Research Paper

Drying process optimisation in a mixed-flow batch grain dryer

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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.

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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, Lötjönen, 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...
The effect of drying air temperatures on the air water binding capacity and the specific energy consumption in an adiabatic drying process. The drying air temperatures (Ahokas & Koivisto, 1983; Morey, Cloud, & Lueschen, 1976; Suomi et al., 2003). Moist air equilibrium drying air temperatures (Palva et al., 2005). In addition to the high energy consumption, the grain drying step can be a bottleneck in 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

| 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, %  
<table>
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<td>117.4</td>
<td>36.3</td>
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</table>

Abbreviations

- d. b.: dry basis
- w.b.: wet basis

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

*N Ambient air temperature is 15 °C and relative humidity 80%. The air is fully saturated after the process (RH_in = 100%).
constant in conventional grain dryers. This also has an effect on the energy consumption of the drying process, since the water transfer rate together with the grain equilibrium moisture determine the humidity of the dryer exhaust air during the falling drying-rate period. Decreasing exhaust air humidity means that unused heat energy remains in the dryer exhaust air, which leads to increasing specific energy consumption. As long as the humidity corresponding to the grain equilibrium moisture is higher than the exhaust air humidity, it is possible to save energy by controlling the airflow. For example for oats this humidity is ∼70% at the grain storage moisture content (14%) and at the typical grain temperature of 30 °C, according to Eq. (3). Grain drying is often described by Eq. (1) given by Page and referenced by Sinicici, Muir, Jayas, and Cenkowski (1994).

\[ MR = \left( \frac{M - M_0}{M_e - M_0} \right) \exp(-kt^n) \]  

(1)

where MR is the moisture ratio, decimal; M is moisture content, decimal (d. b.); \( M_0 \) is the initial moisture content, decimal (d. b.); \( M_e \) is the equilibrium moisture content (d. b.); t is time, min; and k, n are grain dependent coefficients.

Equation (1) can be solved to determine the moisture content of the crop at a point in time by:

\[ M = (M_e - M_0) \exp(-kt^n) + M_0 \]  

(2)

Equilibrium moisture is obtained from the Henderson equation modified by Pfost (Pabis, Jayas, & Cenkowski, 1998, chap. 6):

\[ M_{eq} = E - F \ln \left( \frac{T + C}{T + C \ln \text{RH}} \right) \]  

(3)

where E, F, C are grain dependent coefficients; T is temperature and RH is relative humidity, decimal. When the drying air humidity and the temperature and grain dependent coefficients are known, the grain moisture as a function of time can be solved from Eqs. (2) and (3). Jayas, Cenkowski, Pabis, and Muir (1991) gathered k and n constants for several cereal species for Eq. (1). Constants E, F and C for most common cereals for Eq. (3) were presented by Pabis et al. (1998). Figure 2 shows an example of drying rate of wheat and barley according to Eqs. (2) and (3). The differences between the drying rates of different cereal species are not usually considered in conventional grain dryers.

Although the elevated drying air temperature causes the theoretical dryer specific energy consumption to decline, it may damage or destroy the grain quality features, such as its germination properties for malting and baking qualities. However, quality reduction also depends on the dryer type. Montross, Bakker-Arkema, and Hines (1999) reported that the dryer type had much greater effects on the amount of stress-cracked corn grains than the drying air temperature in corn drying. Peltola (1988) stated that higher drying air temperatures can be used in mixed-flow dryers than in dryers of a cross-flow design. Several studies suggest the drying air temperature of 70–75 °C as a safe level to maintain the quality factors of the yield (Ghaly & Sutherland, 1984; Suomi et al., 2003). Ghaly and Taylor (1982) studied the effect of heat treatment to wheat quality with two different wheat varieties. They found a severe impairment in the germination rate of one variety of wheat they investigated when the grain moisture was 14% (w.b.) and it was heated in a fluidised bed at 80 °C. The same treatment did not have a significant effect on the germination of the other variety. The duration of heating at 80 °C did not have an effect on results, but even a treatment of 10 min at temperature of 100 °C or higher destroyed the germination properties of both wheat varieties studied completely. However, Suomi et al. (2003) noticed in their experiments with barley that drying air temperature of 98 °C did not reduce the grain germination rate in a mixed-flow dryer. In mixed-flow design the grain is exposed to the furnace-hot drying air for a relatively short period of time, which may explain these results.

