EQUILIBRIUM MOISTURE CONTENTS OF PURELINE, HYBRID, AND PARBOILED RICE KERNEL FRACTIONS

G. O. Ondier, T. J. Siebenmorgen, A. Mauromoustakos

ABSTRACT. *The effects of temperature and relative humidity on the equilibrium moisture contents of rough rice, brown rice, and head rice from non-parboiled pureline cultivars Wells (long-grain) and Jupiter (medium-grain), hybrid cultivar CL XL730 (long-grain), and a parboiled rice (long-grain) of unknown cultivar, were investigated. In addition, equilibrium moisture contents of broken kernels, rice bran, and rice hulls of Wells cultivar were also investigated. Air conditions were maintained at temperatures of 10°C to 60°C, and relative humidities of 10% to 70% to measure kernel-fraction moisture contents. For each air condition, rough rice and constituent fractions were allowed to equilibrate, after which the equilibrium moisture content of each fraction was measured. Rice hulls attained the lowest equilibrium moisture content followed by rice bran, brown rice, broken kernels, and head rice; this held for both parboiled and non-parboiled samples. Five, three-parameter equations, namely, the Modified Henderson, Modified Chung-Pfost, Modified Halsey, Modified Oswin, and Modified Guggenheim-Anderson-DeBoer were evaluated for their ability to describe the sorption data of each kernel fraction. The Modified Chung-Pfost and Modified Guggenheim-Anderson-DeBoer equations were the most suitable for describing equilibrium data of rough rice, brown rice, broken kernels, and head rice of both parboiled and non-parboiled samples, followed by the Modified Oswin and Modified Henderson equations. The Modified Oswin equation was the most suitable for rice bran and hulls. The measured equilibrium moisture content of rough rice was closely predicted by the weighted average equilibrium moisture content of the kernel fractions.*

Keywords. *Rice kernel fractions, Parboiled, Equilibrium moisture content.*

Generally, rice is harvested and stored as rough rice with the hull, bran, and endosperm intact, but is primarily consumed as milled rice with the embryo and bran layers removed. A lesser proportion is consumed as brown rice, but this proportion may increase due to the recent classification of brown rice as a whole grain by the U.S. Food and Drug Administration (USA Rice Federation, 2011). Other rice kernel fractions handled by the food industry include rice bran and rice hulls. The value of rice bran has risen due to its nutritional aspects and potential for recovering oil containing essential fatty acids, protein, and functional ingredients such as fiber and carotenoids (Abdul-Hamid, et al., 2007). Rice hulls are increasingly used as fuel because they contain organic volatiles (Bharadwaj et al., 2004), with a heating value of 13 to 15 MJ/kg (Jenkins, 1989; Natarajan, et al., 1998), and are abundantly available, being by-products of rice milling. There is, therefore, a need to determine the handling and processing characteristics of not just rough rice, but also brown rice, milled rice, rice bran, and rice hulls.

To understand sorption behavior of agricultural materials, it is important to study how changes in ambient air temperature and relative humidity (RH) influence equilibrium moisture content (EMC). Hygroscopic materials, such as rice kernel fractions, will gain or lose moisture to attain equilibrium with the surrounding air (Lan and Kunze, 1996; Goneli et al., 2007). Moisture migration into or out of such material is mainly dependent on: 1) chemical composition, e.g., starch, protein, lipids, fiber, and ash; 2) physical dimensions, e.g., surface area to volume ratio; and 3) surrounding air conditions, e.g., temperature and RH (Neuber, 1980; Choi et al., 2010). Some of the water molecules in the rice kernel fractions are held in capillary structures and some are bound to the chemical constituents by some form of interaction (Wellingford and Labuza, 1983). The cohesive forces between the water molecules are strongly dependent on the physicochemical components of the rice kernel; hence different fractions will exhibit varied response to changes in air conditions (Chen et al., 1984).

In theory, the more porous a material is, the greater the adsorptive and desorptive capacity (Chen et al., 1984). Because rough rice is a heterogeneous material consisting of hull, bran layers, and endosperm, the overall moisture sorption isotherm is dependent on the hygroscopic properties of each constituent (Agrawal et al., 1971). The hull, which represents approximately 20% of the rough rice mass, retains less moisture under equilibration conditions than the endosperm (Karon and Adams, 1949), whereas milled rice retains greater moisture than the corresponding brown and rough rice due to a greater starch and lesser fiber content (Juliano and Bechtel, 1985; Fan et al., 2000). In addition, Juliano (1964) indicates that not only the starch content, but also the starch composition plays a major role in moisture adsorption and desorption. Juliano (1964) reports that the ratio of amylose to amylopectin affects hygroscopicity such

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that rice with lesser amylose to amylopectin ratios (waxy rice) tends to be more sensitive to changes in air conditions, attain equilibrium faster, and retains greater moisture at higher RHs than rice with greater amylose to amylopectin ratios. Wolff et al. (1951) observed amylopectin from fractionated starch to be more hygroscopic than amylose. Finally, the starch granule structure can be altered by postharvest processes such as parboiling, which causes partial gelatinization. Hence parboiled rice kernel fractions exhibit significantly different moisture retention capacities compared to non-parboiled fractions (Karon and Adams, 1949; Keum et al., 2000; Reddy and Chakraverty, 2004).

Hybrid rice cultivars are receiving increasing attention because of yield and disease resistance superiority over pureline cultivars (Lafarge and Bueno, 2009). Many studies have shown greater grain yields from hybrids than pureline cultivars (Virmani et al., 1982; Yang et al., 2007), which has prompted many rice farmers to cultivate hybrid rice (Virmani and Kumar, 2004). Studies have also shown differences in processing between hybrid and pureline cultivars. For example, Lanning and Siebenmorgen (2011) found that to obtain the same degree of milling, hybrid cultivars required shorter milling durations than pureline cultivars due to lesser brown rice total lipid contents and greater bran removal rates among hybrids than in pureline cultivars. Similarly, Siebenmorgen et al. (2006) observed that for the same milling duration, hybrids were milled to lower surface lipid contents than pureline cultivars. Further studies are required to fully understand the handling and processing behavior of hybrid cultivars (Sun and Woods, 1997a, 1997b; Goneli et al., 2007).

