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Data-driven modeling of milling and sieving operations in a wheat milling process

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ABSTRACT

Industrial wheat milling processes are based on a gradual size reduction approach, with repeated milling and sieving steps to achieve appropriate breakage of the wheat kernel and its effective reduction into flour. This approach greatly increases the flour yield, but makes the process more difficult to understand and operate. In this respect, mathematical modeling can be very useful to optimize industrial milling operations by relating the operating variables to the final product quality and quantity.

As a first step toward the modeling of an entire wheat milling process, in this study experimental data were generated from roller mills and plansifters, and the data were used to build multivariate statistical models enabling one to improve process understanding and to predict the particle size distribution of the milled material and of the sieved material, as well as the amount of material remaining on each sieve, from the known operating conditions and wheat moisture. The unit operation models were then concatenated, and the propagation of prediction errors was analyzed. The results are very satisfactory, in that a comprehension of the breakage mechanism was obtained with a single modeling framework that unifies the modeling results obtained in existing studies, and the product quality and amount were predicted with good accuracy. The results on prediction error propagation show that, although the models are data-driven, the design of the plansifter model can be done independently of that of the roller mill model, since the prediction error did not propagate across the models strongly.

1. Introduction

Wheat grain is a major global commodity. The Food and Agriculture Organization of United Nations (FAO) reported that the world wheat production in 2014 reached 729.5 million tons (FAO, 2015). Wheat and derived products are used in many sectors: food, animal feed, biofuels, cosmetics, and bio-plastics. Food is the main sector of use, exploiting over 66% of the 2014 annual wheat production (FAO, 2015). In food applications, wheat is mostly ground into flour and used, among others, for bread, pasta and biscuits. In the United States, nearly 11 million tons of flour were produced in the second half of 2014, according to the National Agricultural Statistic Service (NASS) of the U.S. Department of Agriculture (NASS, 2015).

One of the most important parameters to characterize wheat flour is the particle size distribution (PSD). Flours of different particle size distribution differ in physical properties and chemical composition (Wang and Flores, 2000; Tóth et al., 2006). As a consequence, these properties affect flour performance during final product preparation (Hatcher et al., 2002).

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Wheat milling is used to break open the wheat kernel and separate its components (endosperm, bran and germ) in such a way as to recover the maximum quantity of endosperm (flour), with minimum contamination by bran and germ, and at minimum cost (Campbell, 2007). A modern wheat milling process is based on a gradual size reduction approach. This approach implies repeated milling steps (by roller mills) and separation steps (by plansifters) to achieve effective separation of endosperm from bran and germ, and appropriate reduction of endosperm into flour. This approach ensures high flour yield, but makes the process complex and difficult to operate.

Mathematical modeling and simulation can be powerful tools in supporting milling operations, as they can improve process understanding and allow one to predict product quality (i.e., product PSD and amount).

Wheat milling has been investigated with different modeling techniques. Flores et al. (1991) developed an empirical model for a flour mill that relates the wheat commercial characteristics with flour ash and protein. The model allowed determining the impact of commercial parameters on the final product. Fang et al. (1998) developed a neural network model to predict particles characteristics as a function of the wheat properties, such as geometric mean diameter, specific surface area and break release. Several studies rely on the concept of breakage equation, namely a population balance with a breakage function that incorporates relevant input and process parameters (Campbell and Webb, 2001; Campbell et al., 2001, 2007; Fang and Campbell, 2003a,b). As a breakage function requires a large number of parameters, a normalized breakage function was developed (Mateos-Salvador et al., 2011, 2013; Campbell et al., 2012). Yuan et al. (2003) used a logistic model to relate the commercial wheat properties with the output particle size distributions, but a high predictive accuracy was reached only for one unit operation. Recently, Patwa et al. (2014) developed a discrete element method model for a wheat milling process.

