

## Comparison of Work Input Requirement on Laboratory-Scale and Industrial-Scale Mechanical Dough Development Mixers

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### ABSTRACT

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The use of a laboratory-scale mixer for predicting the mixing requirement of flours in an industrial-scale mixer was investigated by measuring the work input required to mix a range of flours to peak consistency on both a laboratory-scale and an industrial-scale mechanical dough development (MDD) mixer. The industrial mixer used was a Tweedy-type mixer, and the mixing optimum was determined using a probe that sensed changes in dough consistency. Work input was estimated from mixer motor power, taking into account expected motor and drive chain losses, and from dough temperature rise measurements. The laboratory mixer

used twin flat-bladed rotors; mixing optimum and work input were determined from the torque measurement. Work inputs from both mixers were highly correlated ( $r^2 = 0.88$ ) but with a large offset (the industrial mixer requiring more work to develop the dough). The two methods of measuring industrial mixer work inputs gave slightly different results leading to uncertainty as to the actual work given by the industrial mixer. Farinograph mixing properties were less well correlated with industrial-scale work input requirement than the laboratory-scale MDD mixer.

Since the New Zealand wheat and flour industry was deregulated in 1987, improved baking quality has become a major target of wheat breeding. This has resulted in a move to stronger wheat varieties. Within the breeding system the baking quality of a new variety is estimated by a range of tests on succeeding generations. Ultimately, a cultivar's suitability for release as a bread-baking wheat is determined, in part, using the Crop & Food Research (C&FR) 125-g mechanical dough development (MDD) test baking system (Mitchell 1989). As a result of these breeding efforts, the average bake score of the New Zealand wheat harvest has increased from 21 to 27 bake score units (~15% volume increase) from 1987 to 1994. At the same time, work input requirement, also measured by the C&FR 125-g MDD test baking system, has increased from 8 to 18 Wh/kg (29–65 kJ/kg) (Lindley and Moore 1988, Simmons 1994).

The increase in work input requirement has caused serious problems for industrial-scale bakeries as their plants were designed to process flour with a work input requirement of up to 11 Wh/kg based on the Chorleywood Bread Process. Plant cycle times, mixer motor size, and mixer cooling capacity all combine to limit the amount of work the mixer is capable of giving the dough. Most New Zealand MDD bakeries were designed to process flours with a work input requirement of up to 12 Wh/kg. Therefore, work input requirement is an important factor for the breeding program. Plant bakery operators in both Australia and England have discussed with the senior author the problems caused by the excessive mixing requirement of some modern cultivars. Oliver and Allen (1994) report on the undesirable increase in mixing requirement in some Australian hard wheats.

The amount of work given to the dough is critical to the quality of the finished bread. Studies in our own laboratories (Mitchell 1989, Griffin and Wooding 1992), and many studies by other workers (Bushuk et al 1965, Skeggs and Kingswood 1981, Kilborn and Tipples 1972) have shown, for any one mixer, large differences in bread quality at different work input levels. It has also been shown that the work required to develop a dough varies with mixer type.

Fortmann et al (1964), and Kilborn and Tipples (1973) have shown different work input requirements for the dough of the same flour mixed on different laboratory mixers, and the same laboratory mixer with different impellor shapes. Thus, the correct amount of mixing to achieve optimum bread quality depends not only on the characteristics of the flour but also on the type of mixer used in the process. There is a large difference between the industrial-scale and our laboratory-scale mixers, both in size (125 g vs. 100–200 kg of flour weight) and geometry (twin flat blades vs. single helix). Therefore, it seems unlikely that the work input requirements on the two systems would be the same. If plant breeding efforts, which rely on laboratory-scale testing, are to produce flours with a work input appropriate to industrial-scale bakeries, then we need to know the relationship between work inputs measured on the laboratory-scale (125 g) and the industrial-scale. Work input on our laboratory-scale mixer is determined by measuring the torque and calculating the energy imparted to the dough.

The most common type of industrial MDD mixer in New Zealand, Australia, and the United Kingdom is the Tweedy (Tweedy, Burnley) or other mixers of this general type. A typical mixer has been described by French and Fish (1981). For this type of mixer the rotor torque is constant and does not reflect changes in dough consistency (Russell Eggitt 1975, Kilborn and Tipples 1981), so the degree of dough development cannot be determined from the standard torque versus time mixing curve. Energy input is determined from motor-power consumption. The amount of work to give the dough in an industrial-scale bakery using this type of mixer is determined from the baker's assessment of the dough feel and the quality of the resulting bread.

