Effects of Compressed Pressure and Speed of the Tandem Mill of Sugar Cane Milling on Milling Performance

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Abstract

Thailand is one of the sugar cane exporters in the world market and it offers a great contribution to the country's national income. It is important for sugar factory to operate efficiently in milling against its competition to achieve a better performance. This study investigated the effects of pressure and speed of the tandem mill in sugar cane crushing based on extraction (EXT), power requirements (POW), specific energy consumption (SEC) and specific extraction per energy consumption (SEE) which are important parameters for sugar factory. Testing was performed using a small milling machine. The compressed pressure was adjusted by using the hydraulic pressure and the inverter was used to change the speed. After the test, the polarization meter was used to measure sugar in juice. It was found that when the compressed pressure increased, the EXT of the tandem mill had a tendency to increase from 2.7 to 6.0 x 10^6 N/m^2 and slightly increased from pressure 6.0 to 10.0 x 10^6 N/m^2. The POW of the tandem mill slightly increased. The SEC of the tandem mill tended to increase its tendency. The SEE slightly increased from pressure 2.7 to 6.0 x 10^6 N/m^2 and severely decreased from pressure 6.0 to 10.0 x 10^6 N/m^2. When the speed of the tandem mill increased, the EXT of the tandem mill had a tendency to decrease, the POW tended to increase their tendency, the SEC slightly decreased from 0.0844 m/s to 0.1 m/s and slightly increased from 0.1 m/s to 0.1631 m/s. The SEE slightly decreased. The maximum extraction (%) is earned at the intermediate compressed pressure and the lowest speed. The minimum power requirement (W) is earned at the lowest compressed pressure and the lowest speed. The minimum specific energy consumption (kWh/t) is earned at the lowest compressed pressure and the intermediate speed. The maximum specific extraction per energy consumption (%.t/kWh) is earned at the intermediate compressed pressure and the lowest speed. The results found in this study can benefit sugar factory to find performance and to make the decision on process operation.

Keywords: Tandem mill, extraction, sugar cane milling
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1. Introduction

Sugar trade averages 56 million tons/year in the world whereas Brazil, Thailand and Australia accounting for 65% of the trade in 2014. The world's largest sugar producer and exporter is Brazil, accounts for 24.01 million tons. Thailand, the second one, accounts for 7.97 million tons [1]. There are several processes in the sugar cane production such as sugar cane growing, sugar cane milling, credit banking, exportation, etc. [2]. The sugar production comprises juice extraction, preheating, evaporation, crystallization, centrifugal and drying [3]. The sugar refinery process is part of sugar cane crushing mills. Furthermore, raw sugar and refined sugar are produced by using sugar cane bagasse as power that take out from milling [4]. Currently, there are 55 mills in Thailand with a sugar cane crushing capacity about 93 million tons per year [5].

A study by Atherton [6] showed the relationships between the pressure and the volume of juice expressed whereas the volume of juice expressed was up to any given pressure increased. The effect of speed, preparation and compression ratio of performance of the experimental sugar mill in the University of Queensland showed that with small mill and no juice grooves, the coarser preparations gave better drainage, resulting in good juice extraction [7]. Compression ratio and performance of experimental sugar mill showed that an increase in roll load led to the uneconomical use of the mill [8].

A small scale sugar cane juice mill was developed for farmers who were involved in the processing of sugar, ethanol and other related products. The extraction efficiency ranged between 40 and 61% at operating speeds of 0.25 and 0.36 m/s and the output capacities were 10.50, 12.00 and 14.25 kg/h at operating speeds of 0.25, 0.3 and 0.36 m/s respectively [9, 10]. Sugar cane milling is one step in sugar process and there are several machines in the sugar process such as sugar cane unloading, sugar cane knives, shredders, sugar cane milling, bagasse conveyor and so on [11]. Normally, there are two ways for juice extraction: 1) extraction by the mills and 2) extraction by the diffusers [12]. The sugar cane milling was simulated by finite element algorithm. Energy dispersing during milling of sugar cane could be presented in terms of four components; juice flow, bulk plasticity, seepage induced plasticity and frictional sliding. In this simulation, constant crushing rate showed that higher roll speeds and thinner blankets reduced power requirements, frictional sliding, roll torque, roll load and increased extraction of juice slightly [13]. The variable speed of the drives and different speeds of the rolls presented almost constant torques on each roll. The results of the tandem mill such as extraction, capacity and power consumption, were very good [14]. The sugar extraction efficiency and energy consumption have been compared with a similar process in a modern fuel alcohol distillery in current sugar extraction process. Distilleries could use more soak water to increase juice extraction during crushing because the fermentation broth must be diluted. An analysis of the substitution process showed that if the steam consumption of evaporator did not rise significantly, the net revenue increased significantly [15]. There was a feed opening which resulted in the maximum throughput at the same speed for a particular mill configuration. However, the feed opening affected mill torque and the forces acting on the mill housing. The maximum throughput could be limited due to insufficient roller roughness causing slippage [16].

