Laboratory Studies of Wet Milling[1]

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ABSTRACT

American malt milled commercially in a wet mill contained a higher proportion of large particles than commercially dry milled malt and occupied 30% more volume. Wet-milled kernels fragmented less than dry-milled kernels, and the husk was less broken and shredded. Amylolysis appeared to have occurred during malt steeping, before wet milling. In model systems, malt steep temperature influenced water uptake more than did time of steeping. Mill-gap setting and milling style strongly affected particle size of the milled malt and influenced extract yield in standard mashes. However, regardless of the milling style used, particle size controlled extract yield, partly as a function of diffusion. The effect of particle size on the rate of diffusion of extract from particles, run-off rate, and bed compaction was clearly demonstrated in mash/lauter models. A system of malt steeping and wet milling may permit some temporal separation between extract production and extract recovery, which occur simultaneously in traditional dry milling/mashing/lautering systems. Development of this idea may permit wet mills to make a greater contribution to highly efficient North American brewhouses.

Key words: *Diffusion, Extract yield, Malt, Milling, Particle size, Wet*

Wet milling offers several potential advantages, including increased brewhouse extract yield and faster runoff from the lauter vessel. Although both advantages may be realized simultaneously in practice (7), they usually have not been in North America (5). The realization of the potential of wet milling depends on the exact details of the practical brewhouse and the brewing process in which it is to be used. In a brewhouse that is already efficient, further improvement in efficiency by merely adding a wet mill may be too much to expect without critical process evaluation and additional changes.

Healy and Armit (3) reviewed the literature of wet milling and noted that most of the pertinent fundamental studies of lautering performance were done using dry-milled malt (4). Using a mathematical approach, these authors proposed a model that identified mean particle diameter, defined by conditions of malt steeping as the focal point between wet milling and lautering that controls brewing performance. We agree that particle size and the rate of diffusion of extract from particles govern lautering performance. In addition, however, malt steeping may have functions that affect mashing as well as lautering. Healy and Armit (3) attempted to provide a framework of logic within which the brewing performance of wet milling could be optimized in a particular brewery. Our objective was to directly compare wet- and dry-milled materials in an attempt to explain their behavior.

Our work led us to separate the concept of extract *production* from that of extract *recovery*. These two events inevitably overlap when dry-milled malt is mashed, but wet milling may permit a temporal separation between them, because extract production can occur during malt steeping.

EXPERIMENTAL

Studies of Particle Size Distribution

Particle size distribution in all samples was measured by sieving. To minimize differences between the behavior of wet and dry materials during sieving, all samples were shaken by hand on a stack of screens under a brisk stream of cold water from a shower head. Separation in this way required 2–3 min for 20 g (dry wt) of material. The screen sizes used were 0.111 in., 0.093 in., 0.065 in., and 0.0195 in. The material on each screen was collected, dried, and weighed. The difference in weight between material applied to the screen and collected material was calculated as throughs (ie, able to pass the finest screen in the stack). The image-analyzing computer was a model 720 Quantimer (Cambridge-Imanco, Monsey, NY 10952). Examinations of particles by light microscopy and scanning electron microscopy were done using standard methods.

Studies of Extract Yield with the Model Mash/Lauter System

Wet-milled malt was steeped in 22°C (72°F) water for 20 min before milling, except where indicated. Wet- or dry-milled malt was mashed according to the ASBC method for extract (1). In the mash-lauter studies, the mash was heated to 78°C (172°F) and held 5 min after the conversion hold. The mash was then transferred to the model lauter vessel and held 30 min before runoff. The initial weak wort was recirculated, then 20 or more 100-ml samples were collected sequentially from the lauter to the end of sparging. Wort was run off at 50 ml/min. The model lauter was a vertical cylinder (9 × 45 cm) with a slotted plate in the bottom above a plenum of minimum volume. A tap was placed in the bottom center of the vessel. The lauter was fully enclosed in a water jacket through which water at 70°C (158°F) circulated continuously. In use, the lauter plate was barely covered with water before the mash was added. In every case, dry malt and wet malt milled at the same mill-gap setting were processed side-by-side in identical vessels to minimize differences in treatment. Wort gravity was determined with a calibrated refractometer, and total polyphenols by the method of Singleton and Slinkard (6).

