ENERGY REQUIREMENTS FOR SIZE REDUCTION OF WHEAT USING A ROLLER MILL

Q. Fang, E. Haque, C. K. Spillman, P. V. Reddy. J. L. Steele

ABSTRACT. *An experimental two-roll mill was developed and instrumented for computerized data acquisition. Milling tests were performed on three classes of wheat. Included in the study were six independent variables each with three levels, namely, class of wheat, moisture content, feed rate, fast roll speed, roll speed differential, and roll gap. Two covariates, single kernel hardness and single kernel weight, were also included in the statistical analysis. Prediction models were constructed for five dependent variables (fast roll power, slow roll power, net power, energy per unit mass and specific energy). The prediction models fitted the experimental data well (r^2 = 0.88 ~ 0.95). The power and energy requirements for size reduction of wheat were highly correlated with the single kernel characteristics of wheat. Feed rate affected fast roll power, slow roll power and net power significantly. Roll gap had a significant effect on roller mill grinding. Additional milling tests were conducted by randomly selecting independent variables and covariates to verify the robustness and validity of the prediction models.*
Keywords. *Wheat, Wheat hardness, Grinding, Roller mill, Energy.*

Roller mills are extensively used in flour mills to grind wheat into flour. Wheat kernels fall into the grinding zone formed by a pair of rolls rotating toward each other at different speeds and are subjected to grinding action. Flour milling involves several pairs of rolls used in sequence. From the first to the last pair of rolls, the roll gap is set successively narrower as the particle size of the feed stock becomes smaller. For size reduction, mechanical energy is needed to break the material, distribute material, and overcome friction between the moving parts of the machine. The energy consumed for breaking solid materials has been studied by many researchers including Von Rittinger (1867), Kick (1885), and Bond (1952). Von Rittinger stated that the energy for size reduction was proportional to the newly created surface area. Algebraically, this relationship can be expressed as:

$$E = K \times \Delta S \qquad (1)$$

where

E = energy required for size reduction,

K = specific surface coefficient, and

ΔS = newly created surface area.

The energy, E, and specific surface coefficient, K, have a high dependence on physical properties of the materials to be ground and the operational parameters of the roller mill. The physical properties include variety, wheat kernel hardness, moisture content, and kernel size and weight. The mill operational parameters are feed rate, roll diameters and roll surface corrugations, roll grinding action, roll gap, fast roll speed, and roll speed differential.

The objectives of this study were to: (1) investigate the effects of physical properties of wheat kernels and the operational parameters of a first-break roller mill on the power and energy requirements for size reduction; and (2) develop prediction models for power and energy requirements when grinding wheat of known physical characteristics.

MATERIALS AND METHODS

MATERIALS

Three classes of wheat, namely Caldwell, a soft red winter (SRW), Karl, a hard red winter (HRW), and a hard red spring (HRS) were used for milling tests. The SRW wheat was grown in Ohio, the HRW wheat was grown in Kansas in 1992, and the HRS wheat was grown in North Dakota in 1993 with original moisture contents of 12.5%, 12.4%, and 13.1% (w.b.), respectively. Wheat was cleaned using a Model CD-XT3 Carter Dockage Tester (Seedburo Equipment Co., Chicago, Ill.) before testing. After cleaning, the soft and hard wheat samples were tempered by adding water to adjust moisture contents to 14.5, 15.5, and 16.5% (w.b.) and storing for 10 and 15 h, respectively. Tempering has been used by the milling industry to toughen bran and soften the endosperm making their separation easier. Since hard wheat absorbs moisture more slowly than soft wheat, more tempering time was allowed.

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PHYSICAL PROPERTY TESTS

Physical properties of wheat as listed below were determined prior to milling each wheat sample.

1. **Test weight** as described in the Federal Grain Inspection Handbook (Federal Grain Inspection Service, 1990) was determined for dockage free samples.
2. **True density** tests were conducted both on the untempered and the tempered wheat samples using a Model MVP-1 Multipycnometer (Quanta Chrome Corporation, Syosset, N.Y.). The Multipycnometer employed Archimedes principle of fluid (helium gas) displacement to determine the volume.
3. **Mean kernel size**. A set of U.S. Standard sieves of no. 6, no. 7, no. 10, no. 12, and no. 14 were used to determine mean kernel size of wheat based on a 100-g sample. The sieving time was 5 min with a Model RX-29 Rotap machine (W.S. Tyler Corp., Cleveland, Ohio).
4. **Thousand-kernel-mass**. The number of kernels in a 40-g clean wheat sample was determined using an electronic seed counter. The mass of 1,000 kernels was estimated from the measurement.
5. **Single kernel hardness**. Single kernel hardness was determined for untempered and tempered wheat samples using the Single-Kernel Wheat Characterization System (SKWCS) recently developed by the USDA Grain Marketing Research Laboratory in Manhattan, Kansas. The system also reports mean and standard deviation for kernel mass, size and moisture using a 300-kernel sample size (Martin et al., 1993).
6. **NIR hardness**-AACC Approved Method 39-70A (1990). A Model 8620 Inframatic NIR Analyzer (Perten, Hamburg, Germany) was used for hardness of a bulk flour sample of wheat.
7. **Air oven moisture**-AACC Approved Method 44-15A (1990). Whole wheat samples were used for moisture determination.