It is very important to have some technique available in order to manage the standard milling operation that Thailand sugar factory has never had it. Therefore, the objectives of this study are to investigate the effects of compressed pressure on the speed of the tandem mill in sugar cane milling on production parameters based on Extraction (EXT), Power requirements (POW), Specific energy consumption (SEC) and Specific extraction per energy consumption (SEC).

2. Materials and Methods

2.1 Equipment used in the test

Testing was performed using a method of Shinde [17]. A small milling machine equipped with two tandem mills with a diameter of 21.5 mm and a length of 43 mm (Figure 1) was used in this study. A 5 kW electric motor was used as a power source. The compressed pressure was adjustable by using the hydraulic pressure. During the test, the inverter was used to change the speed and monitor current, voltage for power requirement, specific energy consumption and specific extraction per energy consumption calculation. After the test, the polarization meter was used to measure sugar in juice for extraction calculation. The test was performed entirely in the laboratory of the sugar factory involved in this study.

(a) (b)

Figure 1. (a) A small milling machine and (b) Two tandem mills

2.2 Test method

Testing of each parameter involved three replications, using 'Khon Kaen 3' sugar cane as a sample. Data were collected from the input sugar cane, the discharge of juice, and bagasse outlet weight. The power requirement for crushing was measured using the inverter display. The parameters obtained were used to calculate the power requirement, specific energy consumption and specific extraction per energy consumption. Moreover, the polarization meter (Anton Paar, model MCP 500 Sucromat, Austria) was used to analyze the extraction. A schematic diagram of milling process in this study is shown in Figure 2.

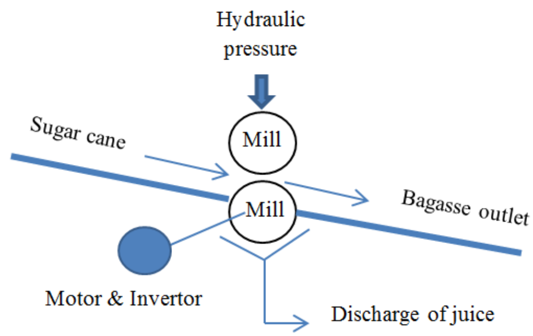

Figure 2. A schematic diagram of milling process

2.3 Indicator parameters

The indicating parameters in the test comprised extraction, power requirements, specific energy consumption and specific extraction per energy consumption.
Extraction was calculated using Eq. (1)

$$EXT = \left(\frac{B}{A+B}\right)\times 100 \quad (1)$$

where, EXT is the extraction from sugar cane milling in percent, A is the weight of sugar from bagasse in grams and B is the weight of sugar from the extracted juice in grams (ICUMSA GS1/2/3-1(1994))[18].
Power requirement was calculated using Eq. (2)

$$POW = 1.732\times VOLT \times I \times PF \quad (2)$$

where, POW is the power requirement in watts, VOLT is the voltage, I is the current in ampere and PF is the power factor.
Specific energy consumption was determined using Eq. (3)

$$SEC = \left(\frac{POW}{FR}\right) \quad (3)$$

where, SEC is the specific energy consumption in kWh/t, POW is the power requirement in watts and FR is the feed rate of sugar cane in t/h.
Specific extraction per energy consumption was determined using Eq. (4)

$$SEE = \left(\frac{EXT}{SEC}\right) \quad (4)$$

where, SEE is the specific extraction per energy consumption in %.t/kWh, EXT is the extraction from sugar can milling in percent and SEC is the specific energy consumption in kWh/t.

2.4 Model development

Linear regression (backward elimination) is used for model development. All the independent variables (X_1, X_2, ...) are entered into the first equation and each one is deleted one at a time if they do not contribute to the regression equation. Assume the original model as Eq. (5).

$$Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_{r-1} X_{r-1} + \varepsilon \, . \tag{5}$$

Step 1:
At the beginning, the original model is set to be Eq. (5).
Then, the following $r-1$ tests are carried out, $H_{0j} : \beta_j = 0, j = 1,2,...,r-1$. The lowest partial F-test value F_l corresponding to $H_{0l} : \beta_l = 0$ or t-test value t_l is compared with the preselected significant values F_0 and t_0. One of two possible steps (step2a and step 2b) can be taken.
Step 2a:
If $F_l < F_0$ or $t_l < t_0$, then X_l can be deleted and the new original model is Eq. (6).

$$Y = \beta_0 + \beta_1 X_1 + \cdots + \beta_{l-1} X_{l-1} + \beta_{l+1} X_{l+1} + \cdots + \beta_{r-1} X_{r-1} + \varepsilon \tag{6}$$

Go back to step 1.