Malt Steeping Experiments

Moisture content of steeped malt was determined by draining off the excess steep water, blotting the adhering surface water, and weighing the malt immediately. Malt was steeped in twice its weight of water, and soluble solids in the excess water were determined by refractometry.

RESULTS

Particle Size of Practical Samples

Commercial samples of wet- and dry-milled malt, mash, and spent grain contained the normal amount of moisture (Table I). These values allowed comparison among samples to be made on a dry-weight basis.

We sieved the commercial samples to estimate particle size. When equal dry weights (20 g) of wet- and dry-milled malt were flushed through a stack of screens, three times as much material remained on the 0.111-in. screen from the wet-milled malt sample as from the dry-milled material (Table I). This difference probably was not due to digestion of small particles in the wet-milled malt sample before analysis, because the amount of throughs was roughly the same in wet- and dry-milled malt. Furthermore, hydrated dry-milled malt yielded the same particle size distribution as milled malt stored in the dry state. The lower value for throughs for wet-milled mash and the spent grain samples probably reflects digestion of small particles.

Volume of Particles

When the number of particles in arbitrarily selected size categories was measured on an image analyzer, we found that wet-milled malt contained more material in the largest size category than did dry-milled malt (Table II). When these area values were

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recalculated as volume, the wet-milled sample had a considerably larger total volume (about 30%) than the dry-milled sample (6). The particles in the largest category (29–45 mm^2) represented about 29% of the wet-milled malt volume but only 9% of the dry-milled malt. The spent grain samples revealed smaller differences.

These observations were confirmed by settling dry- and wet-milled malt in a large volume of cold, aerated water in a measuring cylinder. The settled volume of wet-milled malt was about 175 ml; that of dry-milled material of equal dry weight was 130 ml. Interestingly, the wet-milled material left the suspending medium relatively clear after a few minutes, whereas the water above the dry-milled material remained hazy.

Inspection

The wet-milled malt had a coarse appearance compared to dry-milled malt; all the wet-milled kernels were broken open, but the husks were largely intact. In wet milling, most of the endosperm remained associated with the husk, usually somewhat fragmented but contained within the surrounding husk. The grains split longitudinally. In dry milling, by contrast, the endosperm was much separated from the husk, giving a white, even dusty, appearance to the milled malt. When the endosperm remained associated with the husk, it was considerably more fragmented than in the wet-milled samples. Separated husk fragments and transversely broken grains were a common feature of the dry-milled malt. We confirmed these observations at low and high magnification under the light microscope and observed husk shredding in dry milling; the large husk particles had a torn or fibrous appearance, and husk fibers were among the small endosperm particles.

After extensive inspection under the light microscope, particles that exemplified the descriptions outlined above were selected and prepared for scanning electron microscopy. This inspection confirmed what was already described. In addition, however, we examined individual starch granules and the matrix surrounding them. No evidence of pitting of starch granules was found in the dry-milled samples, although we expected some pitting as a result of the malting process. By contrast, extensive pitting was a common feature of starch granules in wet-milled malt but was not localized to the proximal end of the grain, as would be expected if pitting were a function of malting. We believe this pitting is related to the malt steeping portion of the wet-milling process. When small particles from dry-milled samples were examined, the starch granules were associated with a tenuous and amorphous structure, possibly protein. This feature was absent or at a low level in particles of similar size from the wet-milled samples.

Examination of spent grains under the light and electron microscopes yielded results similar to those already reported for

TABLE I
Analysis of Moisture Content and Particle Size Distribution in Samples of American Malt from Commercial Wet and Dry Mills[a]

	Malt			Wet-Milled Mash	Spent Grain	
	Dry-Milled	Dry-Milled[b]	Wet-Milled		Wet-Milled	Dry-Milled
Moisture (%)	4.3	–	34.1	83.2[c]	85.4[c]	80.2
Material (g) Retained on Screens (dry wt)						
Screen size						
1	2.93	3.65	9.09	10.09	8.87	5.22
2	1.48	1.47	1.44	1.70	1.11	1.93
3	2.62	2.74	1.25	1.08	1.28	2.15
4	5.88	5.07	2.21	4.42	3.93	5.97
Total on screens	12.92	12.93	14.00	17.25	15.19	15.27
Throughs	7.08	7.07	6.00	2.75	4.81	4.73
Material Retained on Screens (percent of total dry wt)						
Screen size						
1	14.7	18.2	45.5	50.5	44.4	26.1
2	7.4	7.4	7.2	8.5	5.5	9.7
3	13.1	13.7	6.3	5.4	6.4	10.8
4	29.4	25.4	11.0	22.1	19.6	29.8
Total on screens	64.6	64.6	70.0	86.2	75.9	76.4
Throughs	35.4	35.4	30.0	13.8	24.1	23.6