Sieving is a simple operation, where in principle the achieved separation only depends on the material size. However, it is well know that non-idealities (such as particle aggregation or breakdown, or incomplete separation of material smaller than a given mesh size) can strongly affect the separation (Posner and Hibbs, 1997). Little has been published so far relating to the performance of plansifters. Posner and Hibbs (1997) concluded that plansifters are often a process bottleneck and that their efficiency is usually very low. Sultanbawa et al. (2001) developed a graphical technique to evaluate the performances of a cascade of sifters. They assumed that the change of concentration of undersize particles remaining on a sieve as a function of sieving time can be described by a first-order rate equation with a screening rate constant that was inversely proportional to the particle size. Li et al. (2002) described a two dimensional computer simulation of the separation of crop seeds by screening. Their results showed that complete separation occurred only with a bed depth of around 30 mm or less. In deeper beds, the small particles could not segregate effectively and migrate to the screen apertures. As a result, a large number of undersize particles remained in the over tails product stream.

In this study, a data-driven modeling approach, namely partial least-squares regression (PLS; Wold et al., 1983; Geladi and Kowalski, 1986) is used to describe both the roller mill units and the plansifter units of a wheat milling process. Given the multivariate nature of the process and the correlation of process parameters, wheat properties and product quality, PLS is a particularly suitable modeling tool for this process, and to the best of our knowledge this is the first attempt to use PLS for this kind of application. The roller mills models are used to improve the understanding of the milling process and to predict the product PSD given the process parameters and wheat properties. The plansifters models are exploited to predict the PSD and amount of each sieved fraction. Finally, as a first step toward the simulation of an entire milling process, the roller mill and plansifter models are linked in series, and the propagation of modeling errors across the concatenated models is discussed.

2. The wheat milling process

A simplified scheme of a wheat milling process is shown in Fig. 1. Overall, the process can be divided in three sections: breakage, purifying and reduction. The objective of the breakage section is to break-open the wheat kernel and to scrap the endosperm material from the bran particles, using fluted roller mills. In Fig. 1, four different roller mills are indicated (B1, B2, B3 and B4), with finer material being processed as one moves from the upper mills to the lower ones. Plansifters are cascaded to each breakage roller mill, so as to achieve a preliminary separation between bran and endosperm. A plansifter is made by a stack of sieves of decreasing sieve dimensions (i.e., mesh sizes) that usually vibrate to facilitate particle separation. The plansifter working principle is simple: the material to be sifted is fed to the upper section of the sieve stack, where it is graded depending on the particle size. The number of sieves and the mesh sizes are passage-dependent.

A process "passage" (Fig. 2) is made by the sequence of a roller mill (which grinds the incoming material) and a plansifter (which separates the milled material into different fractions of bran, semolina, and flour). Passages represent key subsystems of the process: the overall process performance is determined by the performance of each passage, as well as by the interconnection between passages.

The purpose of the purifying section is to grade endosperm, semolina and bran products on the basis of the density, shape and surface area of their particles (through processing units called purifiers). The reduction section aims at reducing endosperm into flour, using rolls with a smoothed surface (eight reduction roller mills are indicated in Fig. 1). The quality of flour recovered from each passage (namely from each roll pair) is different (Greffeuille et al., 2005). At least two different types of flour are usually produced (also depending on the country in which flour is manufactured): one high-quality flour, and one flour of lower quality with higher ash content (i.e., higher bran contamination).

For each roller mill, the adjustable input variables considered in this study are process parameters and one wheat property. The main process parameters are the mass flow (MF, kg/h) of the material fed to the roller mill, and the distance between the rolls (milling gap MG, μm); the adjustable wheat property is the wheat kernel moisture content (MC, %). The product quality is characterized in terms of PSD. For plansifters, the amount of each sieved fraction is also considered as a model variable.

It is to be noted that additional process and equipment parameters (e.g., roll speed, roll speed differential, roll fluting) can affect the milling operation. In this study, their values were set constant as in a typical industrial roller mill. Additionally, raw material characteristics such as the wheat type and the