Moisture content also has an effect on the temperature tolerance of grain, which can be seen in Fig. 3. Abrupt shrinking caused by excessively rapid drying of wet grain kernels may cause the embryo to disengage from the outer shell of the kernel (Ahokas & Koivist, 1983). This separation is caused by high stresses that arise between the core and surface of the grain as a consequence of shrinking (Mujumdar, 2007). Ghaly and Taylor (1982) found in their study that the heat treatment, which severely reduced the germination rate of wheat at 14% moisture content, did not have a significant effect on the same wheat at a moisture content of 12%. Also Ambardekar and Siebenmorgen (2012), who studied the effect
of high temperature exposure on the properties of rice, found that exposure to temperature of 60 °C decreased the germination rate of two rice varieties rapidly at the initial moisture contents of 17.9% and 18.6%, but did not have significant effect with both varieties and moisture contents. Suomi et al. (2003) also considered the low harvest moisture (16.2%) as one reason for the good temperature tolerance of tested barley.

The aim of this study was to examine the energy saving approaches achieved by: 1) using higher drying air temperature, and 2) adjusting the drying air temperature and airflow during the drying process but maintaining the grain germination rates at the same time. This kind of procedure had been suggested by Peltola already in 1988. Peltola (1988) concluded that further research was needed for the control system and about maintaining the vitality of grain. A series of drying tests was conducted in a research dryer to measure the possible energy savings under practical conditions. The grain can tolerate higher drying air temperatures as it becomes dryer, thus the drying air temperature was gradually elevated as the drying process proceeded. The benefit from the elevated drying air temperature also increases towards the end of the process (Fig. 1), which is a further argument for using this procedure. Since the temperature adjustment was done by reducing the dryer airflow, an additional advantage was expected by achieving higher exhaust air RH and thereby the more efficient use of applied heat energy.

2. Materials and methods

2.1. Research dryer

The experiments were conducted using a research grain dryer at the research farm of Helsinki University in the autumn of 2012. A schematic drawing of the dryer can be seen in Fig. 5. The dryer used was a scaled-down model of a commercial hot air batch grain dryer. However, the air ducts inside the dryer were manufactured to the same dimensions as in the full-scale production models, and therefore the air duct volume with respect to the dryer total volume was larger in the research dryer than in a full-scale commercial dryer. Moreover, the surface area of the drying silo with respect to its volume was bigger, which caused relatively large heat losses.

The research dryer had a total of four mixed-flow type drying cells. In this study only two of them were used and the other two served as storage spaces. The total effective volume of the dryer was approximately 700 l. Both drying cells that were used had an individual intake and exhaust air tubes, and the drying air was drawn through the grain by two centrifugal fans located in the exhaust air tubes. The speed of the fans and the pendulum-type grain recirculation device were controlled by frequency controllers. Two 9 kW electric heaters were used for heating the drying air. The power of the heaters was adjusted by means of a thyristor controller regulated by the drying air temperature. The control system kept the drying air temperature constant.

2.2. Instrumentation

The drying process was monitored by a measuring system that was inserted into the dryer. The temperature and relative humidity of the intake and exhaust air and the air volumetric flow rate were the measured variables. When the drying air conditions in different points of the process were known, the changes in the specific humidity and enthalpy were calculated. When the airflow was known, the heat power and water mass flows were calculated from the specific humidity and enthalpy of the air and monitored as a function of time.

Figure 4 shows typical drying air behaviour in the test dryer. Air enters the dryer at point 1 and is heated to point 2. The specific humidity of the air remains constant but the enthalpy increases. Heated air is blown or drawn through the grain to point 3. During this transition, the humidity of air increases and enthalpy remains constant (adiabatic process), apart from changes due to the heat losses in the dryer. As a result of this behaviour, several key figures that describe the efficiency of the drying process can be calculated from these measurements: the amount of removed water, the amount of used heat energy in total and with respect to evaporated water, and the heat losses incurred from the drying silo.

The electricity consumed by the heaters was also measured and recorded, since this was considered to be the most reliable way to determine the energy consumption of the dryer. The electric current was measured by current clamps from one phase of the heaters because the load was symmetrical in all three phases. The grid voltage was measured simultaneously with current to enable the calculation of electric power. The grain temperatures were measured to monitor the effect of drying air temperature on the grain temperature. The measured values were actually the air temperatures of the spaces between the individual grains, which were assumed to represent the grain temperature. The sensors used in the measurements are listed in Table 2, and the layout of the measuring system is illustrated in Fig. 5.
Data was collected via an Agilent 34970 data logger (Agilent Technologies, Santa Clara, California, USA) at 15 s logging intervals. When measuring the electric grid voltage, a voltage divider was used to scale the voltage to fit the measuring range of the data logger. A data logging and monitoring application was built with Test Point software (Capital Equipment Corporation, Billerica, Massachusetts, USA). This enabled the online monitoring of the parameters of the drying process, in addition to the storage of the calculated values and the original measurement data for later analysis. Data analyses were conducted by using the Matlab R2010a software (MathWorks, Natick, Massachusetts, USA).