[a] Twenty grams (db) of each material was applied to the top screen (size 1) of a stack of screens and flushed through with a stream of cold water. The dry weight of material retained on each screen was determined. "Throughs," a calculated value, is that amount not retained on screens.
[b] The dry-milled malt (20 g) was soaked in cold water for 10 min before sieving.
[c] Sample contained some free water that was drained off before moisture content was measured.

TABLE II
Particle Size Distribution in Samples of American Malt from Wet and Dry Commercial Mills Using an Image Analyzer

Sample	Mill	Particle Size and Number[a] Small	Medium	Large	Total Volume	Large Particles as Percent of Total Volume
Malt	Dry	46 (1,900)	51 (7,550)	3 (900)	(10,350)	9
	Wet	30 (1,250)	57 (8,450)	13 (3,950)	(13,600)	29
Spent grain	Dry	30 (1,250)	61 (9,050)	9 (2,700)	(13,000)	21
	Wet	32 (1,350)	54 (8,000)	14 (4,250)	(13,550)	31

[a] Size definitions are: small, 3–12 mm^2; medium, 13–28 mm^2; and large, 29–45 mm^2. Values are the percent of counted particles assigned to each size category. The numbers in parentheses are volume computations (mm^3) based on the same original data.

malt. In dry-milled spent grain, extensive breaking and shredding of husk material occurred, and some starch granules remained associated with these husks. In the wet-milled samples, many husk particles were complete, ie, they contained both the proximal and distal ends, and very small husk particles and fibers were almost absent.

Water Uptake in Model Studies

Malt absorbed water during steeping more as a function of temperature than of time (Fig. 1). At each temperature tested, about two-thirds of the moisture content achievable in 30 min was attained in the first 3 or 4 min. This suggests that the moisture primarily entered the surface layers of the malt. However, at higher temperatures and longer times of malt steeping, when the moisture content exceeded 40%, water probably penetrated to the endosperm. Further studies were conducted with malt steeped for 20 min at 22°C (70°F) and containing approximately 30% moisture. This matched the commercial levels reported (4,6) and determined by our study (Table I), yet permitted us to process the malt in our pilot plant mill. With this treatment, comparatively little extract was lost into the malt steep water (Fig. 2). Such losses became significant in 30 min at 66°C (150°F), when the moisture content of the malt approached 60%.

Mill-Gap Setting and Extract Yield

At a mill-gap setting of 0.1 in. between the rolls, wet or dry malt was virtually unmilled, and almost all of the material applied to the stack of screens remained on the top screen (0.111 in.). As the mill gap was narrowed, the amount of material retained on that screen decreased linearly with dry malt, and smaller particles increased, especially throughs (Fig. 3) and those collected on the 0.0195-in. screen. With wet malt, however, the relationship between particle size and mill setting was curvilinear (Fig. 4). Therefore, at each mill-gap setting below 0.1 in., the 0.111-in. screen retained considerably more material with wet-milled malt than with dry, and throughs accounted for wet malt material not retained on that screen. Thus, at the narrowest gap tested (0.03 in.), throughs and the 0.111-in. screen accounted for about 85% of the wet-milled malt but less than 50% of the dry-milled malt. This is similar to the data reported in Table I for commercial samples.

When we compared wet- and dry-milled malt in an ASBC standard mash, malt extract yield decreased as mill-gap setting increased (Fig. 5), especially in the malt that was milled wet. The values for extract yield of dry and wet malt were similar only at the widest and narrowest mill-gap setting tested. These results were a function of particle size, however, because when the same data were plotted as a function of material retained on the 0.111-in. screen, the curves were virtually identical (Fig. 6).

