Effect of heat insulation on the energy consumption of recirculating mixed-flow batch grain dryer

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Abstract: The effects of heat insulation on the energy consumption and efficiency of a recirculating mixed-flow type grain dryer were examined. Energy saving potential was estimated by theoretical calculations and by heat flow measurements. Actual energy consumption was measured in two identical drying silos, only one of which was insulated. The measurements were conducted in farm-scale dryers under practical farm working conditions. Theoretical heat loss calculations and the heat flow measurements predicted an energy saving potential of ca. 5%–9% of the dryer heating energy. However, the actual energy consumption measurements over three years indicated energy savings of 16%–21% for the insulated dryer compared to its uninsulated counterpart, when energy consumption per kilogram of evaporated water was considered. It was concluded that the heat insulation eliminates the majority of heat losses in the dryer and enhances the evaporation of water, thereby improving the overall efficiency of the dryer.

Keywords: grain drying, grain dryer, energy consumption, efficiency, heat losses, heat insulation

Citation: Jokiniemi, T., and J. Ahokas. 2014. Effect of heat insulation on the energy consumption of recirculating mixed-flow batch grain dryer. Agric Eng Int: CIGR Journal, 16(3): 205−213.

1 Introduction

Grain drying is one of the highest energy consuming operations in agricultural crop production in boreal and northern temperate climate zone countries. Depending on the harvest-time weather conditions, it may consume as much energy as that for all the other field operations for cereal production combined (Mikkola and Ahokas, 2009). The energy for grain drying usually comes from fossil fuel sources, typically from light fuel oil. Energy efficiency requirements in agriculture are continually being improved, thus the grain drying operation offers the potential for making substantial energy savings for cereal production. In Finland an energy saving of 10% in grain drying would account for ca. 150 TJ per year, which equals that of the annual heating energy demand of more than 4,400 typical Finnish dwelling houses. This figure was derived by assuming a mean harvest moisture of grains of 20.2% (Sieviläinen, 2008), a drying energy consumption of 6 MJ per kg water evaporated (Suomi et al., 2003), a mean grain yield in the 2002–2012 period of 3.8 billion kg at 14% storage moisture (Tike, 2012), and a heating energy consumption for an average dwelling house of 10,000 kWh/yr.

Energy savings in grain drying, and in grain preservation can be achieved in several ways. The most obvious way is to preserve grain by some other means than drying. Micro-organisms that spoil the grain need suitable conditions to grow and reproduce, e.g. moisture, temperature, pH-level and oxygen supply (Loewer et al., 1994). Altering one or more of these factors will suppress the activity of the harmful micro-organisms. Many grain preservation methods that do not involve drying also prevent the respiration of the grain, which terminates the grain vital functions. This is acceptable when the maintenance of the viability of the grain is unnecessary, for example when the grain is used as

Received date: 2014-05-28 **Accepted date:** 2014-08-19
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animal feed (Hall et al., 1974). However, grain-drying has sustained its popularity due to the flexibility, proven technology and reliability of the method. Hot air drying is used for some 85%–90% of the harvested grain yield in Finland annually (Palva et al., 2005), although almost 70% of the Finnish domestic grain consumption is as animal feed (Tike, 2013).

Several energy saving approaches to hot air drying can also be found. The most substantial savings could be achieved by heat recovery from the dryer exhaust air, but problems are caused by the complicated technical solutions that would be needed, in addition to problems caused by dust and the high moisture content of the dryer exhaust air. The relatively short operating season together with high capital costs also act as limitations on the implementation of heat recovery systems in grain drying (Lai and Foster, 1977; Wang and Chang, 2001). Another approach for energy savings is by using higher drying air temperatures (Ahokas and Koivisto, 1981; Morey et al., 1976). In this case the viability of the seeds may be compromised, and an accurate process control system would be required when drying grain for uses such as malting, whereby the ability of grain to germinate is essential (Jokiniemi and Ahokas, 2014).

A simple and inexpensive way to save energy in hot air grain drying is to provide heat insulation for the drying silo and also for the drying air ducts between the furnace and the silo. Insulation should eliminate a major part of the heat losses that occur from the hot metal surfaces of the dryer. An advantage of the reduced heat losses is that more heat energy is made available for the evaporation of water from the grain, which should lead to an improvement in overall energy efficiency of the dryer. Despite the simplicity of the method, there are as yet only a few extant scientific studies about the effects of insulating grain dryers. In one such study, Piltti (1979) reported an energy saving of ca. 10% with an insulated dryer compared to its uninsulated counterpart. A more recent study by Grube (2011) reported an energy saving of 8% for cereal grain and up to 20% for maize grain by insulating the dryer. Energy use and energy efficiency have taken an essential and important position in national and EU-level policy, and there is a demand to recruit and update this information.

