BIOSYSTEMS ENGINEERING 122 (2014) 1–15

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Numerical simulations and experimental measurements on the distribution of air and drying of round hay bales

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ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form
7 March 2014
Accepted 13 March 2014
Published online xxx

Keywords:
Round bale dryer
Computational fluid dynamics
Air distribution
Drying simulation
Porous media

The artificial drying of round bales offers the possibility to consistently produce quality hay by reducing field curing time and leaf shattering. Air distribution in the bale must be appropriate in order to achieve a uniform and efficient drying process. The air distribution and drying of four designs of round bale dryer were simulated using computational fluid dynamics. A round bale was modelled as a cylindrical porous media having a soft core. Bales were modelled both as being perfectly formed and as having a lower density close to their circular faces. Simulations showed that the simplest dryer design in which air enters the bale through one end, provides a deficient air distribution and inadequate drying, even when the bale is perfectly formed. Other designs studied showed, to varying degrees, an improved air distribution and drying uniformity. Simulations of a design in which an axial void is created in the bale centre, produced an optimal situation where the air and the drying front moves radially from the centre outwards. Conveying of air through both bale ends also contributed significantly to flow and drying uniformity. However, simulations for bales with a deficient density profile, as often found in practice, showed important distortions in the air distribution negatively affected drying. Therefore the uniformity of bale dry matter density is a determinant for the successful operation of any dryer. Additional efforts must be invested in the field to produce more uniform bales, particularly during raking and baling.

1. Introduction

The use of round bales in agriculture has grown in popularity due to the mechanisation of the production chain, low labour requirements, the ease of their manipulation and transport, and the low requirements and flexibility for their storage (Holpp, 2004; Pöllinger, 2008).

The maximum moisture content recommended in the literature for the safe storage of hay varies from source to source but is in the range 18–12% (w.b.) As soon as mowing occurs a competition begins between drying and spoilage of the forage, the latter being caused by the massive development of the existing microflora, causing nutrient loss and possibly the production of toxic metabolic products (Adler, 2002). Producing good quality hay involves the rapid and

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http://dx.doi.org/10.1016/j.biosystemseng.2014.03.008
1537-5110/

Nomenclature

a	parameter in Eq. (1)
CFD	computational fluid dynamics
h_s	heat of sorption, J kg^{-1}
k	drying constant
P	pressure, Pa
S_h	energy source term, W m^{-3}
S_w	moisture source term, kg m^{-3} s^{-1}
t	time, s
UDF	user-defined function
UDM	user-defined memory
UDS	user-defined scalar
v	air velocity, m s^{-1}
W	moisture content, kg [water] kg $[product]^{-1}$
W_e	equilibrium moisture content, kg [water] kg $[product]^{-1}$
ρ_{bd}	bulk dry matter density, kg m^{-3}

uninterrupted reduction of moisture content from about 80% when the plant is mowed, down to the low levels mentioned above. In wet, temperate climates, such as in central Europe and some North American regions, accomplishing this relying only on field drying can be very difficult and it seldom occurs (Chiumenti, Da Borso, & Donantoni, 1997; Gindl, 2002; Misener & McLeod, 1990; Muck & Shinners, 2001; Pöllinger, 2003). High humidity and precipitation due to frequent rains, low ambient temperatures and high overnight relative humidity, all lead to slow field drying of the crop, particularly during the last stages of the process where further drying requires lower air relative humidity (Arinze, Sokhansanj, Schoenau, & Trauttmansdorf, 1996; Parker et al., 1992). Extended field drying times due to adverse weather conditions reduce product quality by sun bleaching, respiration and the loss of soluble nutrients due to dew and rain (Fonnesbeck, de Hernandez, Kaykay, & Saiady, 1986; Muck & Shinners, 2001; Parker et al., 1992).

Although existing technology permits the artificial drying of forage from its fresh state, eliminating completely the uncertainty imposed by the risk of bad weather, the energy demands of the process make it uneconomic (Muck & Shinners, 2001). Therefore, when artificial drying is used, it is preceded by a short field drying stage to significantly reduce the moisture content of the forage whilst minimising the risk of adverse weather. The duration of this field drying period presents a compromise between weather risk and the subsequent energy requirements during artificial drying (Wirleitner, 2010).

Another advantage of artificial drying comes from the reduced mechanical losses through leaf shattering during harvest and the earlier field operations designed to accelerate and make more uniform the process. These losses are very much a function of moisture content and when these operations are performed (Parker et al., 1992) and are more pronounced in leguminous products. Since leaves have a greater concentration of important nutrients than stems, this not only results in a lower yield but also a reduction in hay quality.

Artificial drying may be performed on loose or baled hay. The increasing popularity of round bales, and the need to consistently produce high quality hay, have led to a growing interest in the drying of round bales. However, this system has its problems, mainly arising from non-uniform air distribution inside the bale. Dryer design influences the manner in which the air is distributed inside the bale and density differences within the bale cause most of the air to flow though the zones of least resistance. Highly compacted zones are difficult to dry to safe moisture levels and extended drying times are needed for bales with large density differences.

A number of studies done on round bale drying have been carried out but they have tended to concentrate on the performance of a specific dryer design. The simplest dryer design consists of a plenum chamber, or air duct, with circular apertures on the top on which the bales are placed on end. The apertures usually have a metal ring, 0.1–0.2 m high, which pierce the bales to avoid air losses between them and the upper dryer wall. It is often necessary to invert the bales after some time to complete the drying. A more complex design allows air to flow through both bale ends, thus improving the air distribution and avoiding the need to turn the bales.

Brandemuehl, Straub, Koegel, Shinners, and Fronczak (1988) produced bales with an axial void by rolling the bale around a 0.2 m diameter PVC (Polyvinyl chloride) tube which was placed in the baler beforehand. They compared their airflow and drying characteristics with those of bales dried axially by wrapping their circumference with a PVC sheet. Results showed lower airflow resistance and more uniform and rapid drying in radially dried bales. No comparison was made with bales dried without void and without wrapping, that is, as dried in the simplest dryer design mentioned above.

In recent years several studies have appeared on the application of computational fluid dynamics (CFD) to analyse the performance of different dryers for agricultural products, for example using tray dryers (Amanlou & Zomorodian, 2010; Margaris & Ghiaus, 2006; Mathioulakis, Karathanos, & Belessiotis, 1998), fixed-bed dryers (Prukwarun, Khumchoo, Seancotr, & Phupaichitkun, 2013; Román, Strahl-Schäfer, & Hensel, 2012), sausage and meat dryers (Mirade, 2003; Mirade & Daudin, 2000) and grain dryers (Weigler, Scaar, Mellmann, Kuhlmann, & Grothaus, 2011). In these studies, CFD has proved to be an important simulation tool for the design and improvement of dryers.

The objectives of this study were, to simulate the airflow and the drying in round bales when using different bale dryer designs with the aid of CFD; to perform drying experiments using round hay bales using the different dryer designs; to assess the agreement between simulation and experimental results; and to compare the performance of the different dryer designs.

2. Materials and methods

2.1. CFD simulations

2.1.1. Flow simulation

In order to assess the air distribution and drying uniformity in a bale with different dryer designs, computational fluid dynamic simulations were carried out using ANSYS Fluent 12 (ANSYS, Canonsburg, Pennsylvania, USA).