It is, therefore, important to establish sorption relationships between individual rice kernel fractions from pureline and hybrid cultivars and air conditions: these relationships can be used in predicting hygroscopic behavior and possible quality changes of the different rice kernel fractions during handling, processing, and storage (Putranon et al., 1979). The objectives of this study were:

- to quantify the EMCs of rough rice, brown rice, and head rice of non-parboiled and parboiled samples of current pureline and hybrid cultivars across a range of temperatures and RHs. In addition, the EMCs of broken kernels, rice bran, and rice hulls were quantified for one of the pureline, non-parboiled cultivars.
- to estimate the empirical parameters of five sorption models commonly used to describe equilibrium data and evaluate the suitability of these models for describing EMCs of rice kernel fractions.
- to compare the measured EMC of rough rice with the EMC determined from the weighted average of constituent rice kernel fractions.

MATERIALS AND METHODS

SAMPLE COLLECTION AND PREPARATION

Long- and medium-grain pureline cultivars, Wells and Jupiter, respectively, and a hybrid long-grain cultivar, CL XL730, were harvested from Arkansas in the fall of 2007 at MCs ranging from 17% to 24% (Moisture contents are expressed on a wet basis unless specified otherwise.). In the spring of 2008, long-grain parboiled rough rice of unknown cultivar was obtained from Riceland Foods (Jonesboro, Ark.) at 29% MC. All samples were cleaned (MC® Kicker Grain Tester, Mid-Continent Industries, Inc., Newton, Kan.) and dried to a target MC of 12.5% on screens held in an environment where temperature and RH were maintained at 25°C and 56%, respectively, by an air control unit (Model AA-558, Parameter Generation & Control, Inc., Black Mountain, N.C.); actual sample MCs ranged from 11.6% to 12.8%. The samples were stored in sealed plastic tubs (0.22 m^3) at 4°C for 4 months. Prior to EMC experiments, approximately 30 g of rough rice was obtained from each bulk sample and MC determined by drying duplicate, 15-g sub-samples for 24 h in a convection oven (Shellblue, Sheldon Mfg., Inc., Cornelius, Ore.) held at 130°C (Jindal and Siebenmorgen,1987).

Duplicate, 150-g samples of rough rice from each lot were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan) to produce brown rice and hulls. Brown rice samples were milled using a laboratory mill (McGill #2, Rapscore, Brookshire, Tex.) for 30 s to produce milled rice and bran. The milled rice was aspirated for 30 s using a seed blower (South Dakota Seed Blower, Seedboro, Chicago, Ill.) to remove loose bran particles from the surface of rice kernels. Head rice was then separated from broken kernels using a double tray sizing machine (Grainman, Grain Machinery MFG, Miami, Fla.). Head rice was considered as kernels that were at least three-fourths of the original kernel length after milling (USDA, 2005).

EQUILIBRIUM APPARATUS

Static and dynamic methods are used in experiments to establish relationships between EMC and equilibrium RH (Choi et al., 2010). Static methods hold the product at set temperature and RH without air movement until equilibrium is attained, whereas dynamic methods maintain a constant flow of set temperature and RH air around the product, which allows for more rapid collection of equilibrium data (Gal, 1981; Wang and Brennan, 1991; Jayas and Mazza, 1993; Chen, 2000). Equilibrium MC can then be determined directly using gravimetric methods (Gal, 1981) or indirectly by measuring the equilibrium RH of the air around the product (Choi et al., 2010). For this study, sorption curves were measured using the dynamic method and EMC was determined using a gravimetric method (Gal, 1981), in which the mass of moisture remaining in the product was estimated using an oven method.

A schematic of the system used to conduct the EMC experiments is shown in figure 1. The apparatus consisted of a controller (ESL 4CA Platinous Temperature and Humidity Chamber, Espec, Hudson, Mich,) capable of automatically maintaining temperature in the range of -35°C to 150°C (±0.5°C) and RH in the range of 6% to 98% (±1%) within a 900-L chamber. The air in the chamber was circulated at 0.38 m^3s^{-1}. Air conditions were monitored using a temperature and RH probe (Hygro-M2, General Eastern, Woburn, Mass.).

A weighing and data collection system, separate from the automated temperature and RH controller, was constructed and installed in the chamber. The system comprised 17, thin-beam, full-bridge load cells (LCL-227G, Omega Engineering, Inc., Stamford, Conn.), each with a capacity of 227 g, which were mounted 10 cm apart on aluminum bars

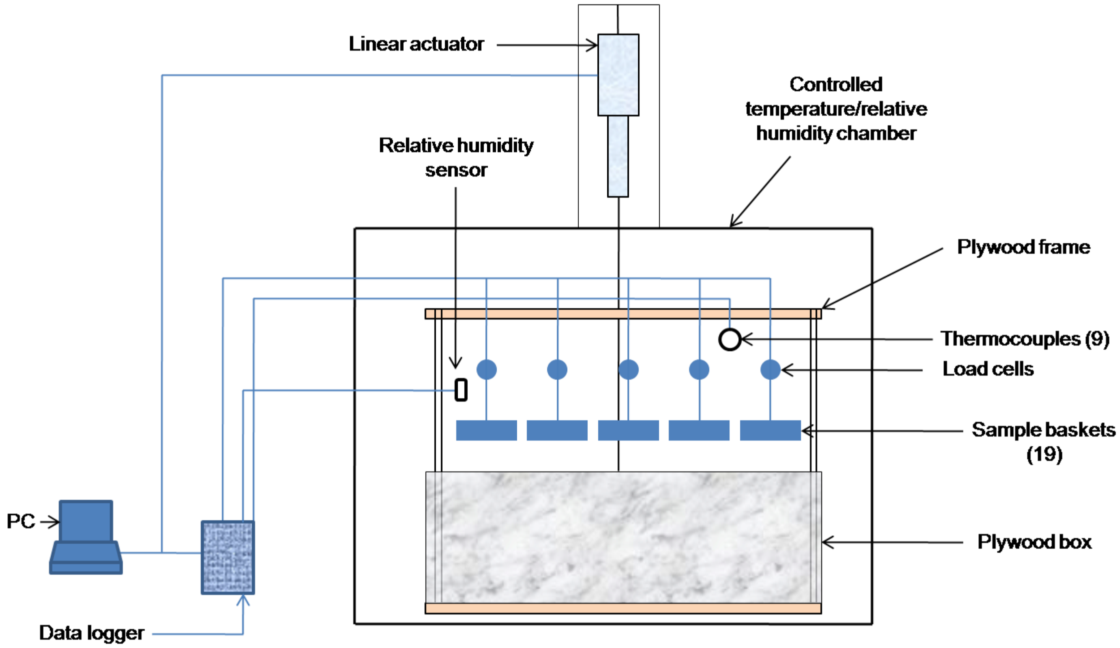

Figure 1. Schematic of the system used to conduct equilibrium moisture content experiments.

