the increased of cylinder rotation speed, power requirement increased with the increased of cylinder rotation speed. These results are in consistent with those of Sudajan at al.[19] in which a drum type of sun flower thresher was tested at four different rotation speeds (675 rpm, 775 rpm, 875 rpm and 975 rpm).

From Fig.6, it is also shown that higher teeth density requires higher rasping power at the same cylinder rotation speed. Teeth density D3 has the highest power requirement followed by D2 and the lowest is D1. These results are in consistent with those of Darma et al.[17]. Higher teeth density requires higher power because more teeth actively engage in rasping process at the same time. There are many factors influence the energy requirements of cutting, some of which are related to the mechanical properties of materials, while others depend on the geometry and adjustment of the cutting edge and on the kinematic condition [18].

B. Rasping capacity (product's amount/hour)

The mass of products i.e. rasped pith (repos) per hour was weighed and recorded. Figure 7 shows the effect of cylinder rotation speed on rasping capacity of three different cylinder's teeth density.

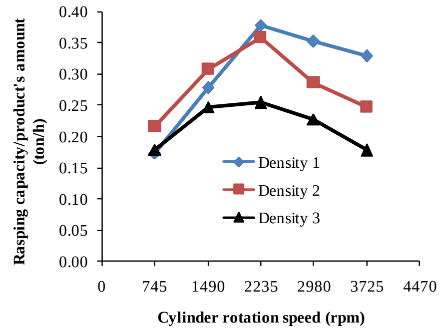


Fig. 7. Effect of cylinder rotation speed on rasping capacity of three different teeth's density

Figure 7 shows that rasping capacity for all cylinder's teeth density increased rapidly with increase in cylinder rotation speed from 745 rpm to 2235 rpm and then decreased as further increase in cylinder speed from 235 rpm to 3725 rpm. The increasing of rasping capacity from 745 rpm to 2235 rpm was due to rasping process at those conditions occurs rapidly. As the cylinder rotation speed is increased further excess of 2235 rpm, the rasping capacity decreases because of insufficient torque available on rasping cylinder. The torque on rasping cylinder decreases while the cylinder rotation speed increases because motor's power is constant [20, 21]. Therefore, in order to maintain uniform cylinder rotation speed, the speed of feeding pith onto cylinder must be reduced otherwise the motor could overload. In extreme cases, the motor would be stopped and even become damage. In these conditions, pressing the sago pith too forcefully reduces the rasping capacity significantly [14]. Meanwhile, when the power source is large enough to surpass the cutting/rasping resistance of the sago pith, increasing rotational speed of cylinder continuously increases the rasping capacity. However, it is important not to press the sago pith too forcefully onto the rasping cylinder surface, as this will seriously reduce the efficiency of the rasping machine. In addition, forcing material onto cylinder will result in coarser repos, fewer cells will be ruptured and more starch will be lost in waste. These results are in consistent with those of Darma at al.[22] in which a disc type of sago rasping machine was tested at three different rotation speeds (700 rpm, 1400 rpm, and 2800 rpm), and Darma et al. [23] where the same type of sago rasping machine was tested at three different rotation speeds (1750 rpm, 2100 rpm, and 2625 rpm). The latter experiment used almost the same size of cylinder made of hard wood but was covered with blunt teeth and powered by 4.1 kW (5.5 hp) gasoline engine.

From Figure 7, it also shows that higher teeth density has lower rasping capacity. It means that lower teeth density rasps more effectively compared with the higher density. This behaviour was related to the rasping torque requirement as well as power requirement where the higher teeth density needs higher torque requirement and vice versa.

The highest rasping capacity for cylinder teeth density D1, D2, and D3 are 0.379 ton, 0.359 ton, and 0.255 ton per hour respectively. This is in consistent with the results by Anom [24] which tested two different teeth densities (1 cm and 2 cm distance) at two rotation speeds (730 rpm and 875 rpm). These results also support those of Darma et al. [25] however the rasping capacity is lower compared to the former due to the power source is being used was smaller.