The aim of this study was to investigate the improvements in grain dryer energy efficiency and performance achieved by heat insulation. Theoretical analyses were made to evaluate potential heat losses in the dryer based on the measured surface temperatures of the dryer parts. Heat flows were also measured using a heat flux sensor. Finally, the effect of heat insulation was verified by comparing the energy consumption of the insulated grain dryer with that of an uninsulated grain dryer with identical design and installation during normal harvest seasons. All measurements were conducted under practical farming conditions in a full scale grain dryer, and thus the results of the study can be directly applied to practical cereal farming in a northern country.

2 Materials and methods

A grain dryer that was installed in the Helsinki University research farm was used for all measurements and theoretical analyses. The dryer was a full scale farm dryer and it was used in a normal way to dry the harvest of the research farm during the research. The dryer had two identical drying silos, which offered a good opportunity to examine the effects of the heat insulation, as one of the drying silos was insulated while the other remained uninsulated. The model of the drying silos was Antti Agrosec 43MF2, and they were manufactured by a Finnish company Antti-Teollisuus Oy. The drying silos were mixed-flow recirculating batch dryers with an effective volume of 16.6 m^3 each. They consisted of four drying cells and three storage cells, which also served as tempering space in the recirculating drying process. Each drying cell had two sets of horizontally placed inlet- and outlet air ducts, as illustrated in Figure 1. The inlet and outlet ends were uniform vertical spaces that allowed the drying air to distribute and freely flow into the air ducts. Each silo was fitted with its individual natural gas fuelled furnace. The furnaces were equipped with sliding two stage capacity regulation burners, which enabled the adjustment of furnace heat output according to the desired drying air temperature. The drying silos were placed inside a building constructed of wood.

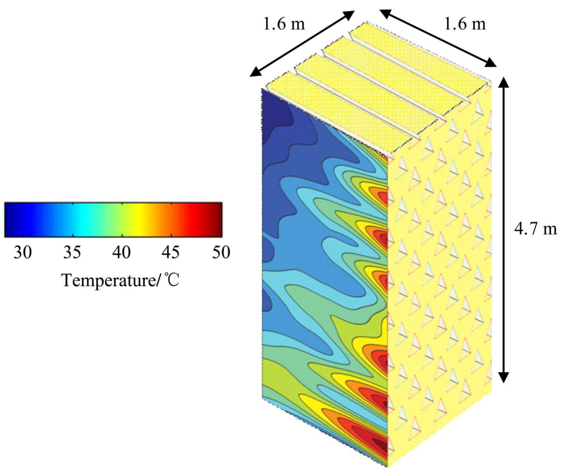

Figure 1 Surface temperature distribution of the drying silo. Air ducts with red border are the drying air inlets and the ducts with blue border are the air outlets

2.1 Theoretical heat losses

The structures of the dryers were thin, 1.5–2 mm metal sheets, thus they warm up quickly and work as effective heat conductors. Figure 1 illustrates the distribution of the surface temperatures as visualized by thermal imaging cameras on the side of a mixed-flow type drying silo. The drying air temperature was 75°C. The location of the half air ducts in the side of the silo can be clearly seen as warmer areas. The half air ducts, which are attached directly to the side walls of the drying silo, are usually used as air inlets rather than outlets, to prevent the condensation of water inside the dryer walls. Therefore, the hot drying air is in direct contact with the drying silo outer wall. Furthermore, the higher temperatures occur close to the inlet end of the dryer compared to the outlet end, which indicates that most of the hot drying air enters the grain at the beginning of the air ducts. Figure 1 also shows that temperatures are higher in the lower part of the dryer. The incoming drying air pipe is attached perpendicular to the bottom of the dryer inlet end, and more air enters the drying silo air ducts in the lower part of the dryer due to the kinetic energy of air.