Table 1 summarizes the results of the physical property tests on untempered samples of the wheat used in this study.

Table 1. Physical properties on untempered wheat*

Physical Properties	Results		
	SRW	HRW	HRS
Test weight (kg/m^3)	809.6	806.0	787.8
True density (g/cm^3)	1.36	1.41	1.40
Mean kernel size (mm)	3.31	2.85	3.61
SD of mean kernel size (mm)	±0.49	±0.33	±0.48
TKW (g)	36.80	32.58	41.77
SKH	9.06	71.17	68.83
SD of SKH	±15.76	±17.25	±15.41
SKW (mg)	35.26	31.56	40.68
SD of SKW (mg)	±6.98	±7.19	±8.45
SKS (mm)	2.67	2.56	3.01
SD of SKS (mm)	±0.36	±0.36	±0.46
SKM (%, w.b.)	12.61	12.69	13.26
SD of SKM (%, w.b.)	±0.24	±0.23	±0.26
NIR hardness index	23.0	50.3	86.0
Moisture (%, w.b.)	12.54	12.41	13.15

* SD = standard deviation, TKW = thousand-kernel weight, SKH = single kernel hardness, SKW = single kernel weight, SKS = single kernel size, SKM = single kernel moisture.

Sieving tests were conducted to determine the mean particle size and total surface area of the ground materials (ASAE, 1995). The mean particle size and total surface area were determined assuming and verifying that the particle size of the ground material followed a log-normal distribution. The new surface area created during grinding was obtained by taking the difference between the total surface area of the ground material and the surface area of the wheat sample.

EXPERIMENTAL ROLLER MILL

Experimental roller mills are not generally equipped to measure energy requirements for grinding. An experimental roller mill with a computerized data acquisition system was developed to acquire power and feed rate data (Fang et al., 1995).

The roll dimensions were 250 mm (10 in.) in diameter and 100 mm (4 in.) in length. The roll surface corrugation profile was no. 19 Getchell with a pitch of 2.12 mm (12 per in.) and a spiral of 41 mm/m (1/2 in./ft). Grinding action was set dull to dull. Each roll was driven by a separate AC motor. Two Bulletin 1336 variable frequency AC motor speed controllers (B005, Allen-Bradley, Milwaukee, Wis.) were used to control roll speeds. The motor speed was selectable from less than 100 to the full speed, 860 rpm. A vibrating feeder (Syntron, E-T01-A, FMC Corporation, Chicago, Ill.) was used to feed grain into the machine. Feed rate was adjusted by changing the vibration amplitude of the feeder. To assist in setting of roll gap, two roll gap indicators were installed; using these indicators and a feeler gauge, the roll gap was set (Fang, 1995).

The computerized data acquisition system consisted of five sensors, one each for feed rate, fast roll speed, slow roll speed, fast roll torque, and slow roll torque, a signal conditioning unit, an A/D board, and a computer for high speed (2000 Hz per channel) data collection and storage. From the collected data, fast roll power, slow roll power, net power, and total energy consumption were determined.

EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

Since many independent variables were involved in the study, a full factorial design was impractical and a response surface experimental design (Box, 1987) was used. Six independent variables, wheat class, moisture, feed rate, fast roll speed, roll speed differential and roll gap, each at three levels were evaluated as shown in table 2. A total of 54 trials were conducted.

Using SAS statistical software (ver. 6.0, SAS Institute), data were analyzed for the Response-Surface-Regression procedure (RSREG). Since the independent variable, class, is not a quantitative variable and represents many physical properties of wheat such as those measured by the USDA Single-Kernel Wheat Characterization System, some of these properties were included as covariants. The covariants

Table 2. Independent variables used in the experimental design

No.	Independent Variable	Unit	Level 1	Level 2	Level 3
1	Class		SRW	HRW	HRS
2	Moisture	% (w.b.)	14.5	15.5	16.5
3	Feed rate	kg m^{-1} min^{-1}	15	20	25
4	Fast roll speed	rpm	425	475	525
5	Roll speed differential	m/s	3.1	3.4	3.7
6	Roll gap	mm	0.66	0.74	0.82

included were single kernel hardness and single kernel weight. Wheat class and single kernel hardness were correlated (R = 0.783). Covariants are additional independent variables for use in the statistical analysis but not in the experimental design. The RSREG procedure was used to determine which independent variables would optimize the response variables. First-order prediction models were developed using the SAS Stepwise-Regression procedure. The criterion for selecting variables entering into models by the stepwise regression was $\alpha = 0.05$ significance level. The general form of the prediction models is:

$$Y = \beta_0 + \beta_1 H + \beta_2 W + \beta_3 M + \beta_4 F + \beta_5 R + \beta_6 D + \beta_7 G + \varepsilon \quad (2)$$

where

- Y = response variable—fast roll power (kW/m), or slow roll power (kW/m), or net power (kW/m), or energy per unit mass (kJ/kg), or specific energy (kJ/m^2),
- β_0 = intercept,
- β_i = coefficient for the corresponding covariant or independent variable, I = 1, 2, . . . 7,
- H = single kernel hardness (dimensionless),
- W = single kernel weight (mg),
- M = moisture content (% w.b.),
- F = feed rate (kg m^{-1} min^{-1}),
- R = fast roll speed (rpm),
- D = roll speed differential (m/s),
- G = roll gap (mm), and
- ε = random error.

