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# The normalised Kumaraswamy breakage function: A simple model for wheat roller milling

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ABSTRACT

A simplified model describing wheat breakage during roller milling is presented. Previous work introduced the breakage equation describing First Break roller milling of wheat in terms of a breakage function that incorporated relevant input and processing parameters such as roll gap, kernel diameter and kernel hardness. The resulting empirical function, based on polynomial fits, was sufficiently flexible to describe the range of particle size distributions encountered in typical milling operations, but contained a high number of coefficients, making the interpretation of the physical significance of the coefficients difficult and requiring an excessive amount of experimental data. The current work simplifies the breakage function by normalising the output particle size distribution against the milling ratio raised to a power. The Kumaraswamy probability distribution function is then used to describe the normalised data obtained following First Break milling of a wide range of wheat at different roll gaps under both Sharp-to-Sharp and Dull-to-Dull roll dispositions. Using this approach, the effects of roll gap and kernel diameter on wheat breakage can be described using just four parameters. This simplified equation is more practical and versatile for implementation in process integration strategies for the purpose of design and optimisation of cereal processes for food and non-food uses.



## 1. Introduction

Milling wheat into flour has accompanied humanity throughout the evolution of Western civilisation. Storck and Teague [1] write on this subject "There is no other single thread of development that can be followed so continuously throughout all [Western] history, and none which bears so constant a cause-and-effect relation to every phase of our progress in civilization." At the beginning of the third millennium, this centrality of flour milling to society and civilisation is poised to take on new significance as the world faces oil depletion and must turn to biorefining of renewable raw materials such as cereals for its chemical and energy needs. Flour milling has for millennia underpinned the security and quality of the food supply—now it must be adapted to contribute to the provision of the non-food needs of society. For both of these purposes – flour milling for food, and wheat biorefining for non-food products – process engineers have a role to play, and require tools for the design, optimisation and operation of wheat milling processes.

The purpose of flour milling is to fractionate the wheat kernel into its components, efficiently and economically, in order to allow recovery of high yields and purity of white flour of consistent quality [2]. Roller mills are employed to achieve this fractionation, as they break the wheat kernel such that particles of different size also vary in botanical origin and composition. For non-food applications, the paradigm of fractionation in the context of a cereal biorefinery will ascend to a more prominent role. This is analogous to fractionation within oil refineries, in which crude oil is extensively fractionated via distillation and catalytic cracking, with the different cuts then sent for further processing and conversion into the great range of oil-derived products that are used by society [3]. This fractionation–conversion model presents great complexity, as numerous reaction and separation routes operate in parallel and simultaneously. This complexity creates opportunity for effective process integration and optimisation in order to give substantial cost reductions and savings. The petrochemical industries currently benefit from low (but increasing) feedstock costs, but also from highly efficient and economical processes achieved through extensive integration. In competing with oil, emergent cereal biorefineries need to model themselves on the highly efficient integrated and optimised processes of the petrochemical industries [4].

The need for systematic methods to enhance process efficiency and flexibility in the petrochemical industries following the 1970s oil crisis led to the birth of Pinch Analysis to design heat exchanger networks [5]. After that, process integration as a discipline became

*Abbreviations:* NKBF, Normalised Kumaraswamy Breakage Function; PSD, particle size distribution; SKCS, Single Kernel Characterisation System; D-D, dull-to-dull milling; D-S, dull-to-sharp milling; S-D, sharp to dull milling; S-S, sharp-to-sharp milling.

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**Nomenclature**

| | |
|---|---|
| $a$ | Collapsing parameter for the NKBF |
| $a_i \ldots d_i$ | Coefficients for the polynomial breakage function |
| $B(x,D)$ | Breakage function |
| CDF | Cumulative Distribution Function |
| $D$ | Size of the input particles for the roller mill. In the case of whole wheat, it refers thickness, the smallest dimension in the kernel |
| D-D | Dull-to-Dull roller mill disposition |
| $G$ | Roll Gap |
| $G/D$ | Milling ratio |
| $k$ | Fitting parameter for the critically dumped function |
| $m$, $n$ | Shape parameters for the NKBF |
| NKBF | Normalised Kumaraswamy Breakage Function |
| $P$ | Cumulative particle size distribution |
| PDF | Probability Distribution Function |
| PSD | Particle Size Distribution |
| SKCS | Single Kernel Characterisation System |
| S-S | Sharp-to-Sharp roller mill disposition |
| $x$ | Output particle size |
| $z$ | Fully normalised output particle size |

*Greek symbols*

| | |
|---|---|
| $\alpha$,$\beta$ | Shape parameters used in the different tested distributions |
| $\chi$ | Partially normalised output particle size |
| $\rho$ | Non-cumulative particle size distribution |

established by developing various comprehensive tools to design and optimise complex processes [6,7]. Modern implementations of process design and integration tools utilise computer-based simulators such as Aspen HYSYS® (Aspen Technology, Inc. USA). In order to adapt process simulators for use in designing and optimising cereal biorefineries or even traditional flour mills, models of the unit operations involved in cereals processing are needed. One point of difference between cereal biorefineries and the petrochemical industries is that the former entails much more handling of granular solids, such as wheat and milled stocks. In fact, even in the established process industries, 70% of the intermediate products and 60% of the final products handled by established process industries are solids [8]. Despite this, process simulators are traditionally strong on models for fluids handling operations and weak on solids handling. Adequate models for operations involving granular solids will be necessary for successful application of process simulation and process integration approaches to cereal biorefineries.