attached to a 3.8-cm thick laminated plywood frame. Each load cell was connected to a data logger (CR3000 Micrologger, Campbell Scientific, Logan, Utah). The load cells were calibrated using standard masses (Fisher Scientific, Pittsburg, Pa.) that ranged from 1 to 50 g. Seventeen square baskets (8.9 cm × 8.9 cm × 2.9 cm deep), fabricated from 6.4 mm welded-wire mesh (4 mesh per 2.5 cm), were suspended from the load cells using 0.67-mm (gauge 23) wires. The baskets were lined with brass wire mesh (80 openings per 2.5 cm, 1.4-mm wire dia.). Loggernet software (version 3.3.1, Campbell Scientific, Logan, Utah) was used to record digital signals from the load cells and the temperature and RH probe at 5-min intervals.

At the start of each experiment, baskets containing rough rice, brown rice, head rice, broken kernels, rice bran, and rice hulls were suspended from the load cells, which were mounted on the laminated plywood frame. To prevent inadvertent loss of moisture from the rice samples during the controller stabilization period, an open top box (54.6 cm × 54.6 cm × 25 cm deep) made from laminated plywood was raised using a linear actuator (LACT12P, IEI, Taiwan) that was connected to the box via a cable (fig. 1). In the elevated position, the laminated plywood box was pressed against the plywood frame, from which the samples were suspended and which served as the top cover of the box, forming a tight seal that enclosed the baskets. When the desired temperature and RH were attained, the box was lowered to expose the samples contained in the baskets.

Equilibrium Moisture Content Determination

Equilibrium moisture contents were determined at 10°C, 20°C, 30°C, 45°C, and 60°C and 10%, 20%, 30%, 50%, and 70% RH; these air conditions represent possible drying and storage conditions experienced in the rice industry (Schluterman and Siebenmorgen, 2004). The EMCs of rough rice, brown rice, and head rice were measured for all rice lots, namely, Wells (pureline long-grain), Jupiter (pureline medium-grain), CL XL730 (hybrid long-grain), and the commercially-parboiled rice of unknown cultivar (long-grain); EMCs of broken kernels, rice bran, and rice hulls were measured for Wells cultivar (table 1). Fifteen-g samples from each rice fraction were placed in each sample basket per run. The samples and baskets were weighed every 5 min until the change in mass for each sample was negligible (less than 0.01 g). The duration required to reach equilibrium varied from 10 to 35 days, depending on the temperature and RH. The final MCs of the samples were determined in duplicates using the oven method previously described (Jindal and Siebenmorgen, 1987) and were defined as the EMCs for a given temperature and RH. Each drying run was replicated.

Statistical Analysis

The experimental variables included rice cultivar (pureline and hybrid), kernel type (medium-grain and long-grain), postharvest treatment (parboiled and non-parboiled), rice kernel fractions (rough, brown, head,

Table 1. Experimental design showing the rough rice and kernel fractions used for equilibrium moisture contents determination for each rice lot (marked by X).

Rice Lot	Description	Kernel Fraction Rough	Brown	Head	Broken	Bran	Hulls
Wells	Pureline, long-grain	X	X	X	X	X	X
Jupiter	Pureline, medium-grain	X	X	X			
CL XL730	Hybrid, long-grain	X	X	X			
Parboiled	Unknown cultivar, long-grain	X	X	X			

broken, bran, and hulls), and air conditions (temperature and RH). The main effects of all variables on EMC were determined using Analysis of Variance (JMP 8.0.1., SAS Institute, Cary, N.C.). Significance was established at $\alpha = 0.05$.

Table 2 shows five models commonly used in describing sorption behavior of most starchy grains, namely; the Modified Chung Pfost (MCP), Modified Henderson (MH), Modified Oswin (MO), Modified Halsey (MHa), and Modified Guggenheim-Anderson-de Boer (MGAB) equations (Gal, 1981; Chen and Morey, 1989b; Jayas and Mazza, 1993; *ASABE Standards,* 2007; Choi et al., 2010). The empirical constants A, B, and C, of these five EMC models were estimated from the experimental data using a non-linear regression analysis platform (JMP 8.0.1. SAS Institute, Cary, N.C.). The model with the least root-mean-square-error (RMSE) and that displayed a random pattern of residuals around the baseline of zero was considered most suitable (Chen and Morey, 1989a).

RESULTS AND DISCUSSION

EQUILIBRIUM MOISTURE CONTENT OF RICE KERNEL FRACTIONS

The EMCs of rough rice, brown rice, head rice, broken kernels, rice bran, and hulls of non-parboiled samples from Wells cultivar at temperatures of approximately 30°C, 45°C, and 60°C and RHs of 10% to 70% are shown in figures 2-4. The equilibrium data were compared to data from Reddy and Chakraverty (2004); similar trends were observed, particularly for the parboiled samples (fig. 5). As expected, the sorption behavior of all rice kernel fractions was temperature dependent such that at constant RH, EMCs decreased with increasing temperatures due to greater kinetic energy of water molecules, but increased with increasing RH at constant temperature (Demertzis et al., 1989; Reddy and Chakraverty, 2004).

In almost all conditions, rice hulls had the lowest EMCs followed by rice bran, rough rice, and brown rice (figs. 2-4). Head rice and broken kernels had the greatest EMCs at all air conditions, and there were no significant differences between EMCs of head rice and broken kernels (p-value > 0.05).