RESULTS AND DISCUSSION

The experimental data on power transmitted to a roll of unit length were obtained from the data collected on speed and torque for the respective shaft:

$$P = \frac{TN}{9549L} \quad (3)$$

where

- P = power delivered to the roll (kW/m),
- T = measured torque (N-m),
- N = measured roll speed (rpm), and
- L = roll length (m).

A special power and energy transmission mechanism characterizes roller mill grinding. When grinding, power and energy are transmitted from the fast roll to the slow roll via the material being ground. The slow roll receives power and energy from the fast roll and generally functions as a braking roll. Thus, the net power (or energy) consumption, P_N, is the difference between power (or energy) transmitted to the fast roll, P_F, and the slow roll, P_S. This is true because relative tangential velocities are different.

The energy per unit mass, E_W, for each roll was calculated by subtracting no-load energy from total energy. Since the slow roll worked as a brake during grinding, the difference between the energies of the fast roll and the slow roll was the energy per unit mass.

Specific energy, E_A, a measure of the energy efficiency, is defined as the energy consumed to create one unit of new surface area. The experimental data for specific energy were obtained by dividing the energy consumed when grinding a 1 kg sample by the new surface area created in the sample. The new surface area created in the sample was determined using sieving tests which were originally developed by Headley and Pfost (1968) and Pfost and Headley (1971) and subsequently adopted by ASAE (1995).

Table 3. r^2 values for the prediction models, covariates and independent variables

Model	Model r^2	Partial r^2 for Independent Variables* H	W	M	F	R	D	G
P_F	0.9256	0.2299	0.0416	0.0084	0.5514	0.0060	---	0.0882
P_S	0.9271	0.1750	0.0257	0.0073	0.3972	0.1227	0.1087	0.0906
P_N	0.9285	0.2266	0.0483	0.0077	0.5531	0.0084	0.0122	0.0722
E_W	0.9525	0.5187	0.1189	0.0366	---	0.0112	0.0357	0.2313
E_A	0.8799	0.7086	0.0216	---	---	---	0.0054	0.1443

* See equation 2 for definitions of variables.

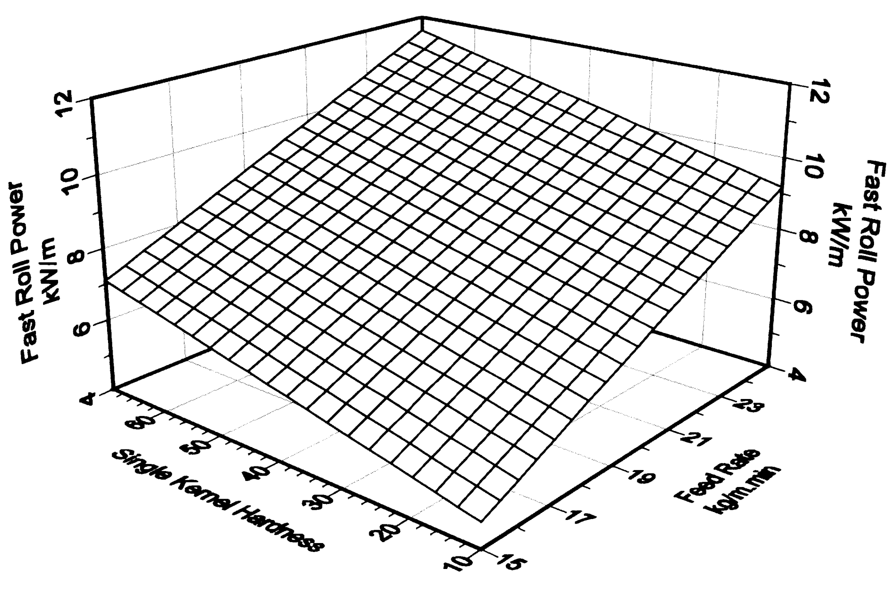

Figure 1–Effects of single kernel hardness and feed rate on fast roll power (G = 0.74, W = 35.26, R = 475, M = 15.5).

From the stepwise regression procedure, the following prediction models were suggested.

