BIOSYSTEMS ENGINEERING 121 (2014) 209–220

Available online at www.sciencedirect.com

ScienceDirect

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

Research Paper

Drying process optimisation in a mixed-flow batch grain dryer

Heikki T. Jokiniemi*, Jukka M. Ahokas

Department of Agricultural Sciences, University of Helsinki, Koetilantie 5, P.O. Box 28, FI-00014 University of Helsinki, Finland

ARTICLE INFO

Article history:
Received 9 September 2013
Received in revised form
16 December 2013
Accepted 14 January 2014
Published online 10 February 2014

One of the most energy intense operations in arable farming in temperate countries is grain drying. Several studies have indicated that using higher drying air temperatures offers opportunities to save energy during grain drying, but although to a certain extent grain can tolerate drying at higher air temperatures, this may compromise the viability of the grain. The aim of this study was to examine the energy saving approaches achieved by using an elevated drying air temperature and by manipulating drying airflow in a scaled-down mixed-flow batch grain dryer. The drying airflow was reduced gradually as the drying process proceeded, and the drying air temperature was allowed to rise. The relative humidity of the exhaust air was used as a control factor to adjust the airflow. Energy savings were expected from the higher drying air temperature and, due to the reduced airflow, from the higher exhaust air humidity. The results showed energy savings of 5% for drying barley and 14% for drying oats. Increases in the evaporation rate of 5% and 17%, for barley and oats respectively. However, some degradation in grain viability was observed especially with oats. Further research is needed to find the correct control parameters and temperature limits for each cereal species.

1. Introduction

Energy efficiency in agriculture is currently undergoing intensive research as a result of setting energy saving objectives in all industry sectors. According to directive 2012/27/EU, member states have an obligation to achieve 20% savings in primary energy consumption by the year 2020, compared to the projections made in 2007 (European Union, 2012). In temperate countries one of the most energy intensive operations in arable farming is grain drying. For example in barley production in Finland, drying represents almost 30% of direct energy inputs and 11% of total energy consumption (including indirect inputs such as fertilisers, seeds etc.). In poor harvest conditions grain drying may consume as much energy as all the field operations added together (Mikkola & Ahokas, 2009).

Typical energy consumption of a hot air grain dryer is 4–8 MJ (1.1–2.2 kWh) per kilogram of evaporated water (Nellist, 1987; Peltola, 1985; Suomi, Lötjonen, Mikkola, Kirkkari, & Palva, 2003). However, much lower energy consumption figures have also been reported. Brinker and Johnson (2010) reported an energy consumption of 2.5 MJ kg^{-1} for mixed-flow and 4.4 MJ kg^{-1} for cross-flow dryers in their study of grain dryers in Wisconsin.

Drying as a grain preservation method remains the method of choice due to its proven technology, reliability and

* *Corresponding author*. Tel.: +358 40 779 5837.
E-mail addresses: tapani.jokiniemi@helsinki.fi (H.T. Jokiniemi), jukka.ahokas@helsinki.fi (J.M. Ahokas).
1537-5110/$ – see front matter
http://dx.doi.org/10.1016/j.biosystemseng.2014.01.002