Rice hulls have a low bulk density of approximately 144 kg/m^3 (Juliano and Bechtel, 1985) and consist mainly of cellulose and silica (Bharadwaj et al., 2004), and trace amounts of aluminum, calcium, magnesium, potassium, and iron (Kaupp, 1984; Natarajan et al., 1998). Scanning electron microscopy revealed the rice hull particle structure to resemble a composite material with fibers regularly interspaced in the matrix: the fiber being silica and the matrix consisting mainly of cellulose, hemicelluloses, and lignin (Bharadwaj et al., 2004). The comparatively lower EMCs of rice hulls than the other rice kernel fractions may thus be attributed to the hull's unique particle structure and low water retention capacity of its components.

Rice bran attained greater EMCs than rice hulls, but lesser EMCs than the starch-containing fractions (figs. 2-4). The proximate composition of rice bran is 21% to 23% lipid, 21% to 27% fiber, and 12% to 16% protein (Kahlon, 2009). It is important to note that rice bran is rarely pure and depending on the degree of milling, may contain finely ground broken kernels, mostly composed of starch, which has considerable water retention capacity (Kahlon, 2009).

Table 2. Equilibrium models used for describing rice fraction sorption data.

Modified Chung-Pfost[a]	$MC_{d.b.} = \frac{-1}{C} Ln\left[\frac{-(T+B)LnRH}{A}\right]$ [b][c]
Modified Henderson[a]	$MC_{d.b.} = \left[\frac{Ln(1-RH)}{(-A)(T+B)}\right]^{\frac{1}{C}}$
Modified Oswin[a]	$MC_{d.b.} = (A+B\cdot T)\left[\frac{1-RH}{RH}\right]^{\frac{-1}{C}}$
Modified GAB[d]	$MC_{d.b.} = \frac{A\cdot B\cdot\left(\frac{C}{T}\right)\cdot RH}{(1-B\cdot RH)\left[1-B\cdot RH+\left(\frac{C}{T}\right)\cdot B\cdot RH\right]}$
Modified Halsey[a]	$MC_{d.b.} = \left[-\frac{\exp(A+B\cdot T)}{(LnRH)}\right]^{\frac{1}{C}}$

[a] Listed in *ASABE Standards* (2007).

[b] where $MC_{d.b.}$ is equilibrium moisture content expressed on a percentage dry-basis; RH is relative humidity, expressed as a decimal; T is temperature in °C; and A, B, and C are grain-specific empirical constants.

[c] To estimate constants A, B, and C of the EMC models, experimental moisture content were converted from percentage wet-basis (w.b.) to percentage dry-basis (d.b.) using the formula:

$$MC_{d.b.} = \frac{100\cdot MC_{w.b.}}{100 - MC_{w.b.}}$$

[d] Described by Jayas and Mazza (1993); Iguaz and Versada (2007).

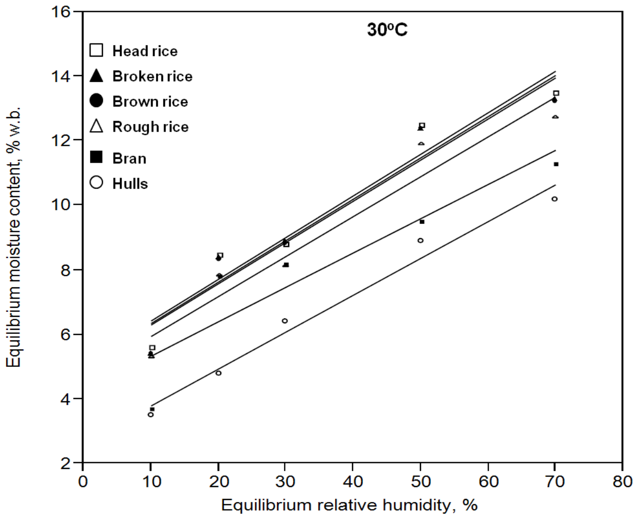

Figure 2. Equilibrium moisture contents of Wells rice kernel fractions exposed to 30°C and 10% to 70% equilibrium relative humidity. Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate. The mean equilibrium moisture content and standard error were 8.85 and 1.37, respectively.

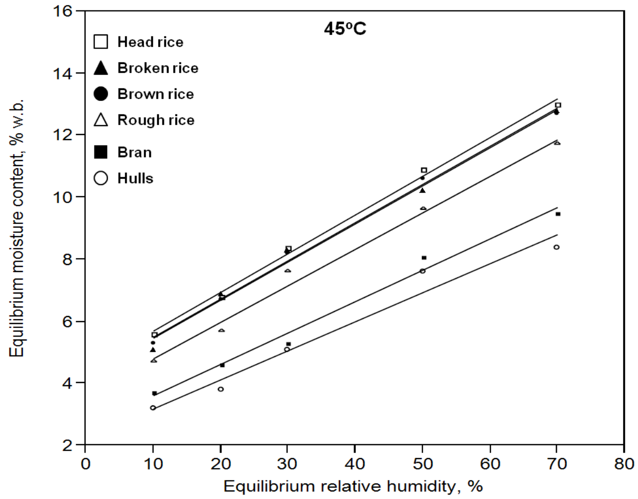

Figure 3. Equilibrium moisture contents of Wells rice kernel fractions exposed to 45°C and 10% to 70% equilibrium relative humidity. Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate. The mean equilibrium moisture content and standard error were 7.67 and 1.24, respectively.

The differences in EMCs observed among rough rice, brown rice, and milled rice (both head rice and broken kernels) may be attributed to physical structure and chemical composition. Firstly, rough rice had lower EMC than brown rice, head rice and broken kernels at most conditions because it includes the hull, which, as previously mentioned, has lower water retention capacity and a much lower bulk density (144 kg/m^3) compared to the endosperm (900 kg/m^3) (Juliano and Bechtel, 1985). Secondly, the lesser EMCs of brown rice compared to head rice and broken kernels may be attributed to the bran layer. Heinemann et al. (2005) observed that milled rice contained less protein, lipid, and minerals such as potassium, phosphorous, and selenium than brown rice, but a greater percentage starch.