Fast Roll Power:

$$P_F = -4.70 + 0.45F + 0.04H - 11.47G + 0.117W + 0.279M + 0.0047R \quad (4)$$

Slow Roll Power:

$$P_S = -0.0843 + 0.149F + 0.0136H + 0.00847R - 1.296D - 4.53G + 0.0358W + 0.102M \quad (5)$$

Net power:

$$P_N = -2.77 + 0.30F + 0.0267H - 6.94G + 0.082W + 0.742D - 0.0037R + 0.177M \quad (6)$$

Energy per unit mass:

$$E_W = 5.927 + 0.0742H - 22.737G + 0.239W + 0.709M + 2.331D - 0.00785R \quad (7)$$

Specific energy:

$$E_A = -6.023 + 0.0481H + 10.689G - 0.0597W + 0.546D \quad (8)$$

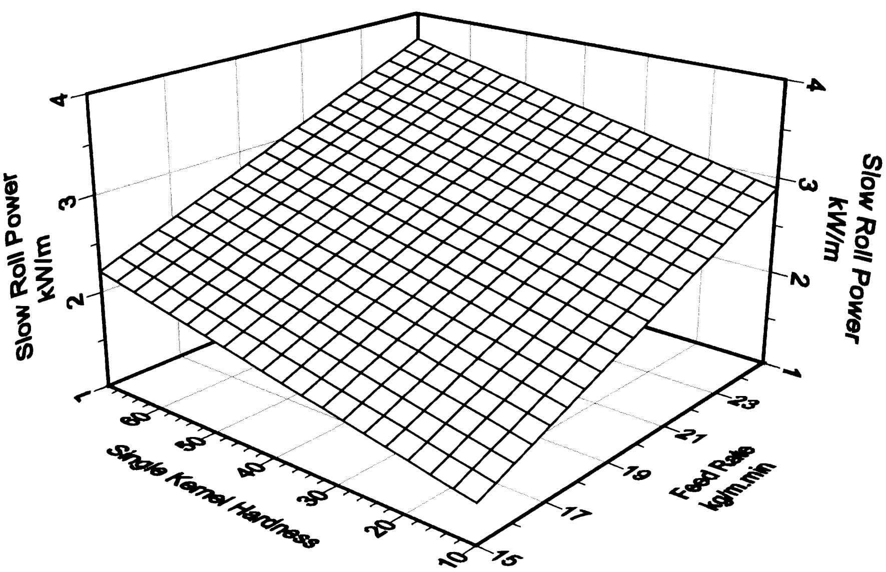

Figure 2–Effects of single kernel hardness and feed rate on slow roll power (G = 0.74, W = 35.26, R = 475, M = 15.5).

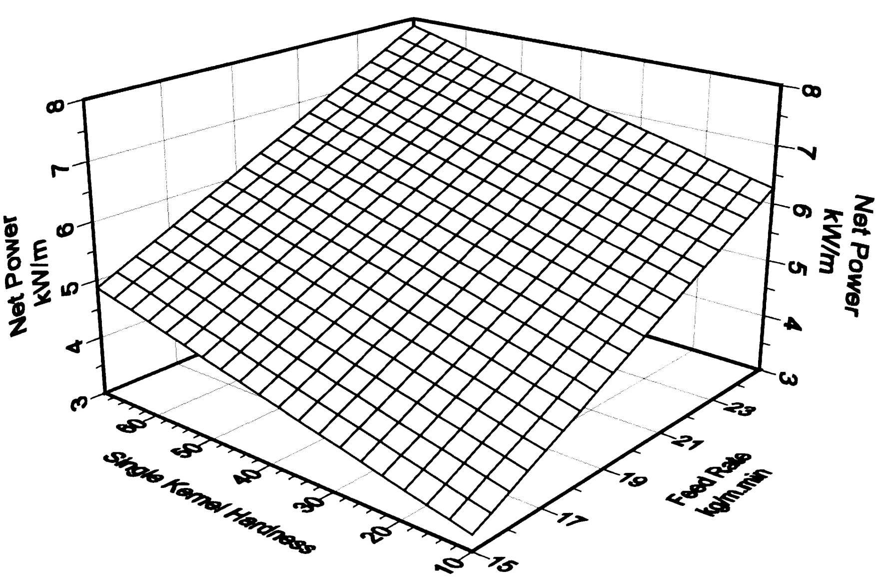

Figure 3–Effects of single kernel hardness and feed rate on net power (G = 0.74, W = 35.26, D = 3.4, R = 475, M = 15.5).

The r^2 values of the prediction models and the partial r^2 values of individual covariants and independent variables are summarized in table 3.

The r^2 values for all three prediction models of roll power were about 0.93. Feed rate had the highest partial r^2 value in all three power models. Physical properties of wheat (single kernel hardness, single kernel weight, and moisture) also had significant effect on power requirements. Single kernel hardness had the second highest partial r^2 value in the power prediction models. Power increased as single kernel hardness and feed rate increased.

The higher the single kernel weight and moisture, the higher were the power requirements. Since single kernel weight was highly correlated with wheat kernel size; wheat with larger kernel size required more power than wheat with smaller kernel size. For instance, power requirements were lower for HRW wheat than for HRS wheat although the single kernel hardness for HRW wheat was higher than HRS wheat. This might be due to the larger kernel size of the HRS wheat (3.61 mm for the HRS wheat compared to 2.85 mm for the HRW wheat).

