Agronomy Research **13**(1), 89–94, 2015

Continuous airflow rate control in a recirculating batch grain dryer

T. Jokiniemi*, T. Oksanen and J. Ahokas

University of Helsinki, Faculty of Agriculture and Forestry, Department of Agricultural Sciences, P.O. Box 28, 00014, University of Helsinki, Finland; *Correspondence: tapani.jokiniemi@helsinki.fi

Abstract. As the energy efficiency requirements in agriculture increase, offers grain drying opportunities for substantial energy saving. Earlier work indicated that energy savings in grain drying can be achieved by controlling the drying airflow rate during the drying process. Aim of this study was to design an embedded control system, based on microcontroller, for continuous airflow rate control in a recirculating batch grain dryer, and to test it in a scaled-down research dryer. The control system proved to be working as designed, reducing the dryer airflow rate smoothly towards the end of the process. However, additional research of the energy efficiency and performance of the dryer using the airflow rate control is needed.

Key words: grain drying, grain dryer, energy efficiency, airflow rate control, drying air temperature.

INTRODUCTION

Grain drying is one of the largest energy inputs in arable farming in boreal and northern temperate climate zone countries (Mikkola & Ahokas, 2009). Considering the ever increasing energy efficiency requirements in agriculture, provides grain drying, and grain preservation in general, opportunities for substantial energy savings. Previous work of the authors indicated that controlling the airflow rate and drying air temperature during the drying process has potential to improve both the energy efficiency and the performance of the dryer (Jokiniemi & Ahokas, 2014). The energy savings were achieved by decreasing the dryer airflow rate towards the end of the process and elevating the drying air temperature concurrently. The energy savings were based on two factors: 1) using higher drying air temperature and 2) obtaining higher exhaust air humidity in the latter part of the drying process.

The effect of the elevated drying air temperature on the energy efficiency of the dryer has been reported by several authors (Morey, Cloud & Lueschen, 1976; Suomi et al., 2003). This is a consequence of the nonlinearity in the moist air equilibrium equations; the same amount of added heat energy increases the water binding capacity of air more in higher temperatures, as Fig. 1 indicates. Additionally, the elevated drying air temperature creates a greater pressure gradient of water vapor between the core and the surface of the whole grains, which enhances the water movement inside the grain and hence also the evaporation.

In addition to the drying air temperature, the humidity of the exhaust air has a significant effect on the energy efficiency of a dryer, as shown by Fig. 1. While the heating power of the dryer remains usually constant, the relative humidity of exhaust air indicates directly the efficiency of evaporation. When the exhaust air humidity is high, the majority of the applied heat energy appears as latent heat in the exhaust air, and the exhaust air temperature is typically low. When the relative humidity of the exhaust air is low, the applied heat appears as sensible heat. It is not thus used for evaporation, but it is lost with the exhaust air. In this case the exhaust air temperature is relatively high and the specific energy consumption in drying is high. When the airflow rate is reduced, the moisture in the grain has more time to diffuse to the surface of individual whole grains. Higher exhaust air relative humidity is thus obtained, leading to lower energy consumption in drying. The effect of the airflow rate on the energy consumption in grain drying has also been recognized by several authors in past. For example Morey et al. (1976) and Peltola (1988) suggested airflow rate control as one possible approach for reducing the energy consumption in grain drying.

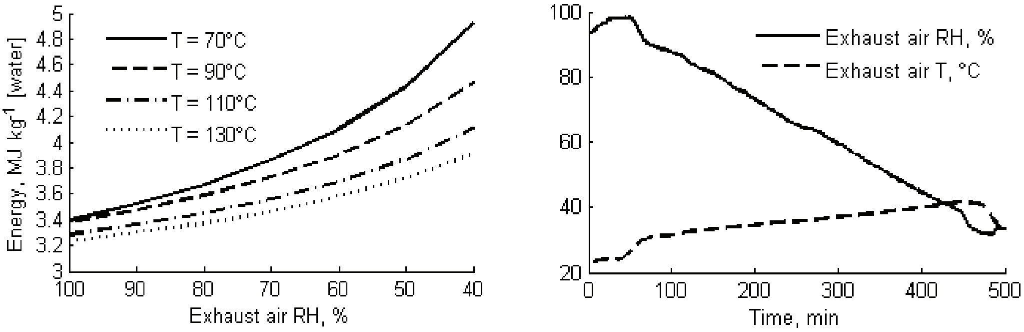

Figure. 1. The effect of drying air temperature *T* and exhaust air relative humidity *RH* on the energy consumption of adiabatic drying process (on the left) and typical exhaust air properties in practical grain dryer (on the right).

