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Research Paper

Kinetics of alfalfa drying: Simultaneous modelling of moisture content and temperature

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The kinetics of the dehydration of alfalfa stems, leaves and the whole alfalfa plant (*Medicago sativa* L) was studied experimentally at lab-scale using a fixed-bed dryer with warm air at 328, 333, 338 and 343 K. Following the evaluation of the influence of bed thickness, air mass rate and air temperature on the kinetics of drying, a kinetic model of globalised parameters is proposed. The kinetic model was designed to simulate the exchange of moisture between alfalfa and the surrounding air and the variation of temperature inside the substrates with time simultaneously. In a first step, the kinetic model was applied to stems and leaves separately. The model reproduced 94.4% and 70.1% of the moisture experimental results obtained for stems and leaves, respectively, within an error band of 15%. Moreover, 95% of the experimental results regarding the variation of temperature inside stems with time were simulated. The kinetic model was then applied to the whole alfalfa plant considering its content of stems (60% wet weight) and leaves (40% wet weight) using the same kinetic parameters and variables fixed for their single modelling. The model reproduced 82.2% of the moisture experimental results obtained for the drying of the whole alfalfa plant. This kinetic model could be a useful tool for the design of a drying device based on scientific evidence.

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1. Introduction

Alfalfa (*Medicago sativa* L) is a valuable herbaceous dicotyledon which is widely used to produce high-value livestock feed due to its high acceptability and digestibility by ruminants. Other uses of this forage crop include soil phytoremediation and the production of paper, hardboard, biofuels and human supplements (neutraceuticals) to treat various diseases (Adapa, Schoenau, & Arinze, 2004; Mahmoud, Arlabosse, & Fernández, 2011). The main properties of alfalfa originate from its high content of proteins, fibre, calcium, vitamin C, carotene (pro-vitamin A), and other pigments such as xanthophylls and oligoelements, which are all valuable in compound feedstuffs. Moreover, alfalfa is a legume and requires little or no nitrogen fertilising. On average, mature alfalfa contains 17% protein, 60% digestible nutrients and 23% fibre (Cuddeford, 1994; Hamm, Debeire, Monties, & Chabbert, 2002).

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Nomenclature

a	Ratio between area and volume, m^{-1}
A	Area, m^2
Cp	Heat capacity, kJ kg^{-1} K^{-1}
Cp_w	Water heat capacity, kJ kg^{-1} K^{-1}
Cp_{ss}	Heat capacity of the dried solid, kJ kg^{-1} K^{-1}
D	Internal diameter of alfalfa stems, m
E	Activation energy, J mol^{-1}
G	Air mass flow rate, kg h^{-1} m^{-2}
h	Coefficient of heat transfer, kJ h^{-1} m^{-2} K^{-1}
H (equal to $h \cdot a$)	Individual volumetric coefficient of heat transfer, kJ h^{-1} m^{-3} K^{-1}
k	Kinetic constant, h^{-1}
k'	Thermal conductivity of air, W m^{-1} K^{-1}
k_0	Pre-exponential constant, h^{-1}
L	Bed thickness, m
λ	Latent heat of water vaporisation, kJ kg^{-1}
R	Universal constant of the ideal gases, J K^{-1} mol^{-1}
Re	Reynolds number
ρ	Density, kg m^{-3}
ρ_s	Density of the dried solid, kg m^{-3}
t	Time, h
T	Temperature, K
Ta	Air temperature, K
V	Volume, m^3
X	Average substrate moisture, kg water kg^{-1} dried solid
X^*	Equilibrium moisture content, kg water kg^{-1} dried solid

Specifically, alfalfa leaves are low in fibre and high in protein and carotenoids, while stems are high in fibre. Fractionation into leaves and stems is a frequent practice as this enables a later, controlled recombination of these components to achieve specific market nutritional requirements for animal feeds or the potential use of the more valuable leaf material in the rapidly expanding neutraceutical and herbal markets (Adapa et al. 2004; Arinze, Schoenau, Sokhansanj, & Adapa, 2003). Separation of alfalfa leaves from stems has been attempted using numerous methods: using a leaf harvesting machine (Ogden & Kher, 1965), a shaking screen surface (Chrisman, Kohler, Mottola, & Nelson, 1971) or aerodynamic fractionation (Bilanski, 1992; Menzies & Bilanski, 1968). As a consequence of its properties, alfalfa is the major forage crop produced in temperate regions, with a dedicated crop area of about 30 Mha worldwide in 2009. In the same year, North America was the largest alfalfa producer by area, accounting for 41% of the dedicated area worldwide, followed by South America (23%), Asia (8%) and Europe (5%), while the remaining crops were produced in Africa and Oceania (Cash, 2009).