Step 2b:
If $F_l > F_0$ or $t_l > t_0$, the original model is the model we should choose [19].

3. Results and Discussion

3.1 Effects of compressed pressure and tandem mill speed on milling performance

Data from Table 1 were used to create analysis of variance and regression equations between the compressed pressure and the tandem mill speed, which affected milling performance such as the extraction (EXT), power requirements (POW), specific energy consumption (SEC) and specific extraction per energy consumption (SEE). The statistical variance analyzed from data in Table 1 revealed that altering compressed pressure and tandem mill speed significantly affected the extraction, the power requirements, the specific energy consumption, and the specific extraction per energy consumption (P<0.01), as shown in Table 2.

Table 1. Effects of compressed pressure and tandem mill speed on the extraction, power requirements, specific energy consumption and specific extraction per energy consumption

P (N/m^2)	V (m/s)	EXT (%)	POW (W)	SEC (kWh/t)	SEE (%.t/kWh)
2.7x10^6	0.0844	43.09±3.02	954±8.50	4.72±0.11	9.13±0.53
2.7x10^6	0.1238	32.44±2.70	1,362±6.93	4.60±0.09	7.05±0.47
2.7x10^6	0.1631	25.53±2.63	2,012±17.00	5.15±0.08	4.95±0.44
6.0x10^6	0.0844	57.41±2.42	1,093±5.20	5.45±0.02	10.53±0.40
6.0x10^6	0.1238	56.06±2.16	1,573±12.00	5.35±0.04	10.48±0.48
6.0x10^6	0.1631	53.72±1.80	2,187±40.73	5.64±0.10	9.52±0.31
10.0x10^6	0.0844	68.11±2.28	1,358±10.00	6.77±0.05	10.06±0.35
10.0x10^6	0.1238	63.02±0.55	1,895±13.5	6.44±0.05	9.78±0.16
10.0x10^6	0.1631	57.32±1.44	2,642±10.39	6.82±0.03	8.41±0.22

P = Compressed pressure, V = Tandem mill speed. Values shown as mean±SE

Table 2. Analysis of variance of extraction, power requirements, specific energy consumption and specific extraction per energy consumption affected by compressed pressure and tandem mill speed

Source of Variation	df	EXT	POW	SEC	SEE
Compressed Pressure (P)	2	429.418*	2162.271*	2058.632*	152.948*
Tandem Mill Speed (V)	2	53.194*	10122.845*	95.782*	76.476*
PV	4	7.818*	40.076*	9.204*	13.927*
Block	2	1.235**	0.931**	3.115**	0.785**

* = Highly significant at P < 0.01, ** = Not significant

3.2 Effects of compressed pressure and tandem mill speed on the extraction (EXT)

Data from Table 1 were used to create regression equations between the compressed pressure and the tandem mill speed, which affected the extraction as shown in Table 3. The EXT model in Table 3 indicates the relationship between the compressed pressure and the tandem mill speed affecting the extraction. For clarifying in optimization (Figure 3), when the compressed pressure increased, the extraction of the tandem mill had a tendency to increase from 2.7 to 6.0 x 10^6 N/m^2 and slightly increased from pressure 6.0 to 10.0 x 10^6 N/m^2. It can be explained that the total volume of juice expressed remains constant at higher pressure [6]. Moreover, the increased compressed pressure brought about increased compaction in the sugar cane inlet, and the increase in high compaction gave a slightly increase in extraction. Effects of speed, when increased the speed of the tandem mill, the extraction of the tandem mill had a tendency to decrease. This finding correlated with a study by Bullock [7], where the mean speed and mean juice extraction determined the mean point on the graph of extraction versus speed. The co-efficient of regression expressed the slope of the best fit to the available data. This result seems to be negative, indicating a falling-off of extraction as speed increases.