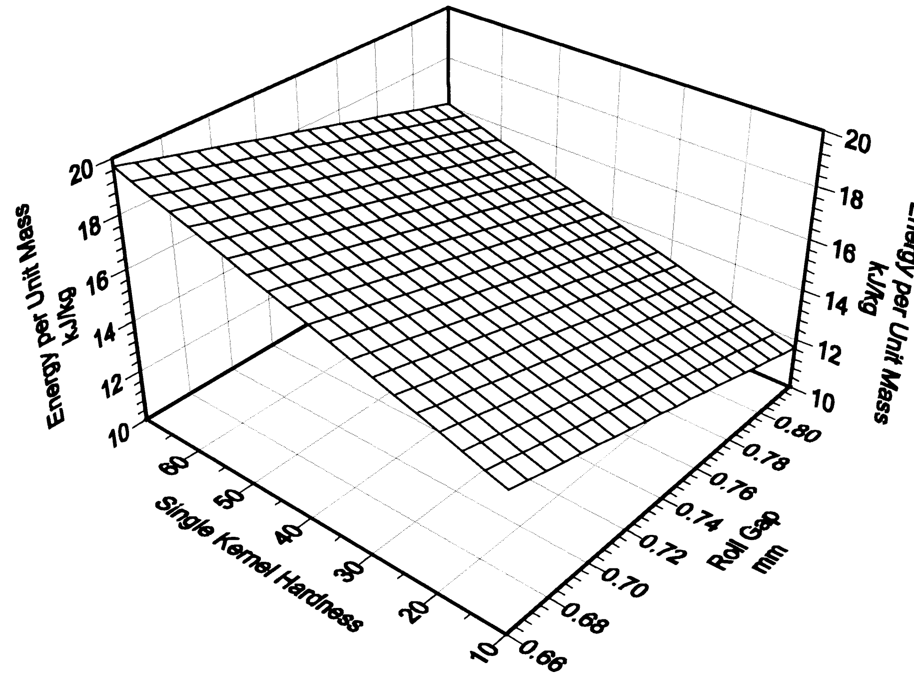

Figure 4–Effects of single kernel hardness and roll gap on energy per unit mass (W = 35.26, D = 3.4, R = 475, M = 15.5).

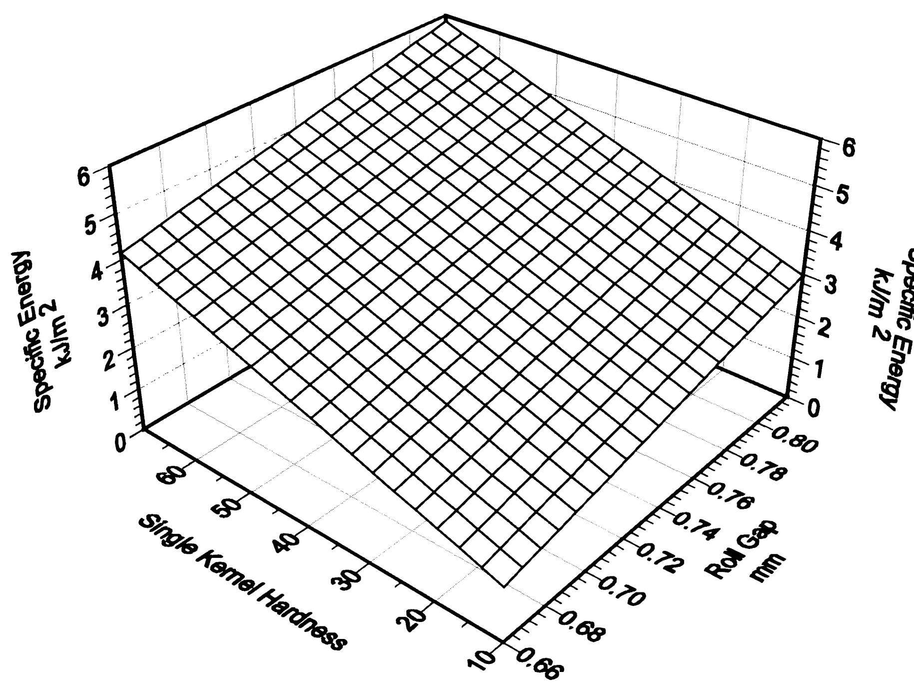

Figure 5–Effects of single kernel hardness and roll gap on specific energy (W = 35.26, D = 3.4).

Roll gap had a negative effect on roll power. The smaller the roll gap, the higher was the power. Fast roll speed was positively correlated with fast roll power and slow roll power, but negatively correlated with net power. The effect of roll speed differential on fast roll power was not significant. It was negatively correlated with slow roll power, but positively correlated with net power.

The effects of the two most significant factors, single kernel hardness and feed rate on fast roll power, slow roll power and net power can be more clearly seen in figures 1, 2, and 3.

Single kernel hardness and single kernel weight had significant effect on energy per unit mass and specific energy. Single kernel hardness had the highest partial r^2 value. Energy per unit mass and specific energy were positively correlated with single kernel hardness. Roll gap was the second most significant factor. It was negatively correlated with energy per unit mass, but positively correlated with specific energy. As roll gap was set wider, energy per unit mass decreased, and specific energy increased. Energy per unit mass increased as moisture and roll speed differential increased. Fast roll speed had a negative effect on energy per unit mass.