Another requirement for the control of grain dryer is to maintain the quality properties of grain, such as germination ability and baking qualities. Previous studies have proved that using high drying air temperature may severely damage these properties, but this vulnerability is also strongly affected by the moisture content of the grain. The grain can tolerate higher temperatures when its moisture content is reduced (Ghaly & Taylor, 1982; Ambardekar & Siebenmorgen, 2012). Therefore it is reasonable to assume that the grain is not so sensitive to heat damage in the latter part of the drying process, when some drying has already occurred, and the drying air temperature can be increased gradually. This is also a beneficial approach considering the energy use, since the dryer exhaust air humidity is inherently high in the beginning of drying, leading to efficient energy use, and begins to decrease towards the end of the process (Jokiniemi & Ahokas, 2014). The benefits of the reduced airflow rate and elevated drying air temperature, considering the energy use, are thus essential in the latter part of the process, which can also be concluded from the Fig. 1.

In the previous work of the authors, the airflow control was conducted by manual control of the speed of the drying air fans when the exhaust air humidity had decreased under a certain level. It was concluded that an automatic control system, which utilizes the exhaust air humidity and temperature information as control factors, would be relatively simple and easy to implement in new or existing grain dryers. (Jokiniemi & Ahokas, 2014) Aim of this work was to build a simple microcontroller based embedded control system for the continuous airflow control in a recirculating batch grain dryer, and test it in a scaled-down research dryer.

MATERIALS AND METHODS

The study was conducted in a scaled-down research dryer at the research farm of the University of Helsinki. A measuring system for observing the essential process variables, such as air temperatures and humidities as well as the air flow rate, was installed into the dryer. A detailed description of the research dryer and the measurement system, including the used sensors and data acquisition, can be found in the previous work of the authors (Jokiniemi & Ahokas, 2014). The measuring system enabled the calculation of the essential process parameters, such as the amount of removed water and energy use in a point in time, as well as during the entire process in total. The amount of removed water was calculated from the changes in the air humidity, while it passed through the grain, and the air flow rate. The heat power was calculated from the changes in the enthalpy of the dryer supply air before and after the heaters, and the air flow rate. Energy consumption was calculated by multiplying the heat power with the measuring interval, and total energy consumption during each test run was received by summing the energy consumptions recorded for all of the measuring intervals.

The airflow rate in the research dryer was controlled by a frequency converter, which was used to control the speed of the drying air fans. The frequency converter could be controlled either manually from the control panel, or by using a 0–10 V external control signal. The 0–10 V input was used to supply the control signal from the microcontroller to the frequency converter.

The airflow rate controller was based on an Arduino Mega 2560 microcontroller development board. A simple setup of two Honeywell HIH-4000 humidity sensors and one LM35 temperature sensor was configured to the Arduino board, and a pulse width modulation (PWM) signal from the microcontroller was used as the control signal to the frequency converter. A control algorithm to generate the PWM-signal on the basis of the voltage readings from the humidity sensors was written in C-language and uploaded to the microcontroller. While the voltage range expressed by the PWM-signal from the microcontroller digital pins was 0–5 V, a power transistor circuit was built to repeat the PWM-signal with a higher voltage level. A supply voltage of 12V was used, and suitable coefficients in the microcontroller program were used to scale the control signal to the correct range for the frequency converter.

The aim of the control algorithm was to decrease the speed of the drying air fans smoothly when the humidity of the exhaust air started to decrease. The control rules were defined by Eq. (1):

$$u_{RH}(t) = u_{init} - (RH_{limit} - RH(t)\,) \cdot K \tag{1}$$

where: u_{RH} controller output; u_{init} = constant term; RH_{limit} = controller threshold RH; RH = measured RH; K = controller gain.