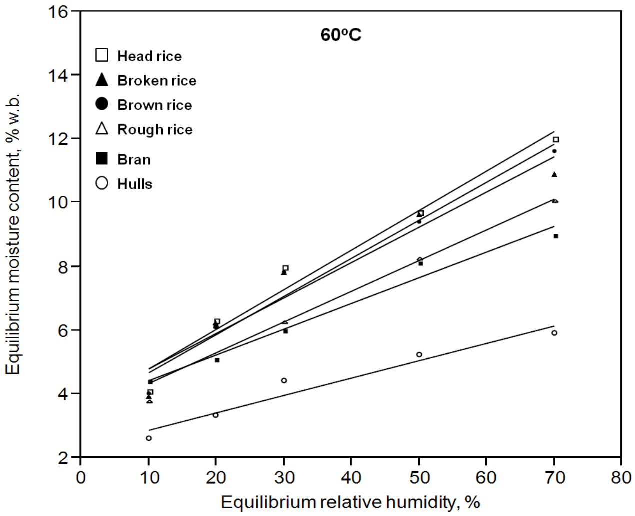

Figure 4. Equilibrium moisture contents of Wells rice kernel fractions exposed to 60°C and 10% to 70% equilibrium relative humidity. Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate. The mean equilibrium moisture content and standard error were 6.85 and 1.11, respectively.

Milled rice, which includes both head and broken kernels, is generally composed of 80% starch, 6% protein, 2% fiber, and 1% lipid (El-Hissewy et al., 2002; Louis, 2003; Cameron and Wang, 2005). As previously mentioned, starch has a greater water retention capacity than protein, lipid, fiber, or minerals (El-Hissewy et al., 2002); hence the greater EMCs were observed in milled rice than the other kernel fractions. A greater degree of milling will increase the percentage of starch relative to other components in milled rice due to the progressive removal of protein and lipid, which are concentrated in the outer layers of the kernel caryopsis (Cameron and Wang, 2005), hence greater water retention capacity and subsequently greater EMCs are expected in milled rice relative to brown rice; EMCs of milled rice would be expected to increase with the increased degree of milling.

Effect of Cultivar, Kernel Type, and Parboiling

The EMCs of rough rice, brown rice, and head rice obtained at all experimental conditions are presented in tables 3, 4, and 5. Though there were a few instances where significant differences were observed among EMCs of the different rice lots (Wells, CL XL730, and Jupiter) kernel fractions (rough rice, brown rice, and head rice), the trends were inconsistent and differences were random. However, the EMCs of parboiled rice kernel fractions were significantly lower ($p\text{-value} < 0.05$) than those of the non-parboiled rice in almost all experimental conditions.

Parboiling, conventionally a two-step process that involves soaking and steaming, is known to alter the physical structure of starch granules and the proximate composition of the rice kernel (Han and Lim, 2009). The degree to which the proximate composition is changed during parboiling is dependent on the solubility of protein, starch, lipid, and minerals during soaking, the physical location of these components in the rice kernel, and the chemical transformations and interactions occurring during steaming (Chinnaswamy and Bhattacharya, 1983). Generally, parboiled brown and milled rice have greater protein, lipid,

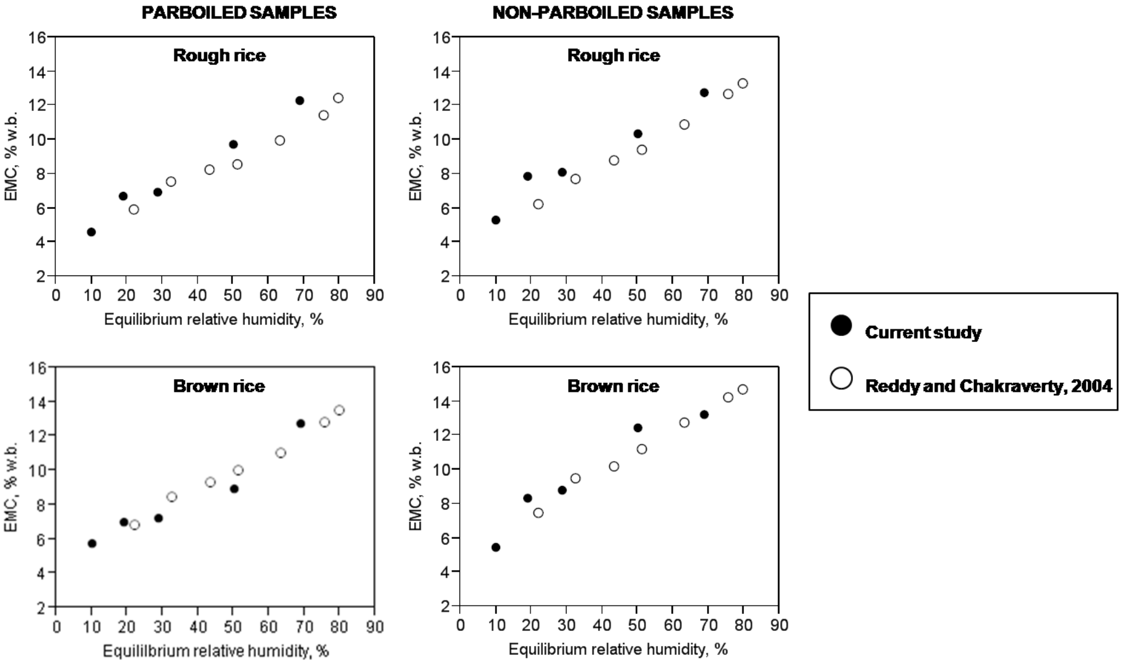

Figure 5. Equilibrium moisture contents of rough rice and brown rice measured at 30°C and 10% to 70% relative humidity for long-grain cultivar Wells, compared to equilibrium data from Reddy and Chakraverty (2004) measured at 30°C and 22% to 80% relative humidity for long-grain cultivar IR-36. Each current observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate.

and fiber contents than non-parboiled brown and milled rice (Han and Lim, 2009; Shallan et al., 2010) because starch (mostly the amylose fraction) and minerals such as iron and zinc, tend to leach out of the kernel and into the soaking

Table 3. Equilibrium moisture contents (% wet-basis) of rough rice from long-grain pureline cultivar Wells, medium-grain pureline cultivar Jupiter, long-grain hybrid cultivar CL XL730, and long-grain commercially-parboiled rice of unknown cultivar.