The convection heat rate can be evaluated theoretically by the empirical convection equations derived by several authors. Incropera et al. (2007) presented equations for calculating the free convection heat flows for different geometrical surfaces. In a typical batch type grain dryer, the major heat losses occur on the vertical plates of the drying silo and on the cylindrical surface of the drying air inlet pipe. The heat losses should be calculated separately for each temperature zone shown in Figure 1 to obtain accurate results. However, this complicates the calculation considerably, since the air velocity in the boundary layer would be different for each zone due to the different surface temperatures. A good practical estimation can be obtained by using the mean temperature for the whole surface. Another assumption is that the room air is quiescent, which is satisfactory since grain dryers are usually located in enclosed buildings.

Surface temperatures for calculating the heat losses were obtained by measuring thermal camera images, which were taken during the steady state of the drying process. Only one set of images were analysed, as no great differences in the drying silo surface temperatures were assumed to occur when the drying air temperature was kept constant. Heat convection on the vertical plates of the drying silo was calculated by Equation (1), Equation (2), Equation (3) and Equation (4):

$$q = \bar{h} A_s (T_s - T_\infty) \tag{1}$$

where, q=heat flow, W; h = convection heat transfer coefficient, W/(m^2 K); A_s= surface area, m^2; T_s= surface temperature, °C; T_∞= quiescent air temperature, °C.

$$\bar{h} = \frac{\overline{Nu_L} \cdot k}{L} \tag{2}$$

where, Nu = Nusselt number, dimensionless; k = gas and temperature dependent coefficient, 26.3×10^{-3} W/(m K); L = height of the plate, m.

$$\overline{Nu_L} = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (0.492/\mathrm{Pr})^{9/16}]^{8/27}} \right\}^2 \tag{3}$$

where, Ra = Rayleigh number, dimensionless; Pr = Prandtl number, gas and temperature dependent coefficient, 0.707.

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\alpha v} \tag{4}$$

where, g = gravimetric acceleration, 9.81 m/s^2; β= (T_s+ T_∞)/2 [K^{-1}]; α = gas and temperature dependent coefficient, 22.5×10^{-6} m^2/s; v = gas and temperature dependent coefficient, 15.89×10^{-6} m^2/s.

Heat convection on the cylindrical surface of the incoming drying air pipe can be consistently calculated for the vertical plates, but the height of the vertical plate L is replaced by the diameter D of the pipe. The Nusselt number is then calculated using the equation suggested by Churchill and Chu (1975) as reported by Incropera et al. (2007) (Equation (5)):

$$\overline{Nu} = \left\{0.60 + \frac{0.387 Ra_D^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\right\}^2 \qquad (5)$$

Heat losses due to radiation emissions were evaluated using Equation (6). A total emissivity coefficient of 0.28 was suggested for new galvanized steel sheet (Fluke, 2009). The emissivity of galvanized steel increases as the material ages, hence the estimated emissivity value of 0.4 was used in calculations.

$$E = \varepsilon\sigma(T_s^4 - T_{sur}^4) \qquad (6)$$

where, E = radiation energy, W; ε = emissivity coefficient, 0.4; σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4); T_s = surface temperature, K; T_{sur} = temperature of surrounding surfaces, 288 K.

Only the sides of the drying silos, the inlet end and the incoming drying air pipe from the furnace were considered in the theoretical heat loss analysis. The outlet end and outlet air pipe were ignored since the air had already travelled through the grain at this point and was about to exit the dryer. The storage cells were also ignored, because they are not in direct contact with the hot drying air. Dimensions and surface temperatures used in the calculations are presented in Table 1.

Table 1 Dimensions and surface temperatures of the dryer components

Dryer component	Height L or diameter D, m	Area A, m^2	Mean surface temperature T_S, K
Sides of the silo	4.72	17.46	313.8
Inlet end	4.72	7.55	320.0
Drying air pipe	0.63	17.81	327.8

Notwithstanding the evaporation and heat losses, part of the applied heat energy was used in heating the grain inside the dryer and the metal structures of the dryer. Heat energy absorbed by the structures and especially by the grain can be substantial since the masses are large. This heat energy is considered to be a heat loss during the drying period, because it is not used for evaporation. However, it will be partially recovered during the cooling period, when some residual evaporation of moisture from grain still occurs as the whole mass cools. Energy needed for heating the grain and the dryer structures was calculated using Equation (7):

$$Q = cm\Delta T \qquad (7)$$

where, Q = heat energy, kJ; c = specific heat capacity of material, kJ/(kg K) (for steel 0.42 kJ/(kg K)); m = mass, kg; ΔT = temperature difference, K.