C. Specific energy consumption

Specific energy consumption (SEC) is an indicator for energy efficiency. SEC is a value that can be used as an indicator to measure the optimization level in the use of energy. It is used as an energy performance indicator to evaluate or measure the performance of energy efficiency [16]. For example, Firdaus and Ma'arif [26] creating the standard for specific energy consumption at palm oil industry in Indonesia. Peng et al. [27] used SEC to evaluate changes in energy efficiency in the Chinese pulp and paper industry over the period between 1985 and 2010. Furthermore, Lawrence et al. [28] used SEC to investigate the possible effects of firm characteristics on energy efficiency in the pulp and paper industry in Sweden, and Fleiter et al. [29] used SEC to study energy efficiency in the German pulp and paper industry and to assess the potential for energy savings.

Torque is measured while energy is calculated. As shown in equation (4), specific energy consumption depends on both power requirement and rasping capacity. The average Specific energy consumption at different teeth densities and cylinder rotation speeds is shown in Fig.8.

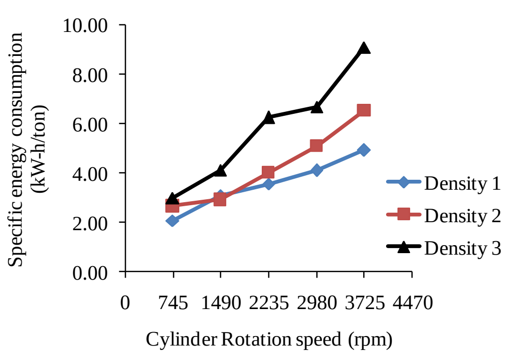


Fig. 8. Effect of cylinder rotation speed on specific energy consumption of three different teeth's density

It was observed in Fig.8. that specific energy consumption for the three teeth density increased moderately with increases of cylinder rotation speed over the full range of cylinder speed tested. This was because higher cylinder rotation speed requires more power compared to the lower one. These results are consistent with those of Sudajan et al. [19]. The authors found that specific energy consumption of sun flower thresher increased as the speed of drum/cylinder threshing increased. It also can be seen that teeth density D3 has the highest specific energy consumption followed by D2 and D1 respectively. It mean that the higher the teeth density, the higher the specific energy consumption. Higher teeth density requires higher power than lower teeth density. The specific energy consumption levels at teeth densities D1, D2 and D3 between 2.08 to 4.92kW-h/ton, 2.67 to 6.53 kW-h/ton and 3.01 to 9.11kW-h/ton, respectively, in the full range of cylinder rotation speed tested. These results indicate that higher teeth density requires more power per unit mass of rasped pith resulted and vice versa.

According to Sitkey [18], numerous factors affect the energy requirements/consumption of cutting, some of which are related to the mechanical properties of the material, while the others depend on geometry and adjustment of the cutting edge and on the kinematic conditions. The mechanical properties depend on the type of material, the stage of growth and moisture content, the location of cutting (close to the root or higher), etc. The thickness of the cutting edge (teeth) influences the cutting resistance in various ways. The greater the thicknesses of cutting edge the greater the energy required for cutting. A thickened edge consumes much surplus energy. With increasing edge thickness the additional deformation increases, whereby the energy required in cutting increases. A Rasping machine using multiple blades (teeth) in which every single teeth work independently as the cylinder rotate. The higher the teeth density mean more teeth engaged in any time, consequently required more energy.

IV. CONCLUSIONS

The rasping cylinder having a higher teeth density requires higher power and specific energy consumption than lower one. Similarly, cylinder with the higher rotation speed has the higher power requirement and specific energy consumption as well. The power requirement levels of teeth density 1 (D1), density 2 (D2) and density 3 (D3) ranged from 0.45 to 1.62 kW, 0.46 to 1.62 kW and 0.54 to 1.62 kW, respectively, when cylinder rotation speed increased over the full range from 745 to 3725 rpm (6.55 to 32.76 m/s). The specific energy consumption levels at teeth density 1 (D1), density 2 (D2) and density 3 (D3) ranged from 2.08 to 4.92 kW-h/ton, 2.67 to 6.53 kW-h/ton and 3.01 to 9.11 kW-h/ton, respectively, as the cylinder speed increased from 745 to 3725 rpm. The optimal performance in term of lowest power requirement and specific energy consumption was obtained at teeth density 1 (D1) with cylinder rotation speed of 745 rpm (6.55 m/s). However, it should be noted that there are some others parameters have to be considered in determining specification to be used in developing cylinder type sago rasping machine.

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