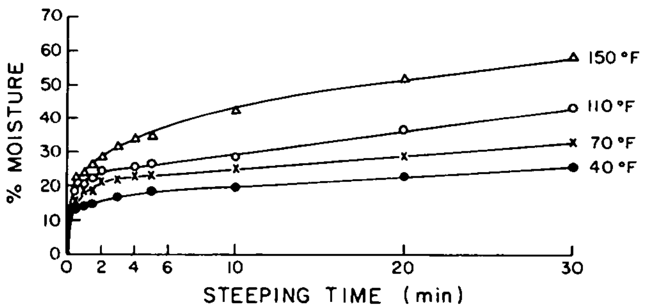

Fig. 1. Effect of steeping temperature on water uptake by malt.

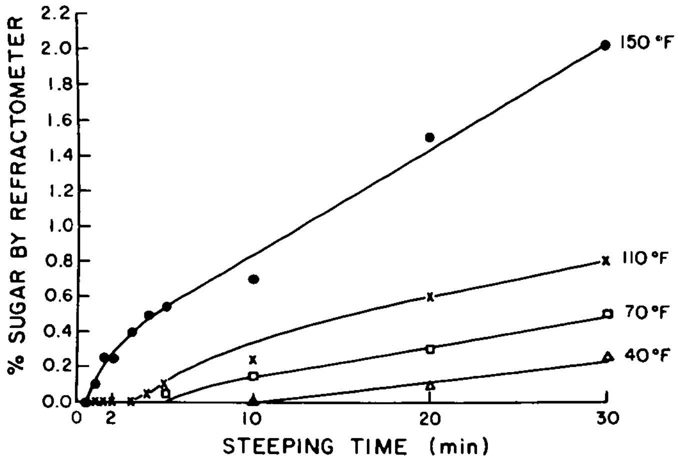

Fig. 2. Effect of steeping temperature on loss of soluble solids from malt into the steep water.

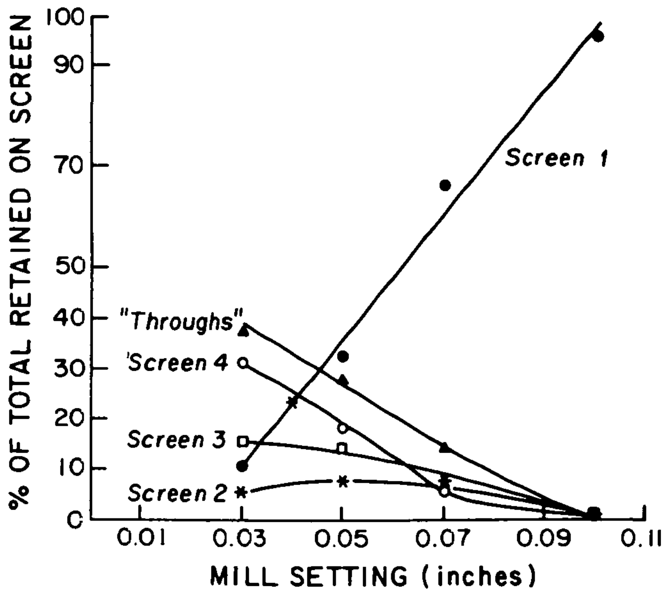

Fig. 3. Effect of mill-gap setting on particle size distribution in dry-milled malt.

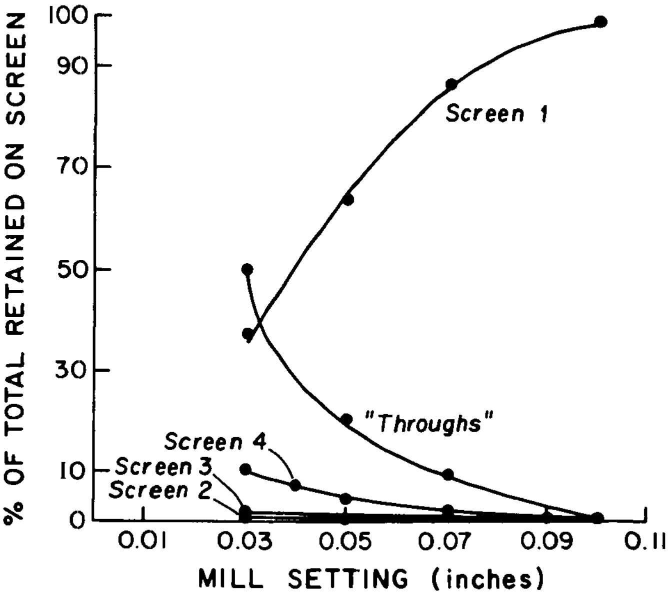

Fig. 4. Effect of mill-gap setting on particle size distribution in wet-milled malt.

