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Moisture profiles during intermittent soaking of an oblate spheroid

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ABSTRACT

Oblate spheroidal geometry and Fickian diffusion with constant diffusivity are used to model moisture absorption in a sorghum kernel with an aspect ratio of 1.48 during intermittent soaking. During the soaking phases the surface is assumed to be saturated while during the drain phases convective transport between the surroundings and the surface is assumed. An explicit finite difference scheme is used to solve the dimensionless form of the diffusion equation. For a three-cycle scenario with a 30-min soak, 2-h drain, 30-min soak, 5-h drain, and a 64-h soak, it is shown that the moisture distribution in the kernel is more uniform (as measured by the standard deviation of the moisture profile) than during a constant soaking scenario regardless of the assumed values of the Biot modulus and the equilibrium surface moisture concentration during the drain phases.

1. Introduction

Malt, hops, water, and yeast are the four principle ingredients in beer, each adding unique contributions to the final beverage. Malt not only provides the source of fermentable sugars but also provides color, flavor, aroma, mouthfeel, and other properties to the finished beer (see, for example, Bamforch, 2003; Lewis and Young, 2002). In most beer sold in the western world, the malt is made from barley although other grains, including oats, wheat, rye, corn, and sorghum, are also used. Hops are added to beer to provide flavor and aroma and also were historically added because their preservative properties enhanced the shelf-life of the beer as well. Water is the primary ingredient in beer, typically 85–95% by weight, and the type and concentration of salts in the water significantly affect the appropriate style of beer that should be brewed with that water. Many historical brewing centers became famous because their local water chemistry serendipitously matched that needed for the style of beer they were brewing. Yeast, the fourth component, is not only the biological organism that converts the fermentable sugars into alcohol and carbon dioxide but also produces other by-products that can significantly affect the aroma and flavor of the beer.

Converting barley kernels into malt can described as a four-step process: kernel preparation, steeping, germination, and kilning (Briggs, 1998). Kernel preparation includes not only removing all foreign debris but also a critical size sorting of the kernels. A typical sort might categorize the kernels into small (2.2–2.5 mm), medium (2.5–2.8 mm), and large (above 2.8 mm) fractions with smaller kernels being rejected for malting (Briggs, 1998). This degree of sorting is necessary to ensure that the kernel-to-kernel variation during the subsequent steps in the process is as small as possible.

During the steeping phase, the sorted barley kernels are immersed in water, some of which they absorb. At the end of the steeping phase, the total amount of water absorbed is critical to a successful germination phase (Briggs, 1998). Typically, the desired water content at the end of the steeping phase is 42–48% by weight, a significant increase over the initial moisture content which is typically 12% or less (Briggs, 1998). Absorbing water into the barley kernel begins the modification process where carbohydrates in the endosperm are converted into fermentable sugars. The water provides one of the reactants and it also increases the diffusivity within the endosperm (Briggs, 1998). This is a critical role since the modification process requires that hormones released from the embryo diffuse through the endosperm to the aleurone layer just beneath the husk. This then triggers the release of the enzymes that catalyze the reactions synthesizing the fermentable sugars.

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Upon completion of the steeping phase, the kernels are removed from the water and are held under controlled temperature and humidity while the kernel is allowed to begin to grow. In traditional practice in the United Kingdom, the germination phase ends when the acrospire is 3/4 to 7/8 the length of the kernel and then the kilning process begins (Briggs, 1998). The kilning process is used to halt any further growth, to develop additional flavor and color in the malt, and to produce a friable malt suitable for milling and mashing in the next steps in the brewing process. Depending on the kilning conditions, especially temperature and time, a variety of malt styles can be produced. Malts produced at low temperatures produce light colored, base malts while those produced at increasingly higher temperatures produce darker colored malts with more intense flavors.

Our interest is in the steeping phase of malting, specifically we are interested in how the process can be designed so that the moisture content is as uniform as possible during the steeping phase. This interest is generated by the desire to successfully malt sorghum that could then be used to produce gluten-free beer, something that cannot be produced using barley as the carbohydrate source. In malting, there appear to be two variants on the steeping process: continuous immersion until the desired moisture content is reached and a series of flood-drain cycles where the sorghum is immersed for a short period of time and then the water is drained off and the sorghum is allowed to stand in air for a period of time before the process is repeated (Briggs, 1998).

Modeling of water absorption in sorghum during soaking has been studied by Kashiri et al., 2010. They used the empirical Peleg relationship to correlate the experimentally measured absorption as a function of time at temperatures of 10, 20, 30, 40, and 50 °C. Using an Arrhenius form for the temperature dependency, they were able to correlate the experimental data with the resulting correlation coefficients greater than 0.99. The diffusivities ranged from approximately 2.2×10^{-12} m^2 s^{-1} to 8.4×10^{-12} m^2 s^{-1} with the reported diffusivity constant and activation energy from the Arrhenius relationship of 6.39×10^{-4} m^2 s^{-1} and 24.21 kJ mol^{-1}, respectively. (The reported units on the diffusivity constant are probably incorrect and should have been cm^2 s^{-1} to have a diffusivity of order magnitude 10^{-12} m^2 s^{-1}.) However, their correlations were independent of geometry and only considered constant soaking of the grains. Kashiri et al., 2012 modeled these results using an artificial neural network that was independent of the geometry and an explicit value of the effective diffusivity.