Table 4. Comparison between experimental data and predicted values for fast roll power, slow roll power, and net power

	Fast Roll Power (kW/m)			Slow Roll Power (kW/m)			Net Power (kW/m)		
Test	Exp.	Pred.	Diff.	Exp.	Pred.	Diff.	Exp.	Pred.	Diff.
1	4.60	3.60	1.00	1.40	0.97	0.43	3.20	2.60	0.60
2	8.10	8.60	–0.50	2.50	2.74	–0.24	5.60	5.83	–0.23
3	8.90	9.01	–0.11	2.80	2.85	–0.05	6.10	6.13	–0.03
4	8.00	9.03	–1.03	2.60	2.85	–0.25	5.40	6.14	–0.74
5	7.10	7.72	–0.62	2.80	2.83	–0.03	4.30	4.86	–0.56
6	10.60	10.52	0.08	3.60	3.64	–0.04	7.00	6.85	0.15
7	9.10	9.56	–0.46	2.50	2.69	–0.19	6.60	6.67	–0.07
8	6.50	6.99	–0.49	1.80	1.80	0.00	4.70	4.99	–0.29
9	8.80	8.94	–0.14	2.70	2.82	–0.12	6.10	6.09	0.01
10	9.80	9.62	0.18	3.10	3.07	0.03	6.70	6.68	0.02
11	6.70	6.56	0.14	2.30	2.41	–0.11	4.40	4.28	0.12
12	8.30	8.12	0.18	2.30	2.12	0.18	6.00	5.80	0.20
13	10.70	10.96	–0.26	3.10	3.09	0.01	7.60	7.66	–0.06
14	7.90	7.70	0.20	2.80	2.73	0.07	5.10	5.10	0.00
15	14.00	13.08	0.92	4.70	4.23	0.47	9.30	8.82	0.48
16	8.10	8.22	–0.12	2.60	2.50	0.10	5.50	5.67	–0.17
17	10.70	10.91	–0.21	3.80	3.86	–0.06	6.90	7.18	–0.28
18	13.50	12.43	1.07	4.80	4.38	0.42	8.70	8.02	0.68
19	8.50	8.99	–0.49	2.70	2.84	–0.14	5.80	6.12	–0.32
20	6.30	6.51	–0.21	1.70	1.62	0.08	4.60	4.69	–0.09
21	11.40	11.56	–0.16	3.20	3.31	–0.11	8.20	8.04	0.16
22	7.50	6.70	0.80	2.20	2.10	0.10	5.20	4.73	0.47
23	10.80	11.42	–0.62	3.40	3.55	–0.15	7.40	7.82	–0.42
24	9.50	9.56	–0.06	2.50	2.64	–0.14	7.00	6.89	0.11
25	7.80	7.63	0.17	2.20	1.93	0.27	5.60	5.50	0.10
26	8.50	8.84	–0.34	2.70	2.79	–0.09	5.80	6.01	–0.21
27	9.90	10.20	–0.30	2.90	2.92	–0.02	7.00	7.08	–0.08
28	6.40	6.76	–0.36	2.10	2.01	0.09	4.30	4.71	–0.41
29	7.30	5.68	1.62	1.90	1.34	0.56	5.40	4.31	1.09
30	10.50	11.40	–0.90	3.70	4.04	–0.34	6.80	7.49	–0.69
31	10.40	10.42	–0.02	3.60	3.64	–0.04	6.80	6.75	0.05
32	9.90	9.58	0.32	3.50	3.47	0.03	6.40	6.24	0.16
33	10.60	10.18	0.42	3.30	3.16	0.14	7.30	6.82	0.48
34	12.80	11.83	0.97	3.90	3.50	0.40	8.90	8.29	0.61
35	6.90	6.72	0.18	1.50	1.32	0.18	5.40	5.19	0.21
36	9.40	9.67	–0.27	2.10	2.30	–0.20	7.30	7.16	0.14
37	9.90	9.93	–0.03	3.50	3.46	0.04	6.40	6.44	–0.04
38	8.10	8.27	–0.17	2.80	2.94	–0.14	5.30	5.46	–0.16
39	7.00	6.93	0.07	1.90	1.79	0.11	5.10	5.09	0.01
40	6.50	6.98	–0.48	2.10	2.11	–0.01	4.40	4.68	–0.28
41	11.00	10.11	0.89	4.10	3.67	0.43	6.90	6.57	0.33
42	6.60	6.86	–0.26	2.30	2.44	–0.14	4.30	4.38	–0.08
43	6.00	6.08	–0.08	2.00	2.16	–0.16	4.00	3.89	0.11
44	6.90	7.01	–0.11	2.50	2.58	–0.08	4.40	4.56	–0.16
45	9.30	9.97	–0.67	2.60	2.80	–0.20	6.70	7.13	–0.43
46	7.30	7.45	–0.15	2.00	2.05	–0.05	5.30	5.37	–0.07
47	9.60	10.10	–0.50	3.10	3.24	–0.14	6.50	6.82	–0.32
48	5.60	5.64	–0.04	1.70	1.76	–0.06	3.90	3.84	0.06
49	11.30	10.18	1.12	4.50	3.94	0.56	6.80	6.38	0.42
50	10.00	10.19	–0.19	2.70	2.83	–0.13	7.30	7.31	–0.01
51	7.40	7.18	0.22	2.80	2.95	–0.15	4.60	4.36	0.24
52	7.30	7.35	–0.05	2.50	2.63	–0.13	4.80	4.69	0.11
53	9.00	9.05	–0.05	2.80	2.86	–0.06	6.20	6.16	0.04
54	5.60	6.58	–0.98	1.50	1.65	–0.15	4.10	4.88	–0.78