Kilborn and Tipples (1981) published a description of a probe they had designed to measure dough consistency during mixing on a Tweedy 35 mixer. Wilson (1992) described the use of a similar probe for measuring dough consistency during mixing in industrial-scale mixers. In this article, we report the results of studies conducted using this probe to determine work input requirement of a range of flours in an industrial-scale MDD mixer and compare them to the work requirement assessed on our laboratory-scale MDD mixer. The problem of accurately measuring work input in industrial-scale mixers is also considered. Due to operational constraints in the plant bakery, and the limited amount of flour available, it was not possible to measure the baking performance response of the flours in this study to different levels of work input.

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## MATERIALS AND METHODS

Two sample sets of flours were used in the trials. The first set comprised 12 flours (flours 1–12) of the same wheat variety that were grown under different sulfur-nitrogen treatments as part of a fertilizer trial (Wooding et al 1994). The first set were all commercially milled (Canterbury Roller Mills, Ashburton). The second set comprised two commercially milled, mixed grist, specialty flours (Champion Flourmills, Christchurch), one with weaker and the other with stronger work input characteristics than normal bread flours.

All flours were analyzed for protein ( $N \times 5.7$ , 14% mb) by near infrared reflectance (NIR) and for rheological properties by farinograph method 54-21 (AACC 1995) (Table I). Flour analyses for the first set were done at C&FR; analyses for the second set were supplied by the mill.

Work input requirement and water absorption were determined in duplicate on C&FR's 125-g MDD test-bake system following the procedure described by Mitchell (1989). A previous report (Wooding et al 1994) used work input values adjusted to give values that agreed with those previously obtained when the mixers used a motor power method for measuring work instead of the motor torque method now employed. Only unadjusted values are used in this report.

### Industrial-Scale Dough Consistency Measurement

The industrial-scale mixer used was a Convaire 200 (designed for 200-lb [90-kg] flour doughs) that had been modified by the addition of an ECS rotor and bowl (ECS Engineering, Christchurch). The dimensions and capacity of the bowl remained the same, but the side baffles were lowered and the rotor arms made larger and heavier. The bowl was also fitted with a glycol cooling jacket. The mixer is driven by a 56-kW motor via multiple V-belts giving a nominal rotor speed of 350 rpm. The control system of the mixer controls addition of flour, water, and liquid fat; the remaining ingredients are added manually. For the work reported here, the flour was added manually from 20-kg sacks, and only the fat and water were added automatically. The mixer is equipped with a vacuum system that is activated 80 sec after mixing commences and remains on until mixing is complete. A vacuum of  $-55$  kPa was applied for all runs. The mixer has an integral kilowatt-hour meter to measure energy consumed by the mixer motor, which has a resolution of 10 Wh. The mixer automatically stopped mixing when the target value had been reached. To conform with standard industry practice, the kilowatt-hour meter circuit has the

facility to trim out the no-load current. The kilowatt-hour meter is set to read zero when the mixer is running empty. This is done in an attempt to remove the effect of energy losses in the motor and drive chain so the work input measured more closely reflects work that actually is given to the dough. In fact, because the energy losses in the motor are a nonlinear function of the load, this correction is likely to be in error. To give a true reading of the motor power, the energy consumed by the mixer motor was also measured by a Hioki HIO, 3134 AC power line meter that has a digital display, plus analog outputs, for volts-amps-watts-volt amps reactive. The analog outputs were recorded by the same computer system that was used for recording the dough probe signals at 10-Hz sample frequency.

The mixing efficiency of a mixer can be defined as the work input required to develop dough to a defined point, for example, to the peak of the mixing curve. This can be done relatively easily on the laboratory-scale by measuring the torque exerted on the rotor arm; the integral of torque  $\times$  angular velocity over the time taken to reach the peak of the torque curve gives the work input to that point (Kilborn and Tipples 1973). On Tweedy-type industrial-scale mixers, the point of peak dough consistency can be measured using a probe, but this only locates the peak, it does not measure the work input. If the power drawn by the mixer motor is used to measure work input, this will contain energy losses in the motor and drive chain that would lead to an overestimate of the amount of energy given to the dough. The energy losses, however, can be estimated from standard tables of motor and drive efficiencies. An alternative method is to measure the temperature rise of the dough during mixing. Using the temperature rise, and the heat capacity of dough, it is possible to calculate the amount of work given to the dough. The main problem with this method is estimating heat transfer to and from the environment that will affect the heat balance calculation. The most accurate method is to measure the mixer rotor torque as is done in laboratory-scale mixers. However, this is not generally practical in standard industrial-scale mixers. In this article, the dough probe is used to locate the point of peak dough consistency in the industrial-scale mixer and both motor power and dough temperature rise are used to estimate the work input to this point.

