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A study of pressure drop in an experimental low temperature wood chip dryer

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Abstract. The use of wood materials, and logging residues in the energy sector is growing rapidly, and will follow the same trend in the following years in the entire EU. This development is related to the target of 20% renewable energy share in the primary energy consumption. Thus it is very important to increase the value of fresh wood materials by application of drying technologies. Drying allows increasing the efficiency and flexibility of combustion, transportation, and storage processes.

The goal of this research is to study wood chip drying process in low temperature conditions as a promising solution for the use of low exergy energy sources, such as solar energy, geothermal, and waste heat. Low temperature drying processes typically require high parasitic consumption of electrical energy that is required to provide the air change in the wood chip body, but allows reduction of heat loss. This study was developed to collect experimental information required for designing, optimization and operation of low temperature dryers.

Experimental setup was used to study wood chip drying process in controlled laboratory conditions. Air pressure loss is settled as the dependent variable. Thickness of wood chip layer and airflow rate were changed between the experiments. A comprehensive analysis of the obtained monitoring data is carried out.

Key words: Biomass dryer, low potential thermal energy, renewable energy.

INTRODUCTION

In 2011 the natural gas price fell by 45% in the USA; however this did not stop the number of woody biomass facilities to grow in 2011 and 2012 (UNITED NATIONS 2012), thus indicating that the growth of wood chip demand will also continue to increase despite the fluctuations in oil prices. Wood chips are used as a source of primary energy for power plants, cogeneration plants, and production processes because of its low prices and renewable energy status.

The carbon released from the biomass fuels when burned is recirculated in the life cycle of biofuels when a new growth absorbs it in the growing process, thus the biomass fuels are largely presumed as carbon neutral. However when taking in to account the full biofuel life cycle, it has to be noted that some additional actions need to be implied in order to bring the raw material to its final user. These actions for harvesting residues (wood chips) are such as forwarding, comminution, transportation and storage (Jäppinen et al., 2014). Each of these actions consume energy and create GHG emissions as well as additional costs. So despite the fact that biomass fuels are renewable, and can serve as a replacement for fossil fuels, it is crucial to use these recourses efficiently.

In the literature it is mentioned that dry wood chips can substitute a good quality fossil fuel while not contributing to the climate change (Le Lostec et al., 2008). Biomass drying is significant for increasing the combustion process efficiency – it allows recovering the heat otherwise used for the evaporation of water during the combustion, the net calorific value is increased, so dimensions of the boiler can be reduced; the unburned solid particulate matter emissions decrease (Li et al., 2012). Storage of fresh wood chips can result in high loss of dry matter (Nurmi & Hillebrand 2007; Pettersson & Nordfjell, 2007) that leads to energy losses and greenhouse gas emissions (GHG) (Jäppinen et al., 2014), so wood chip drying can also be used as a tool for increasing wood chip storage time and quality.

Conventionally it is common that the logging residues are dried in stacks at the roadsides of the logging sites. The drying usually takes 6 to 12 months before chipping. In this way, if the piles are covered with a special paper, the wood chips can reach around 35% moisture content (Lazdāns et al., 2009). In a study by Nord-Larsen et al. (2010) the asymptotic moisture content of firewood left in the open is noted to be 18.7% and for firewood covered with a roof 15.3%. These methods are not optimal because of the necessary long time period leading to the loss of dry matter while the end moisture content still is quite high, and there has to be an extensive area available for the whole drying period.

There are many industrial dryer systems but most of them have some drawbacks. The indirect dryers – contact or conductive dryers – are suitable for fine or granulated solids that cannot be directly exposed to the heat carrier (Devahastin & Mujumdar 2006) and won't be fit for wood chip drying. The direct-heat rotary dryers usually use 400–450 K for steam and 800–1,100 K for oil and gas fired burners (Krokida et al., 2006), these temperatures don't leave an opportunity for the use of low potential heat sources. The fluidized bed dryers have a high drying rate but this method is characterized with high electrical power consumption, and might have some problems with the particulate fluidization (Law & Mujumdar, 2006). A dryer with a perforated floor, and a forced air supply from the bottom is chosen for the investigation in this research. Low temperature settings are chosen to allow the experimental results to be used for the development of a low temperature dryer.

Different mathematical modelling approaches have been applied for the analysis of drying process. In the study by Gebreegziabher et al. (2013) the Fick's second law of diffusion is used for modelling the biomass drying process to determie the optimum operating costs, capital investments and product value. Mahmoudi in his study (Mahmoudi et al., 2014) is applying the Extended Discrete Element Method (XDEM) for a numerical simulation of packed bed biomass drying. In this approach the dried mass is considered to consist of a finite number of particles, for each particle mass and energy equations are solved, and a continuous model applied for the surrounding gas. The whole process is characterised by the summation of all the individual particle processes (Mahmoudi et al., 2014). Another mathematical approach that is used for the characterization of drying process is the Computational fluid dynamics (CFD). CFD has been used in the study by Ström (2013), here both the devolatilization and drying process is described. Apart from the above mentioned some commercially available analysis tools specifically for drying process designing are available, like Simprosys, dryPAK, and DrySel (Gong & Mujumdar, 2008). Nevertheless most often the biomass dryer designs are 'experience based', and there are few scientific studies dealing with the kinetics of the biofuel drying process (Wimmerstedt, 2006). Few experimental studies concerning the pressure drop for the dryer ventilation due to the biofuel layer have been done. Yazdanpanah has studied the pressure drop for wood pellets. In this study the pressure drop was measured for three pellet size categories with airflow rates from 0.0142 to 0.7148 $m^3 sm^{-2}$. The pressure drop increases with the increase of the airflow rate, and the increase becomes more and more significant with greater airflows. The smallest pellets have the highest pressure drop, while larger pellets or a mix of different pellet sizes has lower resistance (Yazdanpanah et al., 2011). In the papers by Kristensen & Kofman (2000) and Kristensen et al. (2003) the pressure drop depending on different wood chip, and chunk-wood types is studied. The wood chipping methods are taken into account for the wood chip particle size distribution. Airflows from 0.1 $m\ s^{-1}$ for ten (Kristensen & Kofman, 2000) and twenty two (Kristensen et al., 2003) wood chip sample types from common tree species are studied. Here the results indicate that depending on the chipping method the pressure drop can be either the same or higher than that for the wood pellets. The conclusion that the pressure drop decreases with an increasing particle size coincide with the work of Yazdanpanah et al. (2011). Wider studies are made for grain and other agricultural product drying, like the study by Pupinis (2008), Kocsis et al. (2011), Aboltins & Palabinskis (2013) and Jokiniemi et al. (2011). The greatest difference between biomass and grain drying is the different dimensions of the dried particles, different initial moisture content, and also different value of the dried product expressed in terms of mass.