In current first generation cereal bioprocessing facilities such as ethanol plants, hammer mills are the standard choice for the preprocessing of raw materials, which only require simple size reduction without fractionation. However the industry is becoming more sophisticated, and the need to fractionate in order to add value is becoming more of a driver of change. Alongside this, the importance of the preparation of the raw material for subsequent process performance is being recognised and appreciated more. For example, even in a relatively simple dry mill bioethanol facility, a small change in the average size of the milled raw cereals has an important effect on the plant's economy [9,10]. Roller mills are more sophisticated than hammer mills and give greater versatility for precise fractionation of cereal kernels. Greater recognition of the importance of milling and of the opportunities given by fractionation will enhance the prevalence of the use of roller mills in cereal biorefineries.

Fractionation (via milling operations), bioconversion (via fermentation and chemical synthesis) and extraction (of functional components) will be key operations within cereal biorefineries. In flour milling, the wheat kernel is fractionated into two major fractions: the endosperm, which is recovered as flour and used in breadmaking and suchlike; and the protective outer layers of the kernel which are recovered as bran and predominantly used for animal feed (see Campbell [11] and Campbell et al. [2] for further detail of the flour milling process and its interaction with the wheat kernel). In cereal biorefineries, the starchy flour is likely to be converted via fermentation into products such as ethanol or succinic acid [12,13], while functional molecules might be extracted from the bran fraction, with the residue burnt for energy or sent to animal feed [14,15]. In both cases, fractionation is the starting point.

Fractionation of wheat into its components entails repeated milling and sifting in a dry, and therefore comparatively cheap, process. In flour milling, roller mills are used, as they have the useful property that they tend to keep the bran layers of the wheat kernel relatively intact as large particles, while shattering the endosperm into small particles, such that bran can be separated from endosperm based on size using sifting [2,11]. The breakage patterns of the wheat and subsequent stocks during roller milling are key to the successful fractionation of wheat. Previous work has aimed to develop models of wheat breakage based on the breakage equation for roller milling. These models have been successful but excessively complicated. The objective of the current work was to develop a simplified model for the roller milling of wheat based on the breakage equation and suitable for inclusion in a process integration framework aimed at the design of optimal cereal bioprocessing facilities for both food and non-food products.

## 2. Previous work

Campbell and co-workers [2,16–20] introduced the concept of the breakage equation to describe First Break roller milling of wheat in terms of the input and output particle size distributions:

$$P_2(x) = \int_{D=0}^{D=\infty} B(x,D)\rho(D)\mathrm{d}D \quad (1)$$

where $P_2(x)$ is the cumulative output particle size distribution (PSD), $B(x,D)$ is the breakage function and $\rho(D)$ is the probability density function describing the input PSD. Eq. (1) simplifies the modelling of wheat breakage to determining the form of the breakage function. Fang and Campbell [19] arrived at the following empirical, polynomial relation for the breakage function:

$$\begin{aligned} B(x,D) = a_0 + b_0x + c_0x^2 + d_0x^3 + \\ + \left(a_1 + b_1x + c_1x^2 + d_1x^3\right)\left(\frac{G}{D}\right) + \\ + \left(a_2 + b_2x + c_2x^2 + d_2x^3\right)\left(\frac{G}{D}\right)^2 \end{aligned} \quad (2)$$

where $a_i$, $b_i$, $c_i$ and $d_i$ are fitted coefficients and $(G/D)$ is defined as the milling ratio, a dimensionless parameter that implies wheat breakage depends on the ratio between the gap ($G$) that separates the rolls and the size of the wheat kernels ($D$) at the input.

Combining Eqs. (1) and (2) yields the following result:

$$\begin{aligned} P_2(x) = a_0 + b_0x + c_0x^2 + d_0x^3 + \\ + \left(a_1 + b_1x + c_1x^2 + d_1x^3\right)G\overline{\left(\frac{1}{D}\right)} + \\ + \left(a_2 + b_2x + c_2x^2 + d_2x^3\right)G^2\overline{\left(\frac{1}{D^2}\right)} \end{aligned} \quad (3)$$

from which the output particle size distribution for breakage of a given wheat can be predicted from a knowledge of the wheat kernel size distribution and the roll gap. Eq. (3) has 12 coefficients that show great