Lautering

A major advantage of wet-milled malt is ease of runoff of the wort. The large particle size of wet-milled malt in a model mash/lauter system allows the malt to run off much faster than dry-milled malt (Fig. 7). However, the need for comparison required that runoff be done at the same rate in all cases, 50 ml/min. At a mill setting of 0.03 in., malt milled either wet or dry yielded essentially the same wort gravity (extract recovery) in the combined wort after sparging (Table III). At wider mill-gap settings, combined wort gravity decreased substantially, especially in wet-milled malt. The parenthetic values in Table III show that for malt milled wet, loss of extract yield was roughly parallel in the model mash/lauter system and in the ASBC mash as mill gap was increased. For dry-milled malt, however, extract recovery was poorer in the mash/lauter system than in the ASBC mash at equal mill-gap settings, and extract recovery in the ASBC mash was less affected by wider mill-gap settings.

The pattern of runoff of a wet-milled mash differed somewhat from that of a dry-milled mash (Figs. 8 and 9). Initial wort gravity varied from roughly 5.5 to 7.8° P for malt milled wet and from 6.3 to 7.1° P for dry-milled material, depending on mill-gap setting. The gravity of the wort collected decreased in two steps. This was most obvious with wet-milled material (Fig. 8). The first step down in collected wort gravity occurred when wort above the settled bed of malt (spent grain) began to exit the lauter; the second step down occurred when sparge water and wort began to exit the vessel. The first step down in gravity occurred sharply at fraction no. 5 with the 0.07-in. mill (Figs. 8 and 9) setting for malt milled wet but more progressively in all other cases. The second (sparge-related) step down in wort gravity was also related to mill setting and style of milling and generally occurred earlier with wet-milled malt than with dry-milled malt. These phenomena (yield and gravity steps) reflect rate of diffusion of extract from particles.

A pattern of steps similar to those in collected wort gravity was observed when polyphenol was measured in the wort samples from malt milled at the 0.06-in. mill setting (Fig. 10). At every stage, wet-milled malt yielded less material reacting as gallic acid than did dry-milled malt. Gallic acid equivalents in the combined wort was 253 mg/L from dry malt and 221 mg/L from the malt milled wet. These values are essentially the same if corrected for differences in extract recovery at this mill setting.

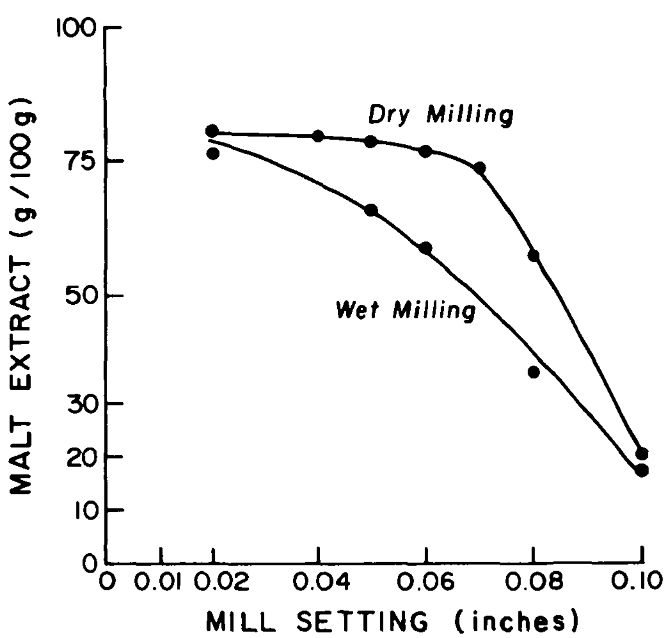

Fig. 5. Effect of mill-gap setting and milling style on extract yield of malt determined by the ASBC standard method (1).

Grain Bed Volume

When first formed in the lauter vessel, the height and volume of the grain bed of dry-milled malt was only slightly less than that of wet-milled malt (Table IV). Mill setting influenced these values more in the case of wet-milled malt than of dry-milled malt. As runoff progressed, the grain bed in every case became compacted. However, this compaction was more severe with dry-milled malt than with wet malts, and more pronounced at narrow mill settings than at wide ones.