2.3. Experiment setup

The oats and barley used in the experiments were harvested from the fields of the research farm of Helsinki University. Two sets of trials were carried out, one on oats and the other on barley. Harvesting moisture content for both cereal species was around 22–23% (w.b.). Each drying batch was weighed before and after drying in order to measure the quantities of the removed water. The weights of individual batches of each cereal species were adjusted to be as close to each other as possible at the beginning of the process to facilitate the comparison between the treatments. Grain moisture was also measured at the beginning and at the end of the process, and also during the drying at 30 min intervals. Grain moisture measurements were taken by means of a Pfeuffer HE 50 grain moisture meter (Pfeuffer GmbH, Kitzingen, Bavaria, Germany). Each experimental set consisted of the following treatments:

1. Conventional process. Drying air temperature and airflow were kept constant during the whole drying process. Temperatures were maintained at 70 °C, which is the temperature commonly used in grain drying.
2. Elevated temperature. Settings were as for the conventional process except that the drying air temperature setting was increased to the higher level of 90 °C.
3. Airflow control. The drying airflow was reduced when the relative humidity of the exhaust air dropped below 70%. At the beginning, the temperature was 70 °C and it was allowed to rise as the airflow decreased. In the last phase, the drying air temperature was 100 °C.

2.4. Equations used in calculations

Several key values can be calculated from the humidity, temperature and airflow measurements. The calculations were made by a program in the Matlab software. Some of the most important equations used in the calculations are presented below.

The voltage signals from the humidity sensors were converted into the corresponding relative humidity readings. Specific humidity \( x, \text{kg [water] kg}^{-1} \text{ [air]} \) was calculated from temperature and relative humidity according to Eq. (4):
\[
\begin{align*}
x &= \frac{a \cdot p_w}{b(p_a - p_w)} \\
p_w &= \frac{RH}{100} p_a \\
p_s &= \frac{77.345 + 0.0057T - 7235/T}{e^{T/2}}
\end{align*}
\] (4)

where \(a\) is the molar mass of water, 18; \(b\) is the molar mass of air [29]; \(p_w\) is the partial pressure of water vapour, Pa; \(p_a\) is ambient air pressure, Pa; \(p_s\) is saturated water vapour, Pa; and \(T\) is temperature, K.

Volumetric airflow was determined using the difference in the dynamic and static pressures of the airflow measurement unit, which was measured by a differential pressure sensor. Airflow of both the intake and the exhaust air were measured, and the air leak from the top and bottom of the dryer was obtained as the difference between the intake and exhaust values. The air mass flow \(q_{m,k} \text{gh}/C_0\) was calculated by Eq. (5) thus:

\[
q_{m,k} = \rho \phi V
\] (5)

where \(\rho\) is air density, kg m\(^{-3}\); \(\phi_v\) is the volumetric airflow m\(^3\) h\(^{-1}\); \(p_a\) is ambient air pressure, Pa; \(M_a\) is air molar mass, 0.0290 kg mol\(^{-1}\); and \(R\) is the ideal gas constant, 8.3143 J mol\(^{-1}\) K\(^{-1}\).

The water evaporation rate \(D_{x,k} \text{gh}/C_0\) was calculated by obtaining the difference in specific humidity between the intake air and the exhaust air, which was multiplied by the air mass flow rate:

\[
D_{x,k} = q_{m,k}(x_{out} - x_{in})
\] (6)

where \(q_{m,k}\) is the air mass flow, kg h\(^{-1}\); \(x_{out}\) is the specific humidity of the exhaust air, kg [water] kg\(^{-1}\) [air]; and \(x_{in}\) is the specific humidity of the intake air kg [water] kg\(^{-1}\) [air].