The threshold value RH_{limit} for the RH of the exhaust air was set to 90%, i.e. the controller became active when the RH of the exhaust air reduced below this level. The constant term u_{init} was the desired control value in the beginning of the drying process. The control algorithm was thus almost equal to the conventional P-controller. However, due to the nature of the process, the RH of the exhaust air decreases inevitably towards the end of the process, and the control algorithm will thus end up reducing the output while the process proceeds. Additional conditional expression was added to the microcontroller program to ensure that the control output u_{RH} did not exceed the constant term value u_{init} in the beginning of the process, when the RH was greater than 90%.

The drying air temperature was adjusted manually to 65 °C in the beginning of the drying process, and it was allowed to rise freely as the airflow was decreased. However, an upper limit of 90 °C was defined for the drying air temperature to avoid heat damage to the grain. The microcontroller program compared the temperature of the drying air to the upper temperature limit threshold value, and when it was reached, the temperature control rule became active:

$$u_T(t) = u_{RH}(t) - (T(t) - T_{limit}) \cdot K \tag{2}$$

where: u_T = controller output; u_{RH} = output from the RH controller; T = measured drying air temperature; T_{limit} = controller threshold temperature; K = controller gain.

The controller gain value K for both controllers was defined in the first test runs. The K values used in the final setup were 1 for the RH-controller and 5 for the temperature controller. The aim for the RH-controller was to decrease the airflow smoothly in such a way that the upper temperature limit was not reached until close to the end of the process. For the temperature controller the aim was to react quickly when the temperature limit was reached, but to avoid the excessive fluctuation of the controller output caused by too high gain value.

Control system was tested in drying trials in the scaled-down research dryer. Altogether eight drying trials were accomplished: four with the airflow rate control system and four references without it. The airflow rate in the reference trials was equal to the initial airflow rate in the control system trials. The grain used in the trials was barley with the initial moisture content of ca. 20% (wet mass basis). The drying process was ended when the moisture content of the barley had decreased to ca. 13.5% in each trial.

RESULTS AND DISCUSSION

Fig. 2 presents the operation of the controller during the drying process. In the beginning of the process the exhaust air humidity was high, and the initial set point for the controller output was used. When the decreasing exhaust air RH reached the threshold value of 90%, the controller started working. The controller operated as designed, reducing smoothly the airflow rate and increasing drying air temperature simultaneously. When the maximum drying air temperature limit was reached at 90 °C, the temperature controller in Eq. (2) became active, starting to increase the airflow. Some oscillation occurred in the control signal value in the end of the process, when the two control algorithms were alternating. This did not, however, have any significant practical effect on the drying air temperature or the airflow rate.

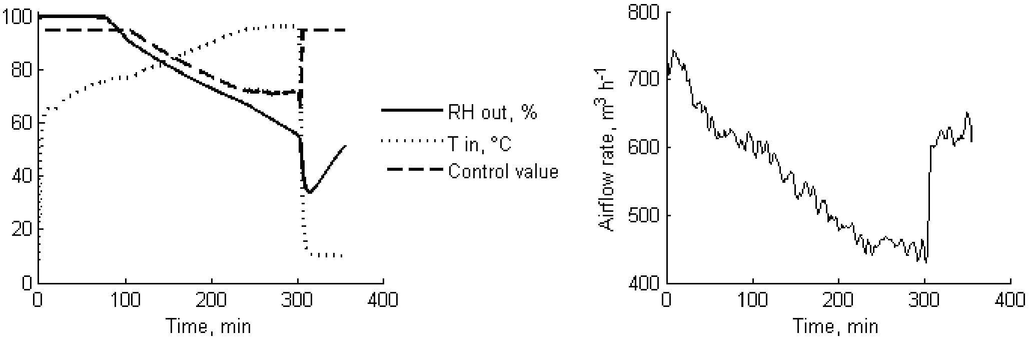

Figure 2. Dryer exhaust air humidity, control signal value and the effect of the control system on the drying air temperature (on the left) and dryer airflow rate (on the right).

Fig. 3 presents the specific energy consumption and the evaporation rate in each trial member. The results do not indicate a clear advantage for the airflow rate control considering the energy efficiency. The average energy consumption was 10% lower with the controller, compared to the conventional drying. However, the coefficient of variation for specific energy consumption in the airflow rate control trials was 17%, while the corresponding figure in the conventional process trials was only 9%.