Heat capacity of grain for Equation (7) was obtained by combining the heat capacities of the grain dry matter with the heat capacity of water (Equation (8)):

$$c = c_g(1-w) + c_w w \qquad (8)$$

where, c = heat capacity of moist grain, kJ/(kg K); c_g= specific heat capacity of grain dry matter, 1.54 kJ/(kg K); c_w= specific heat capacity of water, 4.19 kJ/(kg K); w = moisture content of grain, decimal (wet mass basis, w.b.).

2.2 Heat flow measurements

Heat flows from the walls of the drying silo and the drying air pipe were measured during the drying process, when the dryer had reached a steady state during operation. The measurements were conducted using Ahlborn FQ A017 C heat flux sensors and Ahlborn ALMEMO 2490 measurement instrument. Accuracy of the sensor according to the manufacturer was 5%. The measurement matrix is presented in Figure 2.

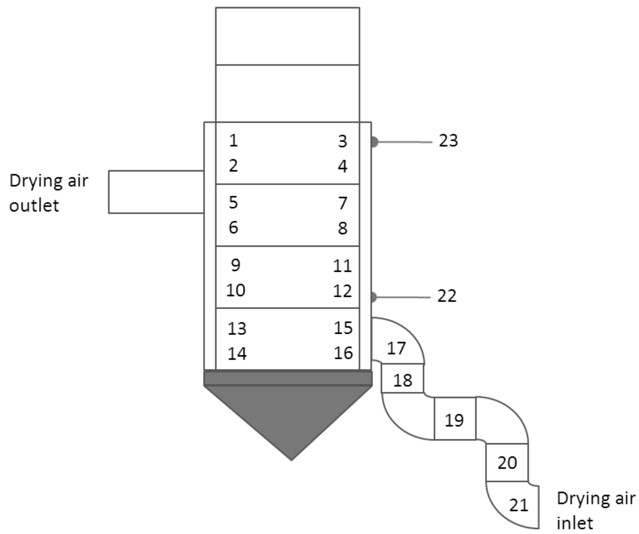

Figure 2 Heat flow measurement setup

As the location of the drying air ducts can be recognized clearly as warmer zones in the drying silo (Figure 1), the heat flow was measured at the locations of the air ducts and also in between them. Total heat flow was calculated by multiplying the surface area of the drying silo by the mean of the measured heat flux values. Heat flows for the inlet end and the drying air pipe were calculated consistently with the drying silo. The dryer outlet end and the storage cells were ignored.

2.3 Energy consumption of insulated vs. uninsulated dryers

Heat insulation was installed on one of the drying silos of the Helsinki University research farm grain dryer in the summer of 2011 (Figure 3). The inlet end and the sides of the silo were insulated, as was the inlet air pipe that led from the furnace. The outlet end, exhaust air ducts and the storage cells on top of the drying cells were not insulated. Insulation material for the drying silo was 50 mm aluminium coated rockwool sheeting (heat conductivity 0.037 W/(m K)) and for the inlet air pipe 80 mm wired rockwool matting (heat conductivity 0.036 W/(m K)). The furnaces of both drying silos were equipped with individual gas meters and the drying silos were positioned so that they were standing on scales.

Figure 3 Heat insulation of the drying silo and the incoming drying air pipe

The grain moisture was measured at the beginning and at the end of the drying process by a precision grain moisture meter (Pfeuffer HE 50) to determine the loss of moisture by difference. The accuracy of the scales installed beneath the dryers was insufficient to determine the mass of removed water directly by the change in the weight of the grain batch. The mass of removed water was thus calculated by Equation (9) from the initial weight of the grain batch and the grain moisture at the beginning and at the end of drying:

$$m_w = m_g \frac{w_i - w_f}{1 - w_f} \tag{9}$$

where, m_w = mass of removed water, kg; m_g = mass of grain at initial moisture, kg; w_i = initial moisture of grain, decimal (w.b.); w_f = final moisture of grain after drying, decimal (w.b.).

A measuring system for continuous monitoring of the drying process was also installed in both drying silos. Gas meter readings were recorded at the beginning and at the end of each drying batch, which gave us the total amount of used energy, whereas the continuous measurement system also enabled the monitoring of the drying process over time. The measured variables were temperatures and relative humidities (RH) of ambient air and dryer exhaust air, temperature of the heated drying air and the air flow rate. The grain temperatures in the bottom of the dryer were also measured. Several key metrics were calculated from the measurements, such as enthalpies of the air, heat energy used by the dryer, heat losses, the quantity of removed water and the specific energy consumption of the evaporation process. It must be noted that the drying air temperature was measured just before the air entered the drying silo, and therefore the heat losses in the drying air pipe from furnace to drying silo were ignored by the continuous measuring system.