The specific enthalpy of air \((H, k) \text{kJ kg}^{-1}\) was calculated from the air temperature and absolute humidity by Eq. (7):

\[
H = c_a m_a(T - T_0) + m_a x(l_v + c_v(T - T_0))
\] (7)

where \(c_a\) is specific heat capacity of air, 1.007 kJ kg\(^{-1}\) K\(^{-1}\); \(m_a\) is the mass of air, kg; \(T_0\) is 273.15 K; \(l_v\) is the water heat of evaporation, 2503 kJ kg\(^{-1}\); and \(c_v\) is water vapour specific heat capacity, 1.87 kJ kg\(^{-1}\) K\(^{-1}\).

The power used for heating the drying air \(P_{H,k} \text{W}\) was calculated from the change of air enthalpy multiplied by the drying airflow:

\[
P_{H,k} = \frac{(H_{amb} - H_{in})q_{m,k}}{3600}
\] (8)

where \(H_{amb}\) is the specific enthalpy of ambient air, kJ kg\(^{-1}\); and \(H_{in}\) is the specific enthalpy of the heated drying air, kJ kg\(^{-1}\).

The electric power used by the electric heaters \(P_{E,k} \text{W}\) was calculated by the product of the measured grid voltage and the current readings:

\[
P_{E,k} = \frac{3UI}{1000}
\] (9)

where \(U\) is the electric grid voltage, V; and \(I\) is the current in one phase, A.

Dryer specific energy consumption \(Q_{spec,k} \text{W h kg}^{-1}\) [water] was calculated by dividing the heating power by the water evaporation rate:

\[
Q_{spec,k} = \frac{P_{H,k}}{D_{x,k}}
\] (10)

3. Results and discussion

3.1. Airflow rates and drying air temperatures

Dryer airflow rates and drying air temperatures with different treatments are presented in Figs. 6 and 7. The airflow rate decreased towards the end of the process, as the grain
moisture content decreased. This is very typical behaviour in a recirculating batch drying process and it is a consequence of an increase in grain bulk density as it gets dryer. The airflow control is also clearly visible in both Figs. 6 and 7. Since the power was not controlled in the airflow test, the drying air temperature was allowed to rise when the airflow was reduced. Figure 7 shows also that the desired temperature was not reached in the beginning of the process. This was particularly noticeable with barley, which had higher airflow rate than oats. This was probably caused by the larger size and rounder shape of barley whole grains and therefore the higher porosity of grain bulk material. Due to the higher airflow rate, the power of the heaters was not adequate to provide the desired temperature rise at the beginning of the process.

3.2 Exhaust air humidity

Figure 8 presents the exhaust air humidity values for different drying treatments for oats and barley. One target of the airflow control was to keep the exhaust air humidity at a high level and thereby use the applied heat energy as efficiently as possible for evaporating water. When the exhaust air humidity falls, heated air and unused heat are blown directly through the dryer, which causes a decrease in dryer efficiency. In this case, the relative humidity is more suitable for monitoring the efficiency of energy use than specific humidity, because it also takes into consideration the increase in the air water binding capacity as the temperature rises. The higher the relative humidity, the smaller is the amount of unused heat energy in the exhaust air of the dryer. Specific exhaust air humidity gives a good indication of the dryer performance, but gives little information about the amount of unused heat energy and thus the energy efficiency of the dryer.

When drying oats, the change in exhaust air humidity when the airflow was reduced could be clearly seen. This occurred when the exhaust air humidity dropped to below 70% for the first time. After this airflow adjustment was made, the humidity rose rapidly before starting to fall again at about 110 min. The next airflow adjustment took place at 150 min. It slowed down the reduction of the air humidity, but did not have as significant an influence as the previous adjustment. The conventional drying at 70 °C and the elevated temperature of 90 °C had very similar behaviour compared to each other. However, the slope for the exhaust air humidity curve was steeper for the elevated temperature, as seen in Fig. 8, because the drying process proceeded more rapidly.
When drying barley, the humidity of the exhaust air generally remained at a lower level than for oats especially at the beginning of the process, even though the harvest moisture content of both cereals was of the same magnitude. Whole barley grains are considerably larger than those of oats; the weight of thousand seeds for barley was 52 g and for oats 34 g. Due to the larger size and rounder shape of the whole barley grains, the distance from the kernel core to the surface of the grain is greater for barley than for oats. According to Jayas et al. (1991), it is generally agreed that the water movement inside the grain is controlled by diffusion. Therefore, the moisture has to diffuse over a longer distance in barley grains compared to those of oats as a result of the size and shape of the grain. This in turn, leads to slower evaporation and thereby lower exhaust air humidity than for oats at the same drier setting. This phenomenon can also be seen in Fig. 2, which shows a comparison between wheat and barley. Theoretical assessments for oats cannot be made since the coefficients $n$ and $k$ in Eq. (2) do not exist in the literature.