In general, drying is an essential component in alfalfa processing. Drying is performed to reduce alfalfa moisture levels to a safe limit for storage (usually 8–15% wet basis). Moisture concentrations above 200 g kg^{-1} (wet basis) can cause negative changes in quality via mould growth which can lead to spontaneous heating within the alfalfa mass, Maillard reactions, and increased concentrations of fungi that produce toxic metabolites (Coblentz, Fritz, Bolsen, King, & Cochran, 1998). Natural climatic drying and induced industrial drying are widely used as preservation methods for alfalfa (Andueza, Delgado, & Muñoz, 2009; Mahmoud et al. 2011). However, induced industrial drying under high-temperature conditions is preferred due to climate and seasonal constraints, more rapid drying, and to facilitate alfalfa transport and storage (Cozzi, Burato, Berzaghi, & Andrighetto, 2002). Moreover, in-field processing leads to handling losses (especially of the leafy parts of the plant where proteins are mainly located) of up to 30–40% total solids (Dermaquilly & Andrieu, 1988; Scales, Moss, & Quin, 1978).

Industrial dehydration can be performed under many different conditions, with temperatures ranging widely between 313 and 1073 K (Hamm et al. 2002; Sokhansanj & Patil, 1996). However, high temperatures should be avoided as they can lead to loss of product quality. Sokhansanj and Patil (1996) studied the kinetics of dehydration of green alfalfa at drying air temperatures ranging from 313 to 1073 K. The optimum temperature for drying from the stand point of colour and protein solubility was found to be 448 K. Furthermore, fractional drying of alfalfa leaves and stems is advisable because alfalfa leaves and stems dry at significantly different rates, thus resulting in over-dried leaves and under-dried stems (Arinze et al. 2003; Bilanski, 1992). Consequently, drying leaves and stems separately is more likely to allow rapid drying without quality damage, as the optimal temperature for each part can be selected separately.

In this regard, the monitoring and modelling of the variation in alfalfa moisture content with time is a critical prerequisite for the better utilisation of biomass, the planning and control of supply chain operations, and the design of dryers (Bakker-Arkema, 1984; Bartzanas, Bochtis, SØrensen, Sapounas, Green, 2010).

The kinetics of drying depends on the nature, form and size of the substrate to be dried, as well as on the physical properties of the air used as a heating medium (temperature, relative humidity and flow rate). Several research studies have been conducted to measure and model commodity drying: for alfalfa (Arabhosseini, Huisman, & Müller, 2011), peeled almonds (Ruiz-Beviá, Fernández-Sempere, Gómez-Siurana, & Torregrosa-Fuerte, 1999), grain (Parry, 1985), carrots (Carbonell, Madarro, Piñaga, & Peña, 1984), aubergines (Chaves, Sgroppo, & Avanza, 2003), mango and cassava (Hernández, Pavón, & García, 2000), cashew nuts (Machado, Oliveira, Santos, & Oliveira, 2010), and apples and potatoes (Lazarides, Gekas, & Mavroudis, 1997). Although both empirical and complex modelling approaches have been developed to simulate the kinetics of drying based on diffusion equations (assuming that the drying process might occur both under isothermal and non-isothermal conditions) or energy balance (considering mass and energy flows), measurements have not always been representative of the complete process of drying. Moreover, these research studies have been conducted under very different experimental conditions, thus justifying the need to study the kinetics of drying for each specific substrate under specific experimental conditions to obtain reliable and informative results for the design of dryers. Sokhansanj and Patil (1996) used three equations to describe the drying of alfalfa that considered initial moisture content and air

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