Temperatures were measured by Pt100 resistance sensors and the RHs of air were measured by a Honeywell HIH-4000 humidity sensor. Air flow was measured by a Halton MSD 630 air flow measurement unit installed on the uninsulated drying silo. The insulated silo was equipped with a pitot tube that averaged the airflow and was comparable to the Halton unit. The function of both air flow measuring units was verified by a manual pitot tube measurement. The pressure difference in both air flow measurement units was measured by Sensirion SDP1000-L05 differential pressure sensors. All sensor data were collected by an HP Agilent 34970 data acquisition unit and saved in a laptop PC for subsequent analysis.

While the drying air temperature was kept constant, the ambient air temperature had a remarkable effect on the energy consumption of drying. Therefore the measured energy consumption was standardized to match a certain temperature and relative humidity of the ambient air. The selected figures were 15°C temperature and 85% RH, which represent typical drying season weather conditions of the region. The difference in the air enthalpy between the measured ambient and standardised conditions was calculated for each drying batch, and it was converted into energy by using the measured drying air flow. This was then added to, or subtracted from, the measured energy consumption of each drying batch. Thus, the variation caused by the ambient temperature was removed from the results by using this procedure.

3 Results and discussion

3.1 Theoretical heat losses and measured heat flows

Theoretical and measured heat losses are presented in Table 2. It was assumed that the surrounding air was quiescent, apart from the vertical flow caused by the warm surfaces. However, some of the air movements in the building that were not considered are possible, e.g. air movements created by open doors, ventilation ducts or other openings. These sources could cause the actual convection rate to be higher than calculated. The uneven temperature distribution on the sides of the drying silo may also cause some turbulence to the vertical air flow, which would lead to an increase in the Nusselt number and thus an increase in the convection heat transfer coefficient. Therefore a sensitivity analysis was carried out, where the surface temperature T_S and heat transfer coefficient h were increased by 20% and the quiescent air temperature T_∞ and the temperature of the outer walls T_{sur} were decreased by 5°C. The effect of changing these variables was relatively large, as indicated by the data in Table 2. The mean heating power of the uninsulated dryer during the drying process was ca. 157 kW. Therefore the heat losses shown in Table 2 represented ca. 5%–9% of that heating energy. This should give the expected order of magnitude of the achievable energy savings for the heat insulation and the studied dryer type.

According to Table 2, ca. 50% or even more of the heat losses occurred from the drying air pipe that leads from the furnace to the drying silo. The air in the pipe is furnace-hot and at 630 mm the pipe diameter in these dryers is quite large, therefore the total heat flow from the pipe to surrounding air is naturally relatively high. Even so, the figures obtained by this study seem to be unusually high. This is probably a result of the particular design features of this studied grain dryer such as: the furnaces being located on the floor of the building, below the level of the base of the drying silos, and the drying air pipes from the furnaces to the silos are long, ca. 9 m. The latter design feature gives them an unusually large surface area, which leads to high potential heat losses.

Table 2 Theoretical and mean measured heat losses in kW for the research dryer, including sensitivity analysis for theoretical values

	Heat losses, kW		
	Drying silo	Drying air pipe	Total
Theoretical, convection & radiation	3.9	4.3	8.2
Sensitivity analysis results	6.9	7.2	14.6
Mean measured heat flow	5.2	7.3	12.5

3.2 Energy consumption in the studied dryers

The energy consumption measurements of the insulated and uninsulated farm scale dryers were the definitive test for the effect of heat insulation. Figure 4 shows the efficiencies of the insulated and uninsulated drying silos during a single drying process run. These were calculated by dividing the theoretical evaporation energy of water by the energy measured for the enthalpy of change for drying air. Data for Figure 4 were collected by the continuous measuring system. As mentioned under heading 2.3, this experimental set up ignored the heat losses in the drying air pipe, thus only the heat losses in the drying silo were taken into account. The drying process was started at the same time for both dryers and the quantities and quality of grain they contained were equal.