For estimating work input from dough temperature rise, the method of Mitchell (1989) was used. Dough temperatures were measured in three places using three separate thermometers (Digitron 1408-K or 3208, Type K thermocouple). The probes were inserted into the dough and left for 20 sec to equilibrate before the readings were recorded. The initial temperature was

TABLE I  
Analytical Results on Flours Used in Work Input Comparison

Flour	Farinograph Values				
	Protein <sup>a</sup> (%)	Water Absorption (%)	Development Time (min)	Stability (min)	Breakdown <sup>b</sup> (10 min)
Weak	9.1	62.7	2.0	1.5	120
Strong	10.7	62.6	6.0	8.5	20
1	10.7	66	4.0	5.3	70
2	9.6	64	3.7	5.7	70
3	9.8	65	4.1	7.2	60
4	10.7	65	4.4	7.4	60
5	11.8	66	6.2	10.0	40
6	12.6	67	5.3	6.7	50
7	10.2	65	4.9	8.3	60
8	10.6	64	4.0	10.9	40
9	11.7	67	5.7	9.0	40
10	11.6	67	4.3	5.0	60
11	10.5	65	4.5	6.1	50
12	12.0	64	3.7	5.5	70
SEM <sup>c</sup>	0.4	0.3	0.4	1.2	9.7

<sup>a</sup> 14% mb.

<sup>b</sup> Brabender units.

<sup>c</sup> Standard error of mean for  $n = 2$ .

taken after ~30 sec mixing. The mixer was restarted and mixing completed (~3 min). The mixer was then stopped and temperatures were measured again. The standard error of the mean of the temperature measurements within a dough was 0.3°C, with a maximum difference of 1.2°C, indicating the temperature was relatively uniform throughout the bulk of the dough.

The dough probe consists of a short stainless steel rod extending into the mixing chamber, with the external end attached to a load cell (Precision Transducers ST100). The metal rod was drilled to allow a type K thermocouple to project ~5 mm beyond the end of the rod into the mixing chamber. The analog signal from the load cell was amplified by a custom-built signal conditioning module that gave a 0–10 V output for 0–100 kg load input. The thermocouple signal was amplified and conditioned by a PST-K12C-S (Hsiang Cheng Corporation) thermocouple isolating transmitter module to give a 0–10 V output for 0–100°C. The analog strain gauge and temperature signals were digitized by a custom-built 2-channel, 12-bit analog-to-digital converter module attached to a Toshiba T1950 laptop computer. Strain gauge data were collected at 100 Hz, temperature data at 1 Hz. A custom program written in ASYST, version 4.0 (Keithley ASYST, Rochester, NY) was used to record and analyze the data. The moving average of the dough probe force signal was plotted versus time. The frequency spectrum over 10-sec intervals was determined with a standard FFT routine (ASYST). The power in the low frequency band (0.1–5 Hz) was calculated and plotted every 5 sec. A smoothing function (ASYST) was fitted to this data to locate the maximum. The maximum in the low frequency power curve coincides with the maximum in the force curve and is generally more clearly defined, so the low frequency power curve is used in preference to the force curve. A typical curve is shown in Fig. 1.

Measurements of dough consistency for the first flour set were randomized over six days using the field plot design with three replicates per plot (except flours 6 and 7, which had four replicates). No corrections were made for daily variations. Dough consistency measurements for the second set were measured in triplicate on the same day.

The standard recipe for white, 700-g, lidded bread comprised flour (80 kg), water (48 kg), yeast (2.1 kg), compound improver (1.60 kg; enzymes, emulsifiers, soya flour, and ascorbic acid), salt (1.60 kg), sugar (0.60 kg), gluten extender (0.60 kg), calcium acetate (0.16 kg), and malt flour (0.16 kg) giving a total dough weight of 135 kg. Water temperature was adjusted and some of the water replaced by ice to achieve a dough temperature after mixing of 32°C. Bakery operating procedures necessitated the use

of a constant water addition level (60% of flour weight) for all doughs even though their water addition levels, as estimated by the C&FR 125-g MDD mixers, varied from 60 to 65%. The low water level was used so the doughs could be readily processed even though they had been overmixed to locate the mixing optimum. Previous work by Larsen and Greenwood (1991) had shown that, at least for the C&FR 125-g MDD mixers, significantly altering water addition levels did not alter work input requirement. The MINITAB statistical package, release 10.1 (Minitab Inc., State College, PA, 1994) was used to analyze results.