The differences between the treatments were not as clearly visible for barley drying as they were for oats drying. The slope of the exhaust air humidity curve was a bit steeper at elevated temperatures compared to conventional process settings in barley drying (Fig. 8). This was caused by a more rapid drying at higher temperatures. With the airflow control process, the humidity of the exhaust air was slightly higher at the end of the drying period compared to conventional process, but the explicit behaviour that had occurred for oats drying could not be detected for barley.

### 3.3. Dryer specific energy consumption

The most common value used to report the energy efficiency in grain drying is the specific energy consumption per kilogram of evaporated water (kWh kg$^{-1}$). Figure 9 presents the specific heat energy consumption for different treatments and grain species as a function of drying time.

The results presented in Fig. 9 do not show any substantial differences in the dryer energy efficiency between the test members. When drying oats, the specific energy consumption at elevated temperature appeared to be at a higher level compared to the conventional process. For barley drying, the airflow control appeared to produce the highest specific energy consumption. However, in all test series the elevated temperature and the airflow control approaches shortened the drying time compared to the conventional process, and thus consumed less energy for the whole drying process.
Energy saving percentages with the elevated temperature and airflow control compared to the conventional process are shown in Fig. 11. For all drying approaches except one, the tested settings improved the energy efficiency of the dryer. The benefits of the airflow control were greater for oats than for barley, which can be explained by the faster evaporation. The larger whole grain volume of barley caused the water transfer rate from the inner parts of the grain to be slower, which inhibited the rate of evaporation. The energy saving achieved with the airflow control was 14% for oats drying but 5% for barley.

One possible explanation for the increased energy consumption for elevated temperature method of barley drying can be the higher heat losses that occurred in the drying silo. When the drying air temperature was elevated, the heat losses in the drying silo also increased because of the higher thermodynamic potential difference. If the heat energy cannot be used for evaporation due to the slow diffusion of water inside the individual barley grains, the increased heat losses may exceed the benefit obtained from using the elevated temperature method.

3.4. Process parameters in total

The total amount of water removed during the drying process can be calculated by three different ways: by determining the weights of the grain before and after drying, by determining the water removed with the airflow, or by determining the weight of grain before drying and the grain moisture before and after drying. The uncertainty in the airflow and grain moisture measurements render weighing the grain before and after drying to be the most accurate method, thus it was chosen to determine the net mass of removed water. Although drying was intended to be stopped at the same grain moisture level for each treatment, there were some differences in the final moisture content values. However, as the energy consumption was calculated per kilogram of evaporated water, this did not have an effect on the results.

Figure 10 presents the dryer specific electric energy consumption for each drying method run. These values have been calculated from the total electrical energy that was used by the heaters during the process and total masses of evaporated water that were driven off. The results showed lower specific energy consumptions for the elevated temperature and the airflow control approaches compared to the conventional process. The only exception was the result for barley, where the elevated temperature had about the same specific energy consumption as obtained for the conventional process (only 0.1 kWh kg\(^{-1}\) higher).

Grain temperature was measured at two locations inside the dryer: at the bottom of the dryer just before the outlet and at the storage cells above the drying cells. The location of the sensors is also illustrated in Fig. 5. The upper measurement reflects the mean grain temperature, because the grain was well mixed in the feeder device and in the elevator. At the bottom of the dryer there are hot zones and cool zones, since the hot air ducts are located vertically in a line. The readings of the lower sensors did not accurately reflect the mean grain temperatures because of the differential temperature zoning, and also because changes in the grain flow during the drying process.

Grain temperatures are presented in Fig. 12. In general, the grain temperatures did not rise very high. The results were very similar compared to the thermal imaging camera results reported by Mellman et al. (2011), who found that the highest grain temperatures were around 30 °C with drying air temperatures of 60 °C and 70 °C. With elevated temperature and airflow control, the highest grain temperatures were about 5–7 °C higher than for conventional drying. With airflow control, the grain temperature remained at the same level as for the conventional drying, and started to rise after the first airflow adjustment. On the other hand, grain should have been able to withstand higher temperatures in the latter phase of the process, when some drying had already occurred.

Figure 13 presents the grain temperatures as a function of grain moisture. The grain temperature for oats was only slightly higher with the elevated drying air temperature compared to conventional drying. In the airflow control method the grain temperatures did not rise above the value of conventional drying until close to the end of the process, by which time the grain moisture had declined to 16%. The grain temperatures for elevated drying temperature and airflow control in barley drying were very close to each other, and were higher than for conventional drying throughout the whole process. Grain temperatures in barley drying were
generally higher compared to those for oats, which is a result of the slower drying rate, as less energy was used for evaporation.