Table 3. Equation from regression analysis of compressed pressure (P) and tandem mill speed (V) on the extraction (EXT), the power requirements (POW), the specific energy consumption (SEC), and the specific extraction per energy consumption (SEE)

Model	Equation	Adj. R2	SE	P-value
EXT	$\mathrm{EXT} = 21.56 + (1.25e^{-5})P - 135.71V - (7.72e^{-13})P^2$	0.950	3.183	0.000
POW	$\mathrm{POW} = -575.29 + (7.21e^{-5})P + 14552.10V$	0.977	84.24	0.000
SEC	$\mathrm{SEC} = 6.40 + (2.56e^{-7})P - 43.62V + (187.70)V^2$	0.968	0.150	0.000
SEE	$\mathrm{SEE} = 5.54 + (2.31e^{-6})P - 28.97V - (2.56e^{-13})P^2$	0.813	0.793	0.009

Adj. R2 = Adjusted coefficient of determination.

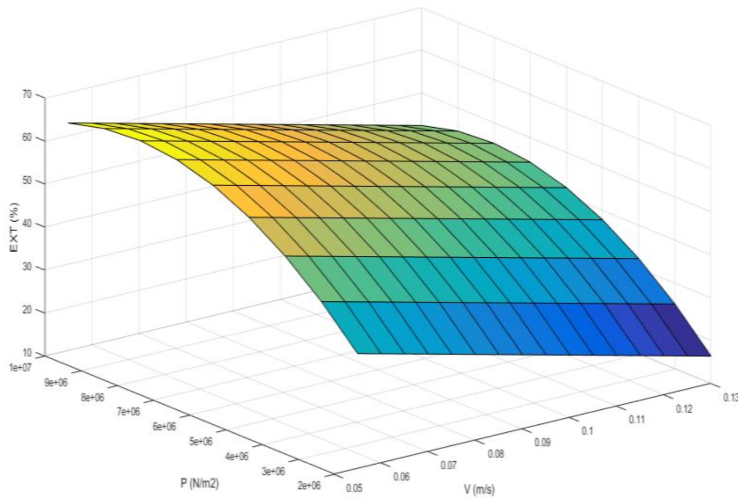

Figure 3. Effects of compressed pressure and tandem mill speed on extraction (EXT)

3.3 Effects of compressed pressure and tandem mill speed on the power requirements (POW)

Data from Table 1 were used to create a regression equation between the compressed pressure and the tandem mill speed, which affected the power requirements as shown in Table 3. The POW model in Table 3 indicates the relationship between the compressed pressure and the tandem mill speed affecting the power requirements. For clarifying in optimization (Figure 4), when the compressed pressure increased, the power requirements of the tandem mill slightly increased from 2.7 to 10.0 x 10^6 N/m^2. This result correlated with a study by Adam and Loughran [13], where the power required increased with by a mill compression ratio. Effects of speed, when the speed of the tandem mill increased from 0.0844 m/s to 0.1631 m/s, the power requirements tended to increase their tendency. Total power consumption in the whole tandem tended to increase when the speed increased [14].

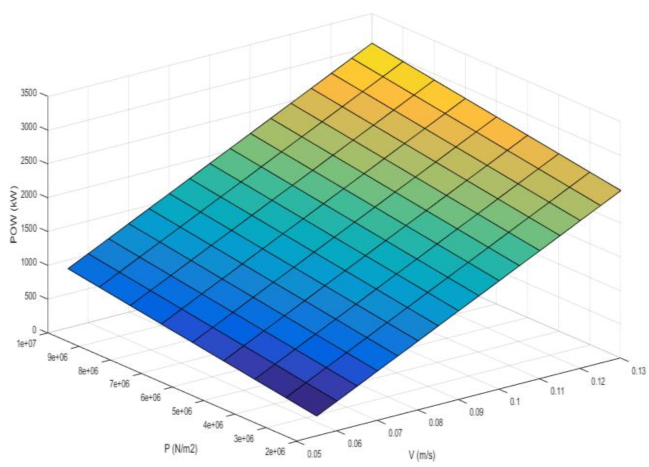

Figure 4. Effects of compressed pressure and tandem mill speed on power requirements (POW)

3.4 Effects of compressed pressure and tandem mill speed on the specific energy consumption (SEC)

Data from Table 1 were used to create a regression equation between the compressed pressure and the tandem mill speed, which affected the specific energy consumption as shown in Table 3. The SEC model in Table 3 indicates the relationship between the compressed pressure and the tandem mill speed affecting the specific energy consumption. For clarifying in optimization (Figure 5), when the compressed pressure increased, the specific energy consumption of the tandem mill tended to increase its tendency from pressure 2.7 to 10.0 x 10^6 N/m^2. Energy dispersing during milling of prepared sugar cane could be presented in terms of four components: bulk plasticity, juice flow, frictional sliding, and seepage induced plasticity. At higher compression rations with normal blanket thickness, frictional sliding on the roll surface could comprise up to 20% of total power consumption [13]. Considering the effects of speed, when the speed of the tandem mill increased, the specific energy consumption slightly decreased from 0.0844 m/s to 0.1 m/s and slightly increased from 0.1 m/s to 0.1631 m/s. According to Adam and Loughran [13], the total specific power consumption increased with increasing roll-surface speed.