Fick's second law was used to model absorption in white kafir and Atlas sorgo sorghum by Fan et al. (1963) using an approximate relationship to account for the non-Cartesian geometry of the sorghum. Their study covered the temperature range 0–100 °C and the resulting diffusivity constant and activation energy were 4.47x10^{-4} cm^2 s^{-1} and 34.9 kJ mol^{-1}, respectively, for the white kafir and 6.20×10^{-4} cm^2 s^{-1} and 35.27 kJ mol^{-1}, respectively, for the Atlas sorgo. The resulting diffusivities ranged from 3×10^{-12} to 40×10^{-12} m^2 s^{-1} over the temperature range studied with only a slight difference between the two forms of sorghum.

In related work, the intermittent drying behavior of sage (Esturk, 2012), yerba mate (Holowaty et al., 2012), rice (Putranto et al., 2011; Dong et al., 2009; Aquerreta et al., 2007; Cihan et al., 2007, 2008; Iguaz et al., 2006; Madamba and Yabes, 2005; Cihan and Ece, 2001; Shei and Chen, 1999), coffee (Putranto et al., 2011), apples (Zhu et al., 2010), Ilex paraguariensis (Ramallo et al., 2010), oregano (Soysal et al., 2009), bananas (Baini and Langrish, 2007), pasta (Xing et al., 2007), lentils (do Carmo et al., 2012) and mullet roe (Fan et al., 2003) has been studied and reviewed (Chua et al., 2003). In intermittent drying, an active drying phase is followed by a rest or tempering phase. This sequence of active drying followed by tempering is continued until the desired dryness is obtained. During the tempering phase, the moisture profile in the drying solid becomes more uniform as the moisture from the high concentration center diffuses to the lower concentration surface by Fickian diffusion (de Lima and Nebra, 2001). The advantages of the intermittent drying process include (Chua et al., 2003) improved drying kinetics, enhanced product quality, and reduced energy consumption.

In the rest of this paper, a simplified absorption model based on Fickian diffusion in an oblate spheroid is developed and numerically solved for both the continuous immersion and flood-drain steeping processes. The oblate spheroid geometry (see Fig. 1), considered to well represent the shape of a sorghum kernel, is constructed by rotating an ellipsoid around its minor axis. A prolate spheroid is constructed by rotating an ellipsoid around its major axis. More specifically, the numerical model is used to determine the conditions for the soak-drain scenarios in which the moisture content in the sorghum kernel was as uniform as possible under some practical operating constraints. The effect of the model parameters on the differences in moisture concentration profiles for various soaking is studied. Finally, recommendations are made regarding how the soak-drain scenario could be used in practical applications.

2. Model formulation

One definition for oblate spheroidal coordinates (μ, v, ϕ) is (Moon and Spencer, 1988),

$$x = f\cosh(\mu)\cos(v)\cos(\phi) \quad (1)$$

$$y = f\cosh(\mu)\cos(v)\sin(\phi) \quad (2)$$

$$z = f\sinh(\mu)\sin(v) \quad (3)$$

where f is the coordinate of the foci of the spheroid. In terms of the major and minor axes of the ellipse, a and b, respectively, used to generate the spheroid by revolution around the minor axis, f is given by

$$f = \sqrt{a^2 - b^2} \quad (4)$$

The expressions for the inverse transformations are given by

$$\tan(\phi) = \frac{y}{x} \quad (5)$$

$$\cosh(\mu) = \frac{\sqrt{(\rho + f)^2 + z^2} + \sqrt{(\rho - f)^2 + z^2}}{2f} \quad (6)$$

$$\cos(v) = \frac{\sqrt{(\rho + f)^2 + z^2} - \sqrt{(\rho - f)^2 + z^2}}{2f} \quad (7)$$

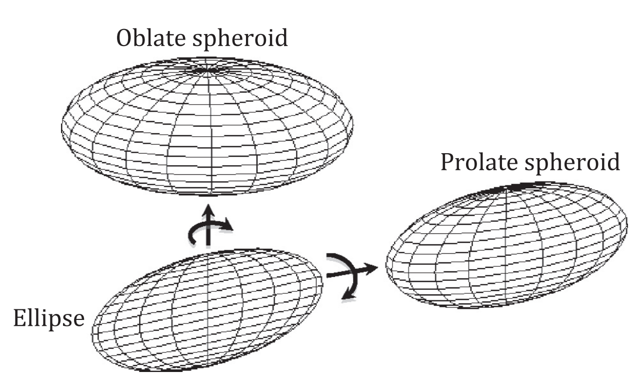

Fig. 1. Generation of oblate and prolate spheroids by rotation of an ellipse around its minor and major axes, respectively.