Table 5. Comparison between experimental data and predicted values for energy per unit mass and specific energy

	Energy per Unit Mass (kJ/kg)			Specific Energy (kJ/m^2)		
Test	Exp.	Pred.	Diff.	Exp.	Pred.	Diff.
1	12.02	11.33	0.69	2.05	2.82	–0.77
2	21.04	20.94	0.10	3.87	3.73	0.14
3	16.99	17.22	–0.23	5.10	5.28	–0.18
4	15.89	17.25	–1.36	6.02	5.29	0.73
5	18.71	18.25	0.46	3.89	4.50	–0.61
6	15.64	14.91	0.73	6.14	6.07	0.07
7	19.02	18.87	0.15	4.46	4.49	–0.03
8	18.16	18.52	–0.36	4.92	5.42	–0.50
9	17.32	17.10	0.22	4.97	5.16	–0.19
10	19.02	18.63	0.39	4.24	4.54	–0.30
11	15.83	15.97	–0.14	4.89	5.09	–0.20
12	16.52	16.32	0.20	7.37	6.20	1.17
13	16.79	17.18	–0.39	5.58	5.34	0.24
14	14.17	13.77	0.40	6.56	5.89	0.67
15	21.22	20.89	0.33	3.91	3.78	0.13
16	12.13	11.55	0.58	2.29	2.92	–0.63
17	15.24	15.68	–0.44	4.41	5.02	–0.61
18	19.22	18.70	0.52	4.12	4.31	–0.19
19	16.43	17.18	–0.75	5.78	5.30	0.48
20	16.83	17.27	–0.44	5.51	5.48	0.03
21	18.47	18.67	–0.20	5.59	5.35	0.24
22	13.53	13.17	0.36	1.94	1.89	0.05
23	17.22	17.60	–0.38	5.18	5.35	–0.17
24	19.06	19.10	–0.04	4.58	4.41	0.17
25	15.65	15.05	0.60	5.94	6.17	–0.23
26	16.00	16.89	–0.89	4.77	5.10	–0.33
27	19.91	20.43	–0.52	3.73	4.54	–0.81
28	15.84	17.28	–1.44	4.55	5.42	–0.87
29	16.50	15.95	0.55	5.80	6.07	–0.27
30	16.18	16.96	–0.78	4.21	4.99	–0.78
31	19.36	19.38	–0.02	4.35	4.61	–0.26
32	17.64	17.51	0.13	3.81	4.17	–0.36
33	20.12	19.43	0.69	4.75	4.87	–0.12
34	19.63	19.21	0.42	3.94	4.48	–0.54
35	15.12	14.60	0.52	2.56	2.29	0.27
36	20.89	20.14	0.75	5.66	4.83	0.83
37	17.97	18.08	–0.11	5.23	4.64	0.59
38	15.11	15.21	–0.10	6.87	5.95	0.92
39	14.72	14.47	0.25	1.88	2.00	–0.12
40	13.06	13.41	–0.35	1.93	2.21	–0.28
41	19.56	18.86	0.70	5.43	4.27	1.16
42	12.20	12.32	–0.12	2.40	2.01	0.39
43	15.16	15.01	0.15	6.97	6.16	0.81
44	16.79	17.16	–0.37	5.68	5.10	0.58
45	19.99	20.19	–0.20	5.05	4.65	0.40
46	20.14	19.43	0.71	4.50	4.64	–0.14
47	14.59	15.28	–0.69	2.16	1.27	0.89
48	14.83	15.36	–0.53	1.80	1.21	0.59
49	18.60	18.05	0.55	4.32	4.45	–0.13
50	16.03	15.95	0.08	5.61	6.14	–0.53
51	12.49	12.38	0.11	1.80	2.03	–0.23
52	13.59	13.59	0.00	2.50	2.13	0.37
53	17.20	17.31	–0.11	4.92	5.23	–0.31
54	12.58	13.46	–0.88	1.68	1.99	–0.31

The specific energy was negatively proportional to single kernel weight. Wheat of smaller kernel mass required more energy to create one unit new surface area than wheat of larger kernel mass.

Figures 4 and 5 are the surface plots for energy per unit mass and specific energy using the two most significant factors, single kernel hardness and roll gap as variables.

A comparison between the experimental data and the predicted values for fast roll power, slow roll power and net power is presented in table 4. The average differences between experimental data and predicted values were 0.4 kW/m (4.7% of the experimental average) for fast roll power, 0.2 kW/m (5.8% of the experimental average) for slow roll power, and 0.3 kW/m (4.0% of the experimental average) for net power.