## RESULTS AND DISCUSSION

### Industrial-Scale Work Input Estimated from Mixer Motor Power

Conforming to standard industry practice, the mixer kilowatt-hour meter has a no-load correction circuit that is adjusted so the kilowatt-hour meter reads zero when the mixer is running empty. The aim of doing this is to remove the energy required to overcome losses in the motor and friction in the drive chain so that the work recorded by the meter more closely reflects the energy used in mixing the dough. Although this method is widely used in the baking industry, it can introduce significant errors into the work measurement. The mechanical output power of an electric motor is a nonlinear function of the electrical power drawn by the motor. A typical motor efficiency chart (output power/input power) for 56kW motor (Brooke Compton specification) shows a low efficiency at low load (75% efficiency at 10% load), plateauing over the remainder of the range (90–92% efficiency for 20–100% load) and falling off again above 100% load.

To check the mixer kilowatt-hour meter, five doughs were mixed and the power drawn by the motor measured using the Hioki power meter. A typical curve of motor power with time is given in Fig. 2; the area under the curve is the energy consumed by the motor. The average ratio of mixer kilowatt-hour meter work to the external kilowatt-hour meter work for the five doughs was  $0.89 \pm 0.01$ , i.e., the mixer kilowatt-hour meter was adjusted to underestimate the energy input to the motor by 11% or 6 kW at full load (56 kW). This correction was made while the mixer was running with an empty bowl. The motor efficiency at 6kW is only 63%. It follows that  $63\% \times 6\text{kW} = 3.8\text{kW}$  is the mechanical power needed to overcome mechanical losses when the bowl is empty. When the mixer is running at full load (56kW), the motor efficiency is 91%. Thus, in the normal operating condition, assuming that the mechanical losses are the same when the bowl is full or empty, the losses are  $9\% \times 56\text{kW} + 3.8\text{kW} = 8.8\text{kW}$ .

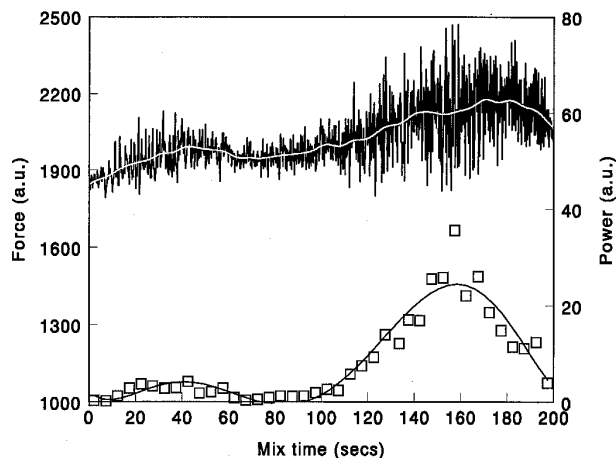


Fig. 1. Dough consistency change in the industrial-scale mixer measured using the dough probe showing force on the probe vs. time, and power at 0.1–5 Hz in the Fourier spectrum of the force vs. time curve. Force —; power □. a.u. = Arbitrary units.

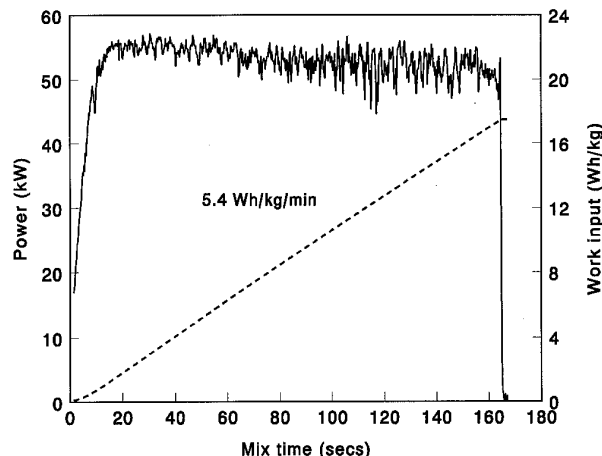


Fig. 2. Motor power and accumulated work input vs. time for a typical dough mixed on the Convaire 200 industrial-scale mixer. Power —; workinput - - -.