Nomenclature

a	molar mass of water
b	molar mass of air
C	grain dependent coefficient
c_a	air specific heat capacity, kJ kg^{-1} K^{-1}
c_v	water vapour specific heat capacity, kJ kg^{-1}
D_x	water evaporation rate, kg h^{-1}
E	grain dependent coefficient
F	grain dependent coefficient
H	specific enthalpy of air, kJ kg^{-1}
I	electric current, A
k	grain dependent coefficient
l_v	water heat of evaporation, kJ kg^{-1}
M	moisture content, decimal (d. b.)
M_0	initial moisture content, decimal (d. b.)
M_a	air molar mass, kg mol^{-1}
m_a	mass of air, kg
M_e	equilibrium moisture content, decimal (d. b.)
MR	moisture ratio, decimal
n	grain dependent coefficient
P	power (heat or electric), kW
p_a	ambient air pressure, Pa
P_E	electric power, kW
P_H	heating power applied to the drying air, kW
p_s	saturated water vapour pressure, Pa
p_w	partial pressure of water vapour, Pa
q_m	air mass flow, kg h^{-1}
Q_{spec}	specific energy consumption, kWh kg^{-1} [water]
q_V	air volumetric flow, m^3 h^{-1}
R	ideal gas constant, J mol^{-1} K^{-1}
RH	relative humidity, %
t	time, min
T	temperature, °C or K
T_0	273.15 K
U	electric grid voltage, V
x	specific humidity, kg [water] kg^{-1} [air]
x_{in}	specific humidity of intake air, kg [water] kg^{-1} [air]
x_{out}	specific humidity of exhaust air, kg [water] kg^{-1} [air]
ρ	air density, kg m^{-3}

Abbreviations

d. b.	dry basis
w.b.	wet basis

flexibility. In Finland it is used for 85–90% of harvested cereal yield (Palva et al., 2005). In addition to the high energy consumption, the grain drying step can be a bottleneck in the harvest production chain, reducing the performance of the whole harvest system.

Several studies have indicated that one possible method to reduce energy consumption in grain drying is by using higher drying air temperatures (Ahokas & Koivisto, 1983; Morey, Cloud, & Lueschen, 1976; Suomi et al., 2003). Moist air equilibrium equations indicate that air water binding capacity increases faster than its enthalpy as temperature rises. This results in added heat energy increasing the air water binding capacity more at higher temperatures than at lower temperatures. Table 1 presents data on the effect of drying air temperature to the process parameters in the adiabatic drying process.

The benefits achieved by the elevated drying air temperatures also depend on the ambient air temperature and relative humidity (RH) of the dryer exhaust air. The data in Table 1 was obtained for an ambient air temperature of 15 °C. As ambient temperatures rise, the received benefits decrease as the need for additional heat decreases. Furthermore, the RH of the dryer exhaust air in Table 1 is 100%, which indicates that the exhaust air was fully saturated. In practice the dryer exhaust air humidity is high (close to 100%) at the beginning and decreases towards the end of the process, as the grain gets dryer. Decreased exhaust air humidity produces a further advantage of an elevated drying air temperature. Figure 1 shows the effect of dryer exhaust air humidity on the specific energy consumption of the adiabatic drying process with different drying air temperatures. It is evident from Fig. 1 that the greatest benefit from an elevated drying air temperature is obtained at the end of the drying process, where the exhaust air humidity is low.

In a practical drying process the drying air humidity and temperature constantly change when the air passes through the grain. Thus, the drying is often examined as a thin-layer drying process, in which individual whole grains are considered to be fully exposed to the drying air (Henderson, Perry, & Young, 1997, chap. 10). The drying process can be divided into two periods: the constant drying-rate period and falling drying-rate period. Figure 1 illustrates the water binding capacity of air, and it can be used to evaluate the evaporation during the constant drying-rate period. During the falling drying-rate period, the rate of evaporation is controlled by the transfer of water from whole grains of cereal to the drying air. This determines the maximum drying rate of different cereal species under the specified circumstances. The airflow is kept

Table 1 – The effect of drying air temperatures on the air water binding capacity and the specific energy consumption during the adiabatic drying process.

Drying air T, °C	Heat energy demand, kJ kg^{-1} [air]	Removed water, g kg^{-1} [dry air]	Energy consumption, MJ kg^{-1} [water]	Energy saving compared to 70 °C drying, %[a]
70	56.1	16.5	3.39	–
90	77.4	22.9	3.38	0.54
110	97.0	29.6	3.28	3.34
130	117.4	36.3	3.23	4.78

[a] Ambient air temperature is 15 °C and relative humidity 80%. The air is fully saturated after the process (RH_{out} = 100%).