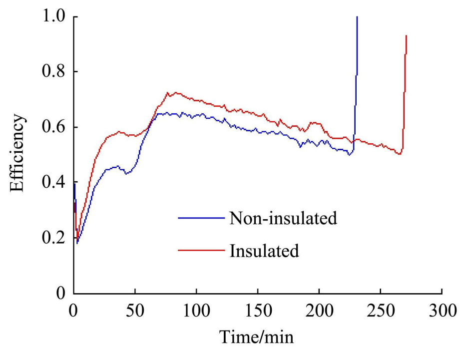

Figure 4 Efficiencies of the uninsulated and insulated dryers

Figure 4 shows that the insulation was advantageous throughout the whole drying process. The greatest benefit of insulation was achieved in the latter part of the warm-up period at the beginning of the drying process. The efficiency decreased somewhat towards the end of the process in both dryers, which is a typical event in grain drying. Drying time was somewhat longer in the insulated dryer. This is probably a result of an inaccuracy in the automatic process control system, which uses the dryer exhaust air temperature as a control negative feedback factor to end the drying process.

Figure 5 presents the specific energy consumption in both dryers during the harvest seasons of 2011–2013 inclusive. Only barley drying was studied in the analysis to decrease the number of variables that would affect the process. The quantity of used energy was obtained from the readings of the gas meters at the beginning and at the end of each drying process and the quantity of removed water was calculated by using Equation (9). Figure 5 shows that there is a considerable amount of variation between the different drying batches. In practical drying experiments that use full scale dryers there are several uncontrollable factors that influence the process, such as grain initial moisture content and also other grain properties. Additionally, the actual amounts of grain in the drying silos were never exactly equal, but this did not affect the overall results, as the energy consumption was calculated per kilogram of evaporated water. The inaccuracy in the process control also caused varying final moisture contents of grain.

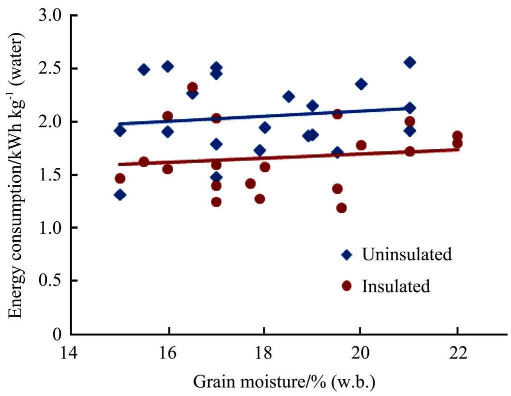

Figure 5 Specific energy consumption of drying batches of barley in the harvest seasons 2011–2013 inclusive

The mean energy savings in the insulated drying silo compared to its uninsulated equivalent were 19%. The variation in the results was considerably large, thus a single factor Anova-analysis was calculated to detect whether the difference was statistically significant. The analysis of the differences in the results between the two dryers was very highly significant (p = 0.00077).

Figure 5 indicates a rising trend in the specific energy consumption as the initial moisture of the grain increases. However, the energy consumption per kg of water evaporated in drying should increase when the grain gets drier (Jokiniemi and Ahokas, 2014). The paradoxical behaviour shown in Figure 5 is thus more probably caused by the differences in the grain quality between the years. Indeed further evidence for this phenomenon is provided by Figure 6, where the results for each harvest season are presented individually and which in all cases shows that the specific energy consumption decreases when the initial moisture of the grain increases.

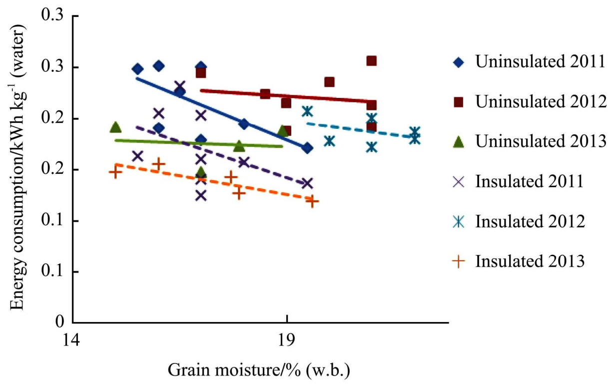

Figure 6 Specific energy consumption of the uninsulated and insulated dryers for the years 2011–2013 individually

The mean energy saving figures for the years 2011–2013 are presented in Table 3. Data in Table 3 show that the mean energy saving was clearly smaller in 2012 compared to other years. Figure 6, on the other hand, shows significantly higher initial moistures for grain in the year 2012 compared to the other harvest years. The heat energy of drying air for high moisture grain is used mainly to evaporate water, and the grain temperature and the temperature of the dryer structures remain relatively low. In contrast less energy is used for evaporation for lower moisture grain, and the temperature of the grain and dryer structures start to rise quicker. Therefore the heat insulation offers relatively greater benefits when the grain initial moisture is relatively low.