This loss is equivalent to 16% of motor input power. Work inputs calculated using this method will be referred to as theoretical efficiency work inputs.

The drive chain of the Convaire mixer is very simple. The mixer motor is directly coupled to a 190-mm diameter pulley that drives (using 5 V-belts) an 800-mm pulley that is directly coupled to the rotor. The estimated efficiency of a V-belt drive is 95–98% (Anonymous 1992). As little energy is expected to be lost in the bearings, the overall efficiency of the mixer would be expected to be the product of motor and belt efficiencies. For 56-kW input power, the mixer motor produces 51-kW output power. If 5% of this is lost in the belt drive, this loss would equal 2.6 kW. This is not too dissimilar to the estimated mechanical loss of 3.8 kW. Unfortunately, no direct measurements of mechanical efficiency were made on the mixer and such measurements are no longer possible as the mixer configuration has since been altered.

### Industrial-Scale Work Input from Dough Temperature Rise

There are two difficulties with using dough temperature rise to measure work input to the dough. The first is the assumption that no heat is lost or gained by the dough from the environment during mixing, and the second is determining the specific heat of dough.

Rask (1989) lists experimentally measured values for the specific heats of dough and bakery products. Values obtained for bread dough varied between 2.61 and 3.16 kJ/kgK with an average value of 2.88 kJ/kgK for dough water contents of 42–46%. The only result for a water content of 46%, equivalent to a water addition of 60%, was 2.81 kJ/kgK, equivalent to a dough temperature rise of 1.28°C/Wh/kg. The specific heat of dough can also be calculated from the specific heats of water (4.18 kJ/kgK at 25°C) (Anonymous 1980) and flour (1.76 kJ/kgK) (Anonymous 1979). Assuming a water addition of 60%, this gives a specific heat for the dough of 2.66 kJ/kgK, equivalent to a dough temperature rise

of 1.35°C/Wh/kg. The discrepancy between the two values for the specific heat of dough leads to a difference in work input prediction of ~5% or 0.5 Wh/kg work at 11 Wh/kg total work input. In New Zealand, a factor of 1.33°C/Wh/kg has traditionally been used (Mitchell 1989).

The heat rise method assumes an insignificant amount of heat is lost to or from the dough during mixing. The main paths for heat loss are by conduction through the metal of the bowl and rotor. Another possible path is from evaporation of dough water during the vacuum phase of mixing. The Convaire mixer consists of a single, vertical, helical rotor in a circular bowl with a lid that can seal against the vacuum drawn during the second half of the mixing cycle. All components are constructed from 304 stainless steel. During mixing, the dough rotates around the bowl contacting only the base and sides but not the lid of the bowl. Because the dough tends to wrap around the rotor, and there are small baffles projecting out of the inner surface of the bowl, dough contact with the bowl sides is limited. To cool the dough, a glycol jacket is attached to the outside of the bowl to reduce the temperature of the sides of the bowl to ~1–2°C. The base of the bowl is not cooled as the rotor base plate covers almost the entire bottom surface of the bowl, with a small air gap in between, so that heat conduction through the base is limited. Thus, the major path for heat loss is expected to be through the bowl sides.

Comparing dough temperature rise with the glycol cooling jacket on (bowl wall at 1–2°C), and off (bowl wall at ambient temperature [25°C]) gives an estimate of the amount of heat normally lost by conduction through the bowl wall. Table II lists the dough temperature rise measured for three consecutive doughs with glycol circulating through the jacket (jacket on) and three consecutive doughs with no glycol circulation (jacket off). The total power drawn by the mixer motor for these doughs is also given. The difference between glycol jacket on (bowl wall at 1–2°C) and glycol jacket off (bowl wall at ~25°C) is only 1.7°C of dough temperature. Thus, increasing the temperature differential between the bowl and dough by ~20°C has only increased the dough heat loss by 1.7°C, implying that only a small amount of heat is lost through the bowl of an uncooled mixer.

Another possible path for heat loss is evaporation of dough water during the vacuum phase of mixing (the last 100 sec). Because the latent heat of evaporation of water (2,300 kJ/kg) is so much greater than the heat capacity of dough (2.7 kJ/kg), the evaporation of only 0.3% of dough water would cool the dough by 1°C. Due to processing constraints, it was not possible to do no-vacuum mixing in the industrial bakery to investigate this effect.