Comparisons between the experimental data and the predicted values obtained using prediction models for energy per unit mass and specific energy have been summarized in table 5. The average difference between the experimental data and the predicted values was 0.42 kJ/kg (2.2% of the experimental average) for energy per unit mass, and 0.42 kJ/m^2 (9.4% of the experimental average) for specific energy.

Verification of the Prediction Models

To test the robustness and validity of the prediction models, 10 samples of wheat with different physical properties were selected. Levels of independent variables were randomly selected (table 6). Single kernel hardness for the selected wheat samples ranged from 9.06 to 83.5, and included an extra soft wheat (SRW) and an extra hard wheat (HRW). Also, soft white wheat (no. 4) was used.

The experimental data and predicted values for the verification tests are presented in table 7. In most cases, the experimental data agreed with the predicted values, especially for fast roll power, slow roll power, net power and energy per unit mass. Only for 2 tests, no. 2 (SRW) and no. 4 (SWW), was the difference over 50% for specific energy.

Table 6. Values of independent variables and covariates for verification tests*

		Independent Variables					Covariates	
Test	Class	F	M	R	D	G	H	W
1	SRW	22	14.5	450	3.5	0.72	9.06	35.26
2	SRW	15	16.5	525	3.1	0.66	18.41	36.20
3	SRW	16	14.5	425	3.2	0.78	24.50	32.50
4	SWW	20	15.5	475	3.4	0.81	40.40	37.10
5	HRW	18	15.5	525	3.3	0.69	41.18	28.50
6	HRW	20	15.5	500	3.4	0.71	53.50	25.80
7	HRW	20	15.5	500	3.4	0.71	60.70	32.80
8	HRW	25	16.0	450	3.5	0.75	65.00	30.10
9	HRS	25	16.5	475	3.7	0.75	79.00	45.90
10	HRW	22	15.0	525	3.6	0.72	83.50	32.60

* SRW = soft red winter, SWW = soft white wheat, HRW = hard red winter, and HRS = hard red spring.
See equation 2 for definition of variables.

Table 7. Results of verification tests*

	Dependent Variables									
	P_F (kW/m)		P_S (kW/m)		P_N (kW/m)		E_W (kJ/kg)		E_A (kJ/m^2)	
Test	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
1	0.72	0.75	0.20	0.21	0.52	0.54	13.32	13.41	1.65	1.70
2	0.56	0.70	0.25	0.26	0.31	0.36	21.88	15.98	3.35	1.52
3	0.62	0.46	0.18	0.13	0.44	0.38	20.76	12.11	4.01	3.12
4	0.90	0.75	0.30	0.23	0.60	0.53	17.23	14.69	2.78	4.16
5	0.72	0.73	0.31	0.27	0.41	0.45	13.40	14.63	3.19	3.34
6	0.83	0.81	0.30	0.28	0.53	0.53	14.47	14.74	3.86	4.28
7	0.85	0.89	0.31	0.31	0.54	0.59	16.49	16.98	4.28	4.36
8	0.99	1.07	0.29	0.30	0.70	0.73	16.45	16.68	4.88	5.17
9	1.13	1.30	0.36	0.37	0.84	0.90	19.77	21.11	5.83	4.91
10	0.86	1.05	0.33	0.36	0.53	0.73	13.8	18.23	6.03	5.53

* Exp. = experimental data, and Pred. = predicted value.
See equations 4 to 8 for definition of variables.

Summary and Conclusions

Power and energy requirements for size reduction of wheat were affected by the physical characteristics of wheat samples and the operational parameters of roller mills. Among the physical properties of wheat, single kernel hardness was useful in predicting the power and energy requirements. Wheat samples with different single kernel hardness behaved differently when subjected to grinding action. The power and energy requirements were positively correlated with single kernel hardness. Soft wheat grinding needed less energy than for hard wheat. Single kernel weight affected the grinding process significantly. In these tests, the HRS wheat had lower single kernel hardness, but higher single kernel weight than HRW wheat. The power and energy requirements for HRS wheat were higher than HRW wheat.

As feed rate increased, fast roll power, slow roll power, and net power increased. It was the most significant factor affecting power requirement. But, feed rate had no effect on energy per unit mass and specific energy.

Roll gap had significant effect on power and energy requirements, and was included in all prediction models. As roll gap increased, the fast roll power, slow roll power and net power, and energy per unit mass decreased significantly. However, the specific energy increased as roll gap increased.

The effects of other factors, such as moisture, fast roll speed and roll speed differential, on the power and energy requirements were also significant. In most cases, however, they had relatively smaller partial r^2 values in the prediction models. Moisture was positively correlated with fast roll power, slow roll power, net power, and energy per unit mass. Fast roll speed was positively correlated with fast roll power and slow roll power, and negatively correlated with net power and energy per unit mass. As roll speed differential increased, slow roll power decreased, and net power, energy per unit mass and specific energy increased.

The results of 10 verification tests suggested that the developed prediction models have potential for predicting power and energy requirements for size reduction of wheat using a roller mill. The models predicted net power and energy for grinding only since the no-load values were subtracted from values measured during grinding.

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