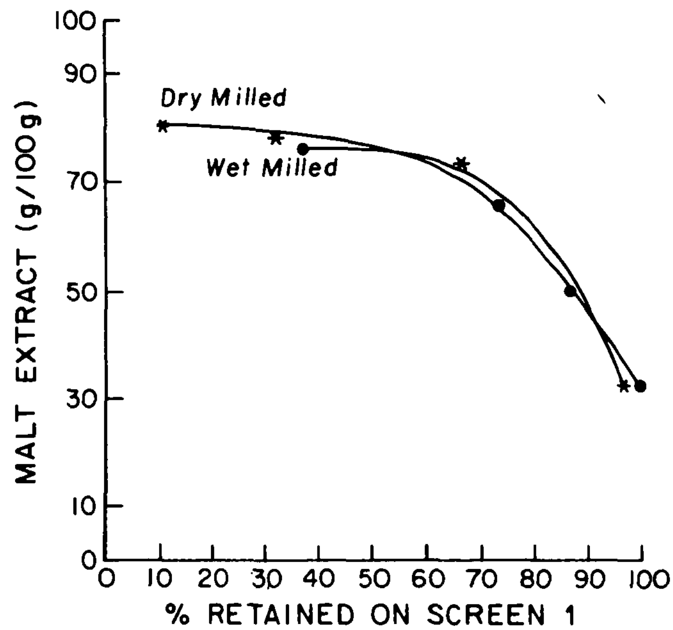

Fig. 6. Effect of particle size distribution on extract yield of malt determined by the ASBC standard method (1).

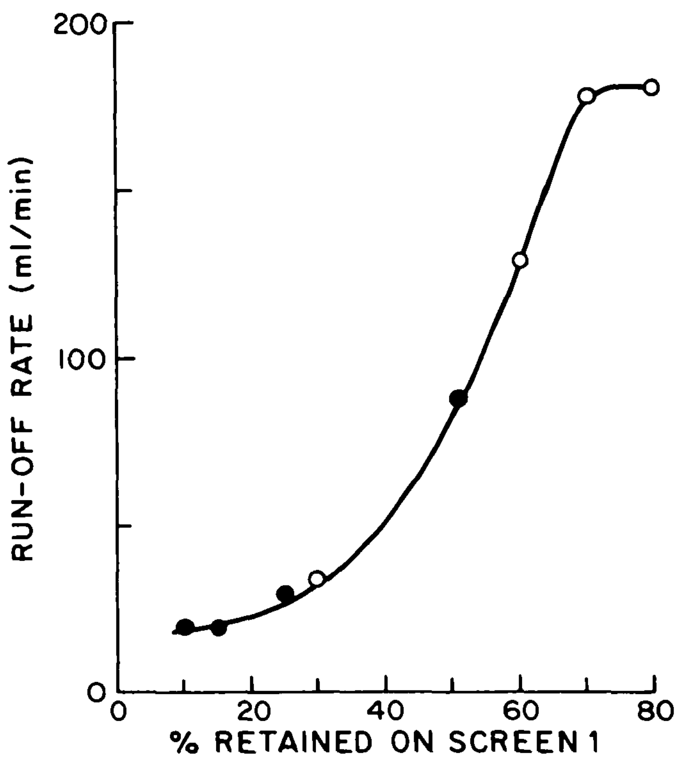

Fig. 7. Effect of particle size distribution on runoff rate of wort from the model lauter vessel. ● = single trial, O = duplicate trial.