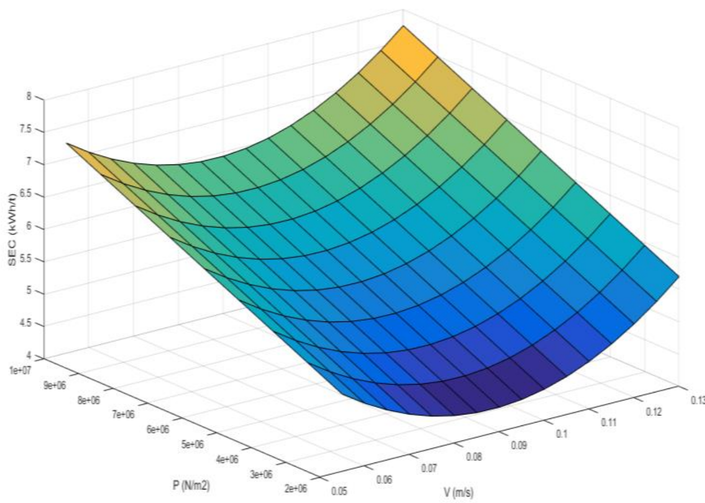

Figure 5. Effects of compressed pressure and tandem mill speed on specific energy consumption (SEC)

3.5 Effects of compressed pressure and tandem mill speed on the specific extraction per energy consumption (SEE)

Data from Table 1 were used to create a regression equation between the compressed pressure and the tandem mill speed, which affected the specific extraction per energy consumption as shown in Table 3. The SEE model in Table 3 indicates the relationship between the compressed pressure and the tandem mill speed affecting the specific extraction per energy consumption. For clarifying in optimization as shown in Figure 6, when the compressed pressure increased, the specific extraction per energy consumption slightly increased from pressure 2.7 to 6.0 x 10^6 N/m^2 and severely decreased from pressure 6.0 to 10.0 x 10^6 N/m^2. When the speed of the tandem mill increased from 0.0844 m/s to 0.1631 m/s, the specific extraction per energy consumption slightly decreased.

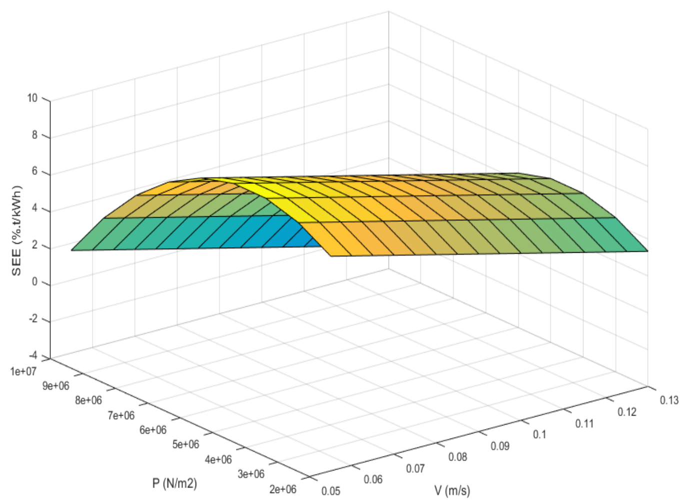

Figure 6. Effects of compressed pressure and tandem mill speed on specific extraction per energy consumption (SEE)

4. Conclusions

This study investigated the optimization of milling performance of a sugar mill. The key objectives were to analyze the effect of compressed pressure and tandem mill speed on 1) the extraction of sugar from sugar cane, 2) power requirements in the mill, 3) specific energy consumption in the mill, 4) specific extraction per energy consumption in the mill. The compressed pressure and speed were adjusted from 2.7 to 10.0 x 10^6 N/m^2 and 0.0844 m/s to 0.1631 m/s, respectively. The results showed that the maximum extraction (%) is earned at the intermediate compressed pressure and the lowest speed. The minimum power requirement (W) is earned at the lowest compressed pressure and the lowest speed. The minimum specific energy consumption (kWh/t) is earned at the lowest compressed pressure and the intermediate speed. The maximum specific extraction per energy consumption (%.t/kWh) is earned at the intermediate compressed pressure and the lowest speed. The method and results of this study can benefit for sugar factory to find performance and to make the decision on process operation

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