TABLE II

Work Input in the Convaire 200 Industrial-Scale Mixer Measured by Dough Temperature Rise for  $16.4 \pm 0.1$  Wh/kg of Motor Work on Three Doughs with Cooling On and Three Doughs with Cooling Off

Conditions	Dough Temperature Rise <sup>a</sup> (°C)	Work Input <sup>b</sup> (Wh/kg)
No cooling	16.2 ± 0.7	12.2 ± 0.5
Cooling jacket on	14.5 ± 0.4	10.9 ± 0.3

<sup>a</sup> Mean and standard deviation of nine replicates.

<sup>b</sup> Assumes 1 Wh/kg raises dough temperature by 1.33°C.

TABLE III

Work Input Requirement Measured by the Dough Probe on a Convaire 200 Industrial-Scale Mixer and Crop & Food Research (C&FR) 125-g Mechanical Dough Development (MDD) Mixer

Flour	C&FR 125-g MDD Mixer <sup>a</sup>		Convaire 200 Mixer <sup>b</sup>	
	Work Input(Wh/kg)	Water Absorption (%)	Motor Power (Wh/kg)	Temperature Rise (Wh/kg)
Strong	10.4	60.5	11.5	10.2
Weak	3.4	60.3	8.4	7.4
1	8.4	62	11.7	10.3
2	9.4	60	11.6	10.2
3	10.3	61.8	12.8	11.3
4	12.0	63.5	15.4	13.7
5	14.1	64	17.5	15.4
6	13	64.3	16.6	14.7
7	12.3	61	14.7	13.0
8	12.9	62	15.6	13.8
9	14.2	64.3	16.7	14.8
10	10.4	65	14.7	13.0
11	9.5	62.5	12.6	11.2
12	11.4	64.3	14.7	13.0
SEM <sup>c</sup>	0.3	0.7	0.5	0.5

<sup>a</sup> All data are means of two replicates, except the weak and strong flours, which are of four replicates.

<sup>b</sup> All data are means of three replicates, except flours 6 and 7, which are of four replicates.

<sup>c</sup> Standard error of the mean.

Further work is required to determine whether evaporative cooling results in significant heat loss.

A comparison between the theoretical efficiency, and dough temperature rise methods, of measuring work input show a reasonable degree of agreement. For total energy input to the mixer motor equivalent to 16.4 Wh/kg in the dough, the dough temperature rise method gives a work input figure of 12.2 Wh/kg (Table II), an efficiency of 74%. Applying the motor and drive chain loss values derived in the previous section (i.e., using an efficiency of 84%) gives a predicted work input value of 13.8 Wh/kg. The difference between the two methods is 1.6 Wh/kg. As the temperature rise method is likely to underestimate, and the theoretical efficiency overestimate, the amount of work given the dough, then the real work input value is likely to lie between the two values.

### Relationship Between Industrial-Scale and Laboratory-Scale Work Input Requirement

Table I lists analytical and farinograph data and Table III lists work input requirement data for the two sample sets. The industrial mixer work input optima are located from the Fourier power spectra optima (Wilson 1992), and the work input values are calculated using the theoretical efficiency and the dough temperature rise methods.

Table IV shows the correlations between farinograph, laboratory-scale, and industrial-scale work input data. The correlation coefficients between C&FR 125-g MDD parameters and farinograph parameters are similar to those obtained previously (Atkins and Larsen 1990), except for water absorption which is lower in this study. As in the previous study, farinograph stability time is the farinograph property that most highly correlates with laboratory-scale ( $r = 0.85$ ,  $P = 0.001$ ) and industrial-scale ( $r = 0.70$ ,  $P = 0.01$ ) work input requirement. For industrial-scale work input requirement, protein content ( $r = 0.77$ ,  $P = 0.01$ ) is more highly correlated than farinograph stability time. However C&FR 125-g work input requirement has the highest correlation coefficient ( $r = 0.94$ ,  $P = 0.001$ ) with industrial-scale work input requirement.

Figure 3 shows the relationship between industrial-scale mixer work input requirements and C&FR 125-g MDD work input requirements. This shows a linear relationship between the two methods with  $R^2$  (adj.) = 0.88. Regression equations for the theoretical efficiency and dough temperature rise methods vs. C&FR 125-g MDD work input requirements are given in Table V. For both equations, the slope is <1 and there is a large positive offset. A slope <1 implies that the industrial-scale mixer is less sensitive

to changes in work input optima than the laboratory mixer. This would be an advantage for an industrial mixer as it would be more tolerant of different flours. Alternatively, the laboratory-scale mixer appears more sensitive to changes in flour properties, which is an advantage for a testing system. The large offset implies that the first few watt hours (~4 Wh/kg) of work input on the industrial mixer does not develop the dough.