DISCUSSION

Our observations with American malt milled in a commercial wet or dry mill do not confirm that endosperm is completely separated from husk in wet milling (2). In the commercial samples, the contrary appeared true. Our model studies (Fig. 4) suggest that such separation is partly possible in wet milling, because, at narrow mill-gap settings, throughs formed a high proportion of milled-malt weight. This may be the result of the sieving process we used, rather than wet milling itself. In the commercial samples and in our own models, however, we repeatedly confirmed the very different particle size distribution achieved in wet- and dry-milled malt. Particle size, primarily, controls the interrelationship between extract yield and runoff rate. Wet-milled malts have large particles that occupy a larger volume for a given dry weight than do dry-milled malts. The larger interstices between the particles and resistance to compaction permit rapid percolation of the grain bed. However, extract diffuses more slowly from large particles than from small ones. Consequently, the rapid runoff achievable with mashes containing large particles must be slowed to permit time for extract to diffuse from the particles into the bulk of the wort (or sparge). An effect of diffusion on extract yield appeared in the difference extract performance in the ASBC mash (which provided excellent opportunity for diffusion of extract from the particles into the wort) compared to the mash/lauter model in which diffusion was restricted (Table III). The first step down in gravity during runoff from the model lauter also reflected diffusion of extract from particles and was a marked feature of runoff of mashes containing large particles (Figs. 8 and 9). In lautering, the gravity of the initial wort collected was established by diffusion of extract from the particles during mashing *and* by additional diffusion into the wort when the settled mash was resting in the lauter. This second stage of diffusion, however, occurred only between the mash particles and that amount of wort contained in the settled grain bed. Wort above the settled bed of grain remained at the gravity produced by diffusion during mashing. A more rapid rate of

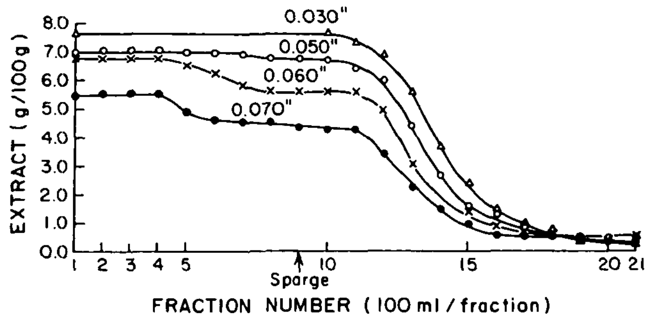

Fig. 8. Effect of mill setting on collected wort gravity (° P) during runoff and sparging of a mash of wet-milled malt.

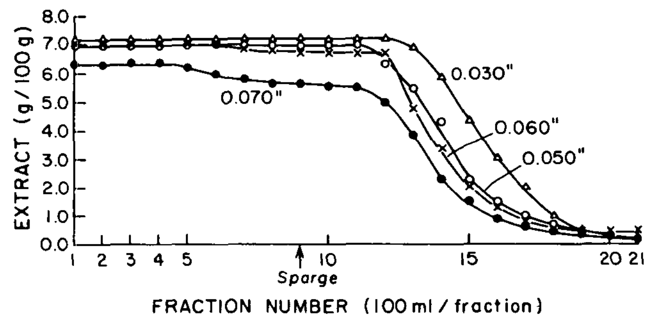

Fig. 9. Effect of mill setting on collected wort gravity (° P) during runoff and sparging of a mash of dry-milled malt.

TABLE III
Effect of Mashing System and Mill-Gap Setting on Wort Gravity[a] from Malt Milled Wet or Dry

Mill Gap (in.)	Mash/Lauter Model System: Wet	Mash/Lauter Model System: Dry	Mash/Lauter Model System: (Dry/Wet × 100)	ASBC Standard Mash System: Wet	ASBC Standard Mash System: Dry	ASBC Standard Mash System: (Dry/Wet × 100)
0.03	4.87	4.88	100	7.8	8.0	98
0.05	4.32 (89)	4.51 (92)	96	6.5 (87)	7.8 (98)	83
0.06	3.82 (78)	4.34 (89)	88	5.8 (77)	7.6 (95)	76
0.07	2.96 (61)	3.46 (71)	86	5.0 (67)	7.4 (93)	68

[a] Specific gravity values are expressed as ° P. Values in parentheses are calculated as a percent of the gravity of the wort derived from the 0.03-in. mill setting.

TABLE IV
Effect of Milling on Grain Bed Compaction During Lautering

Mill Gap Setting (in.)	Wet Milling[b] A	Wet Milling[b] B	Wet Milling[b] C	Dry Milling[b] A	Dry Milling[b] B	Dry Milling[b] C
0.03	9.3[a] (590)	9.1 (580)	6.0 (380)	9.6 (610)	7.4 (470)	4.3 (270)
0.05	9.3 (590)	8.7 (550)	7.5 (480)	9.8 (620)	7.7 (490)	5.3 (340)
0.06	10.2 (650)	9.7 (620)	7.7 (490)	10.0 (640)	8.4 (530)	6.0 (380)
0.07	12.5 (790)	9.9 (630)	8.0 (510)	10.5 (670)	9.3 (590)	7.1 (450)
Mean	10.3 (660)	9.3 (590)	7.3 (460)	10.0 (630)	8.2 (520)	5.7 (360)