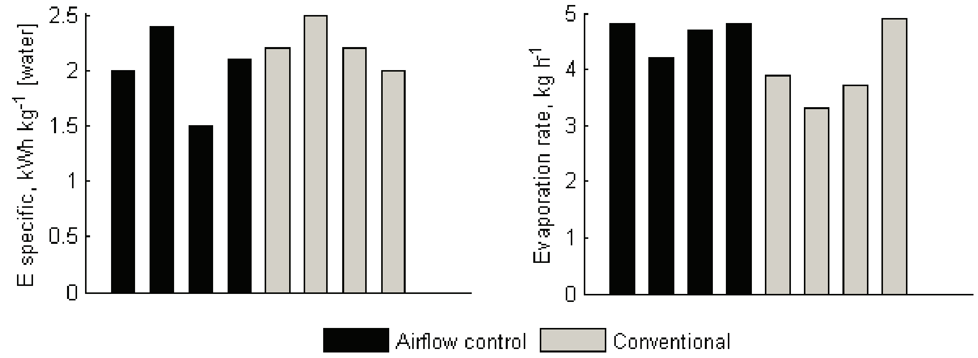

Figure 3. Average specific energy consumption and evaporation rates in each trial with airflow rate control and conventional drying without airflow rate control.

The relatively large variation in the airflow rate control trials is explained mainly by the third test run, which had an exceptionally low energy consumption compared to the other trials in the Fig. 3. This may be a consequence of a possible measurement error in this trial.

The evaporation rate for the airflow rate control trials was in average 15% higher compared to the conventional process, which indicates that the airflow rate control could be used to enhance also the performance of the dryer. However, the variation was large also here, and the last trial in the conventional process showed an exceptionally high evaporation rate compared to the others.

CONCLUSIONS

The simple microcontroller based control system for controlling the drying airflow rate in a recirculating batch grain dryer operated as designed, reducing smoothly the airflow rate towards the end of the drying process. The results indicated that the control system enhanced both the energy efficiency and the performance of the dryer, but the variation in the results was also large. The simple and inexpensive control system could be easily installed in most of the dryers. In the current study the airflow rate was controlled by adjusting the speed of the drying air fans by a frequency converter, but a choke valve in the dryer supply air intake pipe could be used as well. The exhaust air temperature information could be used as a control input, instead of relative humidity, as there is a strong inverse correlation between the exhaust air humidity and temperature. Replacing the sensitive humidity sensors by robust temperature sensors would improve the reliability of the system considerably. However, further research about the effect of the control system on the energy efficiency and performance of the dryer is needed prior to the commercial applications.

ACKNOWLEDGEMENTS. This study was funded by the foundation of Marjatta and Eino Kolli.

REFERENCES

Ambardekar, A.A. & Siebenmorgen, T.J. 2012. Effects of postharvest elevated-temperature exposure on rice quality and functionality. *Cereal Chemistry* **89**(2), 109–116.

Ghaly, T.F. & Taylor, P.A. 1982. Quality effects of heat treatment of two wheat varieties. *Journal of agricultural engineering research* **27**, 227–234.

Jokiniemi, H.T. & Ahokas, J.M. 2014. Drying process optimisation in a mixed flow batch grain dryer. *Biosystems engineering* **121**, 209–220.

Mikkola, H. & Ahokas, J. 2009. Energy ratios in Finnish agricultural production. *Agricultural and food science* **18**, 332–346.

Morey, R.V., Cloud, H.A., & Lueschen, W.E. 1976. Practices for the efficient utilization of energy for drying corn. *Transactions of the ASAE* **19**, 151–155.

Peltola, A. 1988. Viljankuivurin säätö kuivauksen aikana – hyödyksi vai hienostelua? *Työtehoseuran maataloustiedote*, **355**, 8 pp. (in Finnish)

Suomi, P., Lötjonen, T., Mikkola, H., Kirkkari, A.-M. & Palva, R. (2003). Viljan korjuu ja varastointi laajenevalla viljatilalla. *Maa- ja elintarviketalous* **31**, 100 pp. (in Finnish)