From a plant-breeding perspective, the lower work inputs from the C&FR 125-g MDD mixers could lead to the release of wheat cultivars with overstrong mixing characteristics for industrial users. Alternatively, the data indicate that there is scope for improving the efficiency of industrial-scale mixers so they can develop dough as well as the laboratory-scale mixers.

The difference in work input values for the two mixers may be explained by their different rates of work input and different mixing actions. The work input rate of the Convaire 200 mixer (5.4 Wh/kg/min) was significantly higher than the laboratory mixer (1.6–3.2 Wh/kg/min), and their mixing actions are different. The literature is somewhat contradictory on whether rate of work input affects the amount of work required to mix to peak. Kilborn and Tipples (1977), in their studies on introducing rest periods into the mixing process, demonstrated that if mixing was stopped just after the ingredients were combined and the dough rested for several minutes, then the amount of work required to subsequently develop the dough to peak was much reduced. For flour, water, and salt doughs, mixing time on a mixograph was reduced from 3.5 to 2.4 min if a rest period of 2 min was used. The longer the rest time, the greater the reduction in mixing time. For full formula doughs, a 23% reduction in mixing time was produced for an 8-min rest time. However, if mixing was done without rest periods, at a range of work input rates (mixing speeds), the amount of work required to reach peak development was not changed (Kilborn and Tipples 1972). However, the mixing method used by Kilborn and Tipples included a short, slow speed, premix period before development was completed at the nominated mixing speed. Conversely, Frazier et al (1975), who did not use slow speed premixing, found work input to peak did increase with increasing rate of work input. It may be that higher work inputs are required for higher mixing speeds (shorter mixing time) due to time-dependent hydration effects.

The industrial-scale mixing curve shows maximum power being drawn at the start of mixing that only falls off slightly with time (Fig. 2). It is essentially a constant power mixer. The laboratory mixer draws about half power to begin with (work input rate 1.6 Wh/kg/min), then the power consumption rises to peak at the

TABLE IV  
Correlation Coefficients of Convaire 200 Industrial-Scale Mixer Work Input Requirement with Parameters from Crop & Food Research (C&FR) 125-g Mechanical Dough Development (MDD) Mixer and Farinograph

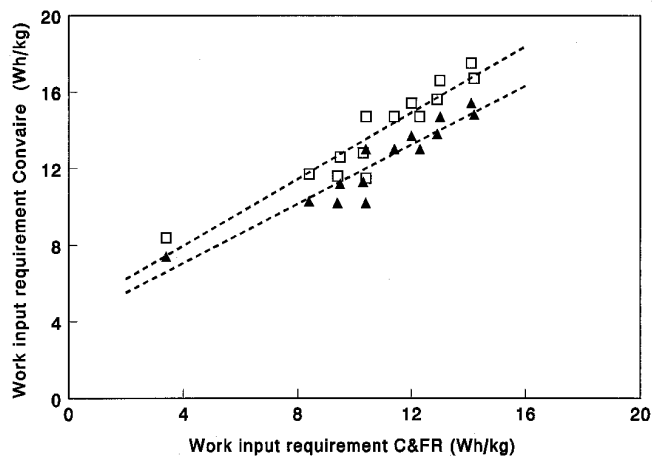
	Convaire 200 Mixer	C&FR Mixer		Farinograph			
	Work Input	Work Input	Water Absorption	Water Absorption	Development Time	Stability	Breakdown
C&FR work input	0.941****						
Water absorption	0.759**	0.572*					
Farinograph water absorption	0.661**	0.527	0.747**				
Development time	0.654*	0.780***	0.363	0.433			
Stability	0.703**	0.853***	0.179	0.190	0.740**		
Breakdown	-0.591*	-0.777**	-0.270	-0.254	-0.880***		-0.846***
Protein	0.774**	0.684**	0.866***	0.642*	0.596*	0.331	-0.494

<sup>a</sup> \*, \*\*, \*\*\* =  $P < 0.05$ ,  $P < 0.01$ , and  $P < 0.001$ , respectively.