[a] Grain-bed depth is reported in centimeters and (in parentheses) as volume.
[b] A, before runoff; B, after 400 ml of runoff; C, after completion of runoff.

diffusion from small grain particles than from large ones explains why no first step down occurred in gravity at narrow mill-gap settings, ie, the diffusion gradient equilibrated during mashing. Similar arguments explain why the second (sparge-associated) step down in gravity was slightly later with dry-milled material than with wet. Ultimately, recovery of extract from the particles by diffusion explains the results reported.

We did not observe an increase in extract yield with wet milling in any experiment; however, we did not design our experiments to optimize or maximize yields. High extract yield may depend on how the malt steep water is used in practical brewing (5,7). Our observation of extensive pitting of starch granules in commercially wet-milled malt strongly suggests onset of amylolysis during malt steeping. This, and the parallel observations of some solution of the protein matrix and lack of starch in spent grain, might predispose wet-milled malt to yield higher extract than dry-milled malt. Superior milling, better mash appearance, faster runoff, and higher extract recovery have been reported (7) when conditions of practical malt steeping at 50°C (122°F) for 30 min encouraged enzyme action in the unmilled wet malt. Much can be said in favor of this; if hot water were added to unmilled malt and penetrated the endosperm, the highest possible concentration of enzymes and substrates could be established within the microcosm of each malt kernel. Intense, and perhaps highly efficient initial amylolysis and

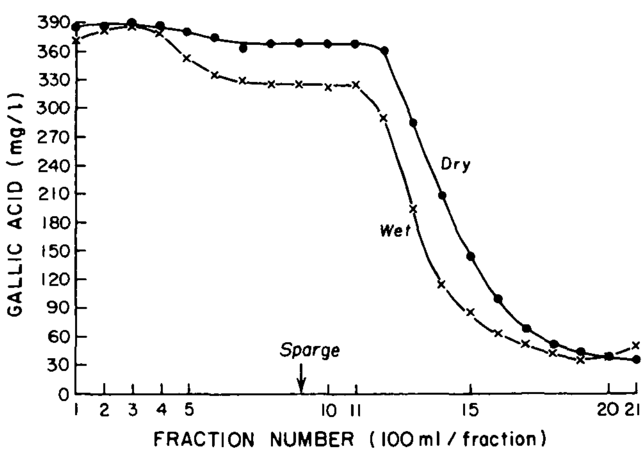

Fig. 10. Effect of wet or dry milling on substances reacting as gallic acid in wort during runoff and sparging of a mash of malt milled at a mill-gap setting of 0.06 in.

extract production could occur under these conditions. In contrast, the traditional brewing method of adding a large volume of cool water to dry-milled malt inevitably dilutes enzymes and substrates, to the detriment of enzyme action (in the initial stages). This traditional practice overlaps the two stages of mashing, namely, extract production (conversion, or enzyme action) and extract recovery (the physical processes of diffusion of extract into the bulk of the wort). If the potential of wet milling were projected on the basis of the above discussion, then extract *production* might be encouraged to proceed during malt steeping. Wet milling, mash mixing, and lautering, then, are primarily extract *recovery* processes and should be optimized for this purpose. For too long a time, the potential advantages of engineering (related to lautering) of wet-malt milling may have overshadowed the potential biochemical advantages (related to mashing) of wet-malt steeping; malt steeping may thus have a major role in wet milling beyond controlling particle size (3). North American brewhouses are already efficient; significant improvement by merely adding a wet mill to an otherwise unchanged process may be too much to expect. With the approach suggested here, wet mills may well contribute to new levels of brewhouse efficiency.

Although our observations on commercial samples bear directly on practical events in the brewhouse, our model systems were not intended to imitate practice, but rather to exaggerate and exemplify conditions difficult or impossible to observe directly in practical brewing. These models have shown some of the interrelationships between particle size, diffusion, and extract yield and have helped crystallize the difference between extract production and extract recovery in brewhouse processes. These concepts may have value in understanding not only wet milling, but traditional dry milling, mashing, and lautering, as well.

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