Table 3 Energy consumption in uninsulated and insulated dryers for the years 2011–2013

Dryer	Mean specific energy consumption, kWh/kg [water]		
	2011	2012	2013
Uninsulated	2.07	2.22	1.69
Insulated	1.64	1.87	1.35
Energy saved, %	21	16	20

The mean detected energy savings of 16%–21% were significantly higher than the theoretical and measured heat losses of ca. 5%–9% of the heat energy in the uninsulated dryer (Table 2). The difference in theoretical heat losses and actual energy savings achieved by the insulation can be caused by a number of factors. First, some error is always present when physical phenomena are measured. The gas consumption meters used in the study were the standard regulation meters installed by the gas company, and they were calibrated in the company's own laboratory accredited by the standard EN ISO/IEC 17025. Second, the amount of removed water was calculated from the weight of the grain and its initial moisture content subtracted by the weight and moisture content after drying. The accuracy of the dryer scales was adequate when weighing the total mass of the grain batch instead of the change in the mass during drying. Accuracy of the moisture measurement was more crucial: a measurement error of 1% in moisture content is the equivalent of 100 kg of water in grain batch of 10 tons. This can be more than 20% of the amount of removed water, depending on the initial moisture content of the grain.

Grain moisture content measurements were probably the biggest error sources in the results. However, Table 4 has relatively similar energy saving percentages for the three different harvest years. This implies that the random variations cannot be very large, and in any case the heat insulation actually reduced the energy consumption more than theoretical calculations predicted. It is possible that the higher grain temperatures caused by the insulation led to more efficient evaporation and thereby to an increase in the overall efficiency of the dryer. In this scenario the benefit gained by the heat insulation was substantially greater than the theoretical heat losses or the measured heat flow from the dryer surfaces.

Some air movements that were not considered may have also affected the results. Air movements through open doors and other openings may have caused the heat convection rate to be higher than calculated. The uneven temperature distribution on the sides of the uninsulated dryer may have produced turbulence in the gravimetric air flow, which would cause the Nusselt number, and the resulting convection heat rate, to be higher than theoretically evaluated. Additionally, the emissivity of the surfaces may have been higher than estimated in the theoretical calculations, which would cause an increase in the radiation heat losses.

4 Conclusions

Results obtained from the present study indicated that grain dryer heat insulation offers the means for making substantial energy savings. Theoretical heat losses calculated for the dryer surface temperatures were ca. 8 kW and, with the sensitivity analysis for the surface temperatures and the heat flow coefficient ca. 14 kW. The actual heat flow measured by the heat flux sensor was 12 kW in the uninsulated dryer. These figures represent 5%–9% of the dryer heat output. However, the actual energy consumption measurements under practical conditions indicated an energy saving of 16%–21% for the insulated dryer compared to its uninsulated reference, when specific energy consumption (kWh per kg of evaporated water) was considered. These figures are higher than the theoretical heat losses and measured heat flows. Several reasons, such as air movements through doors or other openings or the emissivity of the dryer surfaces may have increased the heat losses in the uninsulated dryer with respect to the theoretical calculations. These results indicate that the heat insulation not only substantially eliminated heat losses, but it also increased the overall evaporation efficiency of the dryer. This improvement may be a consequence of higher grain temperatures inside the drying silo of the insulated dryer.

Dryer design and installation also have effects on energy consumption and the drying air pipes from the furnace to the drying silo in our study were relatively long, which proportionately increased heat losses and hence the benefits from the heat insulation. Consequently, the results are considerably well in line with the figures presented in the literature (Grube, 2011; Piltti, 1979). If the drying silo was to be located outdoors, the heat convection rate would be considerably greater due to the wind. In such a case heat insulation is highly recommended. This would also be the case if higher drying air temperatures were to be used, as an increase in the drying air temperature also increases the heat gradient between the dryer and the surroundings, causing higher heat losses.

Acknowledgements

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

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