Air Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (% wet-basis)[a]			
		Jupiter	Wells	CL XL730	Parboiled
		Medium-grain	Long-grain		
10.0	10.2	8.5a	8.0a	8.2a	6.7b
10.0	17.3	9.0a	8.6a	9.1a	7.3b
10.0	28.2	10.0a	9.7a	10.9a	8.4b
10.0	49.4	11.7a	11.3a	12.4a	10.4b
10.0	68.5	13.6a	13.0a	13.0a	12.8a
20.3	9.7	7.2b	7.4b	7.3b	6.6b
20.1	18.3	7.2b	8.0a	8.1a	7.0b
20.1	28.5	8.8b	9.3a	9.6a	8.4b
20.7	49.8	11.8a	12.3a	12.4a	11.3b
19.8	69.8	13.8a	13.6a	13.5a	12.4b
30.0	10.1	5.5a	5.3a	4.8a	4.6b
30.2	19.2	7.6a	7.8a	7.6a	6.7b
30.0	28.9	8.2a	8.1a	8.3a	6.9b
30.0	50.3	10.2a	10.3a	10.4a	9.7b
29.9	69.1	12.9a	12.7a	12.9a	12.3a
45.0	10.0	4.9a	4.7a	4.4b	3.9b
46.1	18.7	5.8a	5.7a	5.4a	4.6b
45.1	30.2	7.4a	7.6a	7.4a	6.6b
45.3	50.0	9.6a	9.6a	9.7a	8.7b
44.7	71.8	11.8a	11.7a	11.6a	11.3b
60.0	10.3	4.0a	3.7a	3.6a	2.8b
60.1	20.0	5.6a	6.1a	5.6a	4.7b
60.2	29.6	6.4a	6.2a	6.7a	5.1b
60.4	49.6	8.6a	8.6a	8.5a	8.1b
59.9	71.6	10.5a	10.6a	10.8a	9.1b

[a] For each temperature and relative humidity, values designated by the same letter are not significantly different among cultivars. Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate. The mean rough rice equilibrium moisture content and standard error were 8.46 and 0.55, respectively.

Table 4. Equilibrium moisture contents (% wet-basis) of brown rice from long-grain pureline cultivar Wells, medium-grain pureline cultivar Jupiter, long-grain hybrid cultivar CL XL730, and long-grain commercially-parboiled rice of unknown cultivar.

Air Temperature (°C)	Relative Humidity (%)	Equilibrium Moisture Content (% wet-basis)[a]			
		Jupiter	Wells	CL XL730	Parboiled
		Medium-grain	Long-grain		
10.0	10.2	8.6a	8.3a	8.2a	7.4b
10.0	17.3	9.0a	8.8a	8.9a	8.0b
10.0	28.2	10.5a	9.8b	10.2a	9.1c
10.0	49.4	12.4a	12.4a	11.5b	10.7b
10.0	68.5	14.1a	13.4b	14.0a	13.1b
20.3	9.7	7.2b	7.4b	7.3b	6.6b
20.1	18.3	8.1a	8.0a	8.1a	7.0b
20.1	28.5	9.3a	9.4a	9.6a	8.4b
20.7	49.8	12.6a	12.3a	12.4a	11.2b
19.8	69.8	13.9a	13.6a	13.5a	12.8b
30.0	10.1	5.6a	5.4a	5.2a	5.7a
30.2	19.2	8.3a	8.3a	8.1a	7.0b
30.0	28.9	8.4a	8.8a	8.8a	7.2b
30.0	50.3	12.6a	12.4a	10.4b	8.9c
29.9	69.1	13.4a	13.2a	13.5a	12.7b
45.0	10.0	5.1a	5.3a	4.8a	3.6b
46.1	18.7	6.2a	6.7a	6.5a	5.2b
45.1	30.2	7.9a	8.2a	8.0a	6.6b
45.3	50.0	9.8a	10.6a	10.3a	9.1b
44.7	71.8	12.4a	12.7a	13.0a	11.9b
60.0	10.3	4.3a	4.0a	4.0a	2.9b
60.1	20.0	5.8a	6.1a	6.2a	4.3b
60.2	29.6	6.9b	7.8a	7.2b	5.3c
60.4	49.6	9.5a	9.4a	9.1a	8.4b
59.9	71.6	10.7b	11.6a	11.6a	11.6a

[a] For each temperature and relative humidity, values designated by the same letter are not significantly different among cultivars. Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate. The mean brown rice equilibrium moisture content and standard error were 9.02 and 0.57, respectively.

medium during soaking (Almana, 2000; Lestienne et al., 2005; Han and Lim, 2009). In addition, the high kernel temperatures attained during steaming causes starch to gelatinize (Han and Lim, 2009). The change in starch granule structure due to gelatinization, coupled with the change in proximate chemical composition, is reasoned to be the cause for the lesser EMCs observed in parboiled, compared to non-parboiled, rice kernel fractions.

ESTIMATION OF EMPIRICAL CONSTANTS AND EVALUATION OF EQUILIBRIUM MODELS

Equilibrium data of parboiled and non-parboiled rice kernel fractions were analyzed using nonlinear regression to estimate the empirical constants A, B, and C of the sorption models given in table 2. For each rice fraction, the EMC data of the non-parboiled rice cultivars Wells, Jupiter, and CL XL730 were pooled because the few instances in which significant differences were observed were random and lacked a consistent trend. The model with the lowest RMSE and that also yielded a residual plot following a random pattern around the baseline of zero was considered most suitable (Chen and Morey, 1989a; Aviara et al., 2004).

The estimates of constants A, B, and C of the sorption models and the statistical parameters used to evaluate them are given in tables 6 and 7 for non-parboiled and parboiled rice kernel fractions, respectively. For the air conditions of this study, i.e., temperatures from 10°C to 60°C and RHs from 10% to 70%, the models that best described equilibrium data of rough rice, brown rice, and milled rice for both parboiled and non-parboiled rice were the Modified Chung-Pfost (MCP) and Modified Guggenheim-Anderson-DeBoer (MGAB) equations, followed by the Modified Oswin (MO) and Modified Henderson (MH) equations. The MO gave the best fit for equilibrium data of rice bran and rice hulls. The Modified Halsey (MHa) equation gave the worst fits with high RMSEs and patterned residual plots, and was thus deemed unsuitable for describing parboiled and non-parboiled rice kernel-fraction equilibrium data measured within the range of experimental conditions. Reddy and Chakraverty (2004) reported similar results where the MH and MCP were established as the best models for describing equilibrium data of rough rice, brown rice, and rice bran at temperatures of 13°C, 30°C, and 40°C and RHs from 20% to 80%.