3.6. Germination rate

The germination rate of each test treatment was determined after the drying run to examine the effect of elevated temperature and airflow control on the viability of grains. Germination tests were conducted by the grain laboratory of the Finnish food safety authority, Evira according to the ISTA standard procedures. Results of the germination tests are presented in Table 3.

The presence of harvest and disease damages complicated the analysis, and it was difficult to differentiate between damage associated with these effects from those caused by drying. Some degradation in viability of seeds occurred with oats especially for the airflow control process (Table 3). This was probably caused by the high temperatures in the latter part of the drying process. On the other hand, the proportion of dead seeds of oats was slightly lower for the airflow control compared to the other tested methods. With barley the different treatments did not affect the viability, in fact the highest germination rate was observed with the airflow control method. This may be a consequence of the greater grain size of barley, which is associated with the longer time it takes for the whole individual grains of barley to warm up, or simply to an unidentified, but inherent, difference in the temperature tolerance between different cereal species and varieties.

<table>
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<th>Cereal species</th>
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<th>Normal</th>
<th>Incompletely germinated</th>
<th>Dead</th>
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<td>Oats</td>
<td>Conventional</td>
<td>73%</td>
<td>11%</td>
<td>16%</td>
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<td>Elevated temp.</td>
<td>70%</td>
<td>14%</td>
<td>16%</td>
</tr>
<tr>
<td>Oats</td>
<td>Airflow control</td>
<td>65%</td>
<td>22%</td>
<td>13%</td>
</tr>
<tr>
<td>Barley</td>
<td>Conventional</td>
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<td>11%</td>
<td>12%</td>
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<tr>
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<td>Elevated temp.</td>
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<td>13%</td>
<td>13%</td>
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<td>Barley</td>
<td>Airflow control</td>
<td>80%</td>
<td>8%</td>
<td>12%</td>
</tr>
</tbody>
</table>
3.7. Drying time

Under practical on-farm conditions the performance of the grain dryer is at least as important as the energy efficiency. In temperate countries, the grain drying step is often a bottleneck in the harvest processing chain, and therefore the drying time has to be as short as possible. Figure 14 presents the mean evaporation rates of each tested method, which gives a good indication of the drying speeds of tested drying methods. These figures are calculated from the total mass of removed water over the drying process divided by the drying time for that process. The fastest evaporation rates for both cereal species was achieved with the elevated temperature method. The evaporation rate for oats was 24% faster with the elevated temperature approach and 17% faster with the airflow control method. The corresponding figures for barley were 16% and 5%, respectively.

4. Conclusions

The results indicated that controlling the temperature and airflow during the drying process in a mixed-flow batch grain dryer has the potential for improving both the energy efficiency and performance of the dryer. The energy savings achieved with the airflow control were 5% for barley drying and 14% for oats. Moreover, improvements in the evaporation rates were 5% and 17%, for barley and oats respectively. The advantages of the airflow control system depend on the type of cereal dried. In this study, only oats and barley were tested. It would be interesting to determine the behaviour of other grains.

The advantage of the airflow control was greater when drying oats compared to barley. This probably resulted from the larger individual grain size and rounder shape of barley, which predisposes barley grains to a longer moisture diffusion times and thus lower evaporation rates. High temperatures in the latter part of the airflow control process caused some degradation in the viability of oats. No drying damages were observed for barley, even though the grain temperatures were generally higher during barley drying.

A control system that uses the drying air temperature, exhaust air humidity and grain temperatures as control factors for setting the drying airflow would be technically straightforward and cheap to install into new dryers, or even as a retrofit in those dryers already in use. With this kind of control system, drying process parameters, such as drying air temperature and airflow, could be optimised for each cereal species, according to a combination of the moisture content and the moisture release rate of the grain. This would also enable the choice of the drying mode according to the end-use purpose of the grain.

More information is needed about the temperature tolerance of different cereal species and varieties at different moisture contents. Moreover, the differences in the water diffusion rates inside the individual whole grains between different cereal species must be taken into account when designing the control system. The correct control parameters should be resolved to automate the control system. Another option would be to use a model-based drying control for a particular cereal species and initial moisture content as input data.

**Fig. 14** – The mean evaporation rates over the drying process for different dryer settings for oats and barley.

**REFERENCES**