TABLE V  
Regression Equations Describing the Relationship Between Work Input Requirement in the Convaire 200 Industrial-Scale Mixer and Crop & Food Research (C&FR) 125-g Mechanical Dough Development (MDD) Laboratory-Scale Mixer

Convaire 200 Work Input	Regression Equation <sup>a</sup>	$R^2$ (adj)
Estimated from motor power (84% of motor work)	$4.51 + 0.87 \times W_{lab}$	0.88
Estimated from dough temperature rise (74% of motor work)	$4.00 + 0.77 \times W_{lab}$	0.88

<sup>a</sup>  $W_{lab}$  = work input requirement on laboratory-scale C&FR 125-g MDD mixer.



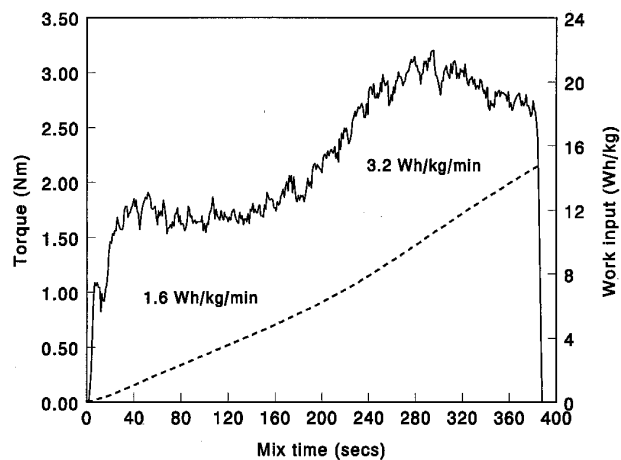
**Fig. 3.** Work input requirement from the Convaire 200 mixer estimated from motor power ( $\square$ ), and dough temperature rise ( $\blacktriangle$ ) vs. Crop & Food Research's (C&FR) 125-g mechanical dough development mixer work inputs for both flour sets.

mixing optimum (3.2 Wh/kg/min) (Fig. 4). If, during the early stages of mixing, the ingredients are just combining and hydrating, then work input to the dough at this point may have little effect on developing the dough. If this hydration and combining process is more time-dependent than energy-dependent, then the commercial mixer will be expending its maximum energy at the time when it has the least effect. From observations of dough in the industrial mixer, it takes ~20 sec to physically combine the ingredients to a dough. In this time, 2.2 Wh/kg of work has been expended, whereas for the laboratory mixer, only 0.35 Wh/kg has been expended. The hydration time in the industrial trial doughs reported in this article may have been extended because the flour was added manually, then the water and other ingredients added on top. Usually, the flour and water are added together, allowing the major ingredients to be combined more rapidly. Unfortunately, Tweedy-type, industrial-scale developers do not allow slow speed premixing so its effect on lowering total work input cannot easily be investigated.

### CONCLUSION

This work shows a linear relationship between work input to dough consistency optimum measured on a laboratory-scale and industrial-scale MDD mixer. Farinograph mixing properties were less well correlated with industrial-scale work input requirement than were the laboratory-scale MDD mixer. Because of the difficulty of accurately determining what portion of the motor power ends up as work in the dough, the absolute values of the industrial mixer's work input optima are in doubt. This uncertainty does not affect the goodness of fit of the regression equation which has an  $R^2$  of 0.88, but does affect the slope and intercept estimates. Thus, while the C&FR 125-g mixers are useful in ranking flours for their work input requirement on industrial-scale, Tweedy-type, MDD developers, they underestimate the work input values. Overall, the industrial mixer requires more energy to develop the dough than the laboratory mixer. This result has implications for plant breeders and others who use small-scale mixers to indicate industrial-scale performance of flour. Wheat lines that had acceptable work inputs on the C&FR 125-g MDD system could have industrial-scale work inputs that were beyond the capacity of the industrial bread plants.

The regression line suggests the 4 Wh/kg work input difference between the C&FR 125-g MDD system and the industrial mixer is due to a large offset which implies that the first 4 Wh/kg work on the industrial mixer has little effect on developing the dough. This



**Fig. 4.** Mixer torque and accumulated work input vs. time for a typical dough mixed on the Crop & Food Research's (C&FR) 125-g mechanical dough development mixer. Torque—; work input - - -.

may be due to the faster rate of work input of the industrial mixer or its mixing action, especially the high power drawn by the industrial mixer during the early stage of mixing. This suggests that slow speed premixing to combine the ingredients before high speed development may be a way of lowering the work input requirement of industrial-scale Tweedy-type developers.

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