RELATIONSHIP BETWEEN MEASURED EMC AND WEIGHTED-AVERAGE EMC

The EMCs of rough rice were compared to the EMCs obtained from the weighted averages of the constituent kernel fractions, namely, 1) brown rice and hulls; 2) milled rice, bran, and hulls; and 3) head rice, broken kernels, bran, and hulls, for Wells cultivar at approximately 45°C and 10% to 70% RH (table 8). No significant differences were observed between the measured rough rice EMCs and EMCs of the weighted averages from the constituent kernel fractions at all RHs. Similar results were observed at approximately 10°C, 20°C, 30°C, and 60°C. These findings show the strong influence that the hygroscopic properties of each constituent fraction have on the EMC of a heterogeneous material (Agrawal et al., 1971).

Table 5. Equilibrium moisture contents (% wet-basis) of head rice from long-grain pureline cultivar Wells, medium-grain pureline cultivar Jupiter, long-grain hybrid cultivar CL XL730, and long-grain commercially-parboiled rice of unknown cultivar.[a]

		Equilibrium Moisture Content (% wet-basis)			
Air Temperature (°C)	Relative Humidity (%)	Jupiter	Wells	CL XL730	Parboiled
		Medium-grain	Long-grain		
10.0	10.2	7.9a	7.9a	7.7a	7.3b
10.0	17.3	8.9a	9.0a	9.0a	7.8b
10.0	28.2	10.4a	10.2a	10.0a	8.9b
10.0	49.4	12.4a	12.3a	11.4b	10.5c
10.0	68.5	14.2a	14.2a	14.0a	13.3b
20.3	9.7	7.1a	7.2b	6.9b	6.5b
20.1	18.3	8.2a	8.3a	8.5a	7.0b
20.1	28.5	9.7a	9.7a	9.8a	8.4b
20.7	49.8	12.5a	12.4a	12.1a	11.1b
19.8	69.8	14.2a	14.0a	13.5b	12.9c
30.0	10.1	5.1a	5.6a	5.2a	5.1a
30.2	19.2	8.5a	8.5a	8.2a	7.3b
30.0	28.9	8.8a	8.8a	8.4a	7.6b
30.0	50.3	12.7a	12.5a	10.1b	9.2c
29.9	69.1	13.4a	13.5a	13.4a	12.4b
45.0	10.0	4.9a	5.6a	5.0a	4.0b
46.1	18.7	6.6a	6.8a	6.1a	4.9b
45.1	30.2	7.7a	8.4a	8.3a	6.6b
45.3	50.0	10.2a	10.9a	10.6a	9.0b
44.7	71.8	12.8a	13.0a	12.9a	11.7b
60.0	10.3	4.2a	4.1a	4.1a	3.4b
60.1	20.0	6.4a	6.3a	5.2b	4.7c
60.2	29.6	7.1b	8.0a	6.7b	5.6c
60.4	49.6	9.6a	9.7a	9.7a	8.5b
59.9	71.6	10.9b	12.0a	10.6b	10.6b

[a] For each temperature and relative humidity, values designated by the same letter are not significantly different among cultivars. Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate. The mean head rice equilibrium moisture content and standard error were 9.05 and 0.57, respectively.

SUMMARY

Measuring the EMCs of rice kernel fractions, namely, rough rice, brown rice, head rice, broken kernels, rice bran, and rice hulls, from both parboiled and non-parboiled rice revealed the following;

- Consistent with previous studies, EMC decreased with increasing temperature at constant RH and increased with increasing RH at constant temperature.
- Of the rough rice fractions, rice hulls had the lowest EMCs, followed by rice bran, brown rice, broken kernels, and head rice. There were no significant differences between the EMCs of head rice and broken kernels.
- The EMCs of parboiled rice kernel fractions were less than those of non-parboiled rice kernel fractions for most air conditions.
- There were no significant differences among EMCs of rice kernel fractions from pureline and hybrid cultivars or medium- and long-grain kernel types; similar findings are reported in Ondier et al. (2011).
- The Modified Chung-Pfost and Modified Guggenheim-Anderson-DeBoer equations were the best models for predicting EMCs of both parboiled and non-parboiled rough rice, brown rice, and milled rice kernel fractions, for the air conditions of this study, i.e., 10°C to 60°C and 10% to 70% RH. The Modified Oswin equation was best for rice bran and hulls.
- The measured EMCs of rough rice were accurately predicted by the weighted-average EMCs of rice kernel fractions.

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Table 6. Estimated constants of the Modified Chung-Pfost (MCP), Modified Henderson (MH), Modified Oswin (MO), Modified Guggenheim Anderson DeBoer (MGAB), and Modified Halsey (MHa) equations.[a]

Non-parboiled Rice Fraction	Model	Model Constants[b]			Statistical Parameters	
		A	B	C	RMSE	Residual Plot Pattern
Rough	MCP	498.9584	20.3125	0.2322	0.611	Random
	MGAB	11.4659	0.3975	601.7981	0.691	Random
	MO	14.455	-0.0925	3.8219	0.740	Random
	MH	1.1518×10^{-4}	16.0667	2.9326	0.841	Random
	MHa	6.2906	-0.0208	2.4958	0.835	Random
Brown	MCP	572.7456	26.9868	0.2190	0.670	Random
	MGAB	11.5380	0.4343	638.5563	0.667	Random
	MO	14.6400	-0.0085	3.8219	0.790	Random
	MH	8.3662×10^{-6}	21.4933	2.9387	0.826	Random
	MHa	6.3855	-0.0180	2.5064	0.932	Trend
Head	MCP	567.5001	29.7166	0.2123	0.714	Random
	MGAB	11.5227	0.4487	610.8201	0.710	Random
	MO	15.0500	-0.0854	3.7230	0.792	Random
	MH	9.5663×10^{-6}	23.4725	2.8589	0.820	Random
	MHa	6.2369	-0.0175	2.4461	0.962	Trend
Broken	MCP	617.7767	32.6043	0.2161	0.7706	Random
	MGAB	11.3443	0.4506	646.8532	0.7404	Random
	MO	14.8703	-0.0813	3.7747	0.8029	Random
	MH	8.3183×10^{-6}	25.9576	2.8989	0.8275	Random
	MHa	6.3015	-0.0169	2.4827	0.9880	Trend
Bran	MCP	374.0921	22.0710	0.2308	0.899	Random
	MGAB	10.9495	0.4023	393.8938	0.924	Random
	MO	13.1828	-0.0958	3.2665	0.852	Random
	MH	4.7910×10^{-5}	15.8222	2.4823	0.876	Random
	MHa	5.2025	-0.0213	2.1594	1.009	Trend
Hulls	MCP	348.6157	15.7268	0.3016	0.844	Random
	MGAB	9.5507	0.3235	423.1776	0.832	Random
	MO	10.7693	-0.0869	3.3804	0.725	Random
	MH	8.2374×10^{-5}	11.0014	2.5665	0.834	Random
	MHa	4.9649	-0.0248	2.2410	0.883	Trend

[a] The data from the three non-parboiled cultivars, namely, Wells, Jupiter, and CL XL730 were pooled. Equilibrium moisture contents estimated using these constants are expressed on a percentage dry-basis.

[b] To estimate constants A, B, and C, equilibrium moisture content data of this study were first converted from percentage wet-basis (w.b) to percentage dry-basis (d.b) using the formula:

$$MC_{d.b.} = \frac{100 \cdot MC_{w.b.}}{100 - MC_{w.b.}}$$

Table 7. Estimated constants of the Modified Chung-Pfost (MCP), Modified Henderson (MH), Modified Oswin (MO), Modified Guggenheim Anderson DeBoer (MGAB), and Modified Halsey (MHa) equations.[a]

Parboiled Rice Fraction	Model	Model Constants[b]			Statistical Parameters	
		A	B	C	RMSE	Residual Plot Pattern
Rough	MCP	406.9023	23.6173	0.2303	0.684	Random
	MGAB	10.1470	0.4599	443.9291	0.811	Random
	MO	13.2783	-0.0908	3.3586	0.735	Random
	MH	3.4322×10^{-5}	19.5649	2.5603	0.879	Random
	MHa	5.3244	-0.0198	2.2059	0.849	Random
Brown	MCP	407.6028	30.3865	0.2121	0.651	Random
	MGAB	9.7243	0.5363	441.0837	0.711	Random
	MO	13.4463	-0.0806	3.2608	0.943	Random
	MH	3.0631×10^{-5}	24.1943	2.5169	1.025	Random
	MHa	5.1497	-0.0165	2.1296	0.934	Trend
Head	MCP	435.7464	26.0542	0.2233	0.509	Random
	MGAB	9.8401	0.5092	472.3943	0.668	Random
	MO	13.4496	-0.0830	3.3649	0.732	Random
	MH	2.7142×10^{-5}	21.9874	2.5940	0.839	Random
	MHa	5.3283	-0.0176	2.1972	0.753	Trend

[a] The equilibrium data were for commercially parboiled rice of an unknown cultivar. Equilibrium moisture contents estimated using these constants are expressed on a percentage dry-basis.

[b] To estimate constants A, B, and C, equilibrium moisture content data of this study were first converted from percentage wet-basis (w.b) to percentage dry-basis (d.b) using the formula:

$$MC_{d.b.} = \frac{100 \cdot MC_{w.b.}}{100 - MC_{w.b.}}$$

Table 8. Comparison of equilibrium moisture contents (% wet-basis) of rough rice and equilibrium moisture contents estimated from the weighted average of the constituent kernel fractions, namely, 1) Brown rice and hull, 2) Milled rice, bran, and hull, and 3) Head rice, broken kernels, bran, and hulls, for Wells rice cultivar at approximately 45°C and 10% to 70% relative humidity.[a]

Rice Fraction	Mass (g)	Proportion of Rough Rice Kernel	Relative Humidity (%)				
			10.0	18.7	30.2	50.0	71.8
Rough	150.0	1.000	4.7^{a}	5.7^{a}	7.6^{a}	9.6^{a}	11.7^{a}
Brown	125.9	0.839	5.3	6.7	8.2	10.6	12.7
Milled	106.4	0.709	5.6	6.8	8.4	10.9	13.0
Head	81.6	0.544	5.6	6.8	8.4	10.9	13.0
Broken	24.7	0.165	5.1	6.9	8.3	10.2	12.8
Bran	19.5	0.130	3.7	4.6	5.3	8.1	9.5
Hull	24.1	0.161	3.2	3.8	5.1	7.6	8.4
Brown + Hull[b]			**5.0^{a}**	**6.2^{a}**	**7.7^{a}**	**10.1^{a}**	**12.0^{a}**
Milled + Bran + Hull			**5.0^{a}**	**6.0^{a}**	**7.5^{a}**	**10.0^{a}**	**11.8^{a}**
Head + Broken + Bran + Hull			**4.9^{a}**	**6.0^{a}**	**7.4^{a}**	**9.9^{a}**	**11.8^{a}**

[a] For each relative humidity (within column), values designated by the same superscripted letter are not significantly different ($\alpha = 0.05$). Each observation is an average of four measurements, i.e., two EMC replications with each replicate moisture content measured in duplicate.

[b] The weighted average equilibrium moisture contents were determined using the formulas below where 'Prop' refers to the mass percentage of the indicated kernel fraction and 'EMC' refers to the equilibrium moisture content of that fraction:
Brown and Hull = $[(\text{Prop}_{\text{brown}} \times \text{EMC}_{\text{brown}}) + (\text{Prop}_{\text{hull}} \times \text{EMC}_{\text{hull}})]$
Milled, Bran, and Hull = $[(\text{Prop}_{\text{milled}} \times \text{EMC}_{\text{milled}}) + (\text{Prop}_{\text{bran}} \times \text{EMC}_{\text{bran}}) + (\text{Prop}_{\text{hull}} \times \text{EMC}_{\text{hull}})]$
Head, Broken, Bran, and Hull = $[(\text{Prop}_{\text{head}} \times \text{EMC}_{\text{head}}) + (\text{Prop}_{\text{broken}} \times \text{EMC}_{\text{broken}}) + (\text{Prop}_{\text{bran}} \times \text{EMC}_{\text{bran}}) + (\text{Prop}_{\text{hull}} \times \text{EMC}_{\text{hull}})]$

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