The objectives of this research were to develop and collect experimental data on the pressure drop of ventilated wood chips, and to carry out a comprehensive analysis.

MATERIALS AND METHODS

Design of experiment

The selected variable factors in this study are the airflow velocity and thickness of wood chip layer in the dryer. The Table 1 shows an overview of the defined factors.

Table 1. Defined factors

Factor name	Units	Type	Role	Lower limit	Upper limit
Airflow velocity	$m\ s^{-1}$	Continuous	Controllable	0.04	0.22
Thickness	m	Continuous	Controllable	0.5	1.5

The Lower limit of the airflow velocity is chosen so that it would provide the approximate necessary air amount that is standard practice for solid drying (Francescato et al., 2008). The upper limit of the airflow velocity is chosen based on the screening of literature sources of similar experiments (Kristensen & Kofman, 2000; Kristensen et al., 2003) common practice (Francescato et al., 2008), and also the selected air fan capacity. When designing a dryer that could service large amounts of wood chips the thickness of the wood chip layer in the dryer is strictly related to the area that the dryer is about to take. Thus the lower limit is chosen to match the layer thickness used in some dryers

(Ivanova et al., 2012), and the upper limit is chosen to evaluate the possibilities for increasing the dryer layer thickness. The defined response is the pressure drop.

For the pressure drop experiment Changing a single factor at a time (COST) approach is selected. The airflow velocity is varied from 0.04 to 0.22 m s^{-1} with a 0.01 m s^{-1} step for each wood chip layer thickness (0.5; 1.0 and 1.5 m). One replicate experiment is carried out, and in total 108 measurements are recorded.

Based on fluid-dynamic principles that describe the pressure drop as a non-linear function of the flow rate, see the Ergun-type model equation (1) (Kashaninejad et al., 2010)

$$\Delta P = A \cdot Q + B \cdot Q^2, \tag{1}$$

where ΔP is pressure drop (Pa m^{-1}), A, B is the Product dependent coefficients, and Q is the airflow rate (m^3 Sm^{-2}), a quadratic model is selected to describe the factor interactions. The general form of the quadratic model is the following (Eriksson et al., 2008):

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2. \tag{2}$$

The STATGRAPHICS Centurion 16.1.15 statistical data analysis tool is used to create the design of the model.

Wood chip sample preparation

Wood chips are sampled manually from an uncovered pile. The used wood chips are visible in Fig.1.

Laboratory analysis are carried out determining the ash content, initial moisture content (as received), calorific value, bulk density of the sample, and fraction distribution. The summary of the analysis results is visible in Table 2.

Figure 1. The sample of wood chips used in the experiment.

Table 2. Parameters of the wood chips used

Parameter	Value	Unit	Testing method
Moisture content, as received	50.8	%	LVS EN 14774-2
Ash content, dry basis	1.8	%	LVS EN 14775
Gross calorific value	19.65	MJ kg^{-1}	LVS EN 14918
Net calorific value, as received	7.76	MJ kg^{-1}	LVS EN 14918
Bulk density, as received	330	kg m^{-3}	LVS EN 15103
Bulk density, dry mass	170	kg m^{-3}	LVS EN 15103

The moisture content of the wood chips varies between the experimental runs, with the average value of 53.3% but the maximum deviation from the average is 2.0%. The fractional distribution of the wood chip particles is determined according to LVS

CEN/TS 15149-1 standard method. Fig. 2 represents the cumulative particle share in the wood chip mass.

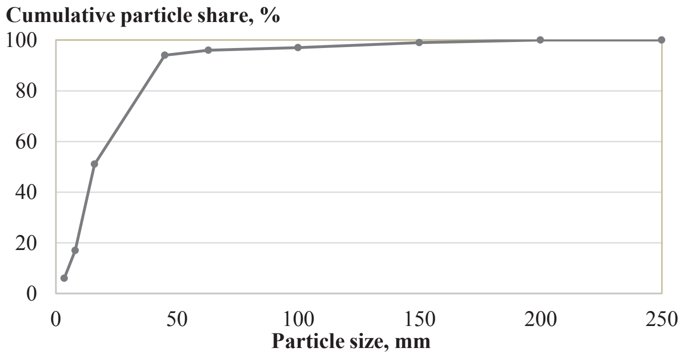

Figure 2. Wood chip cumulative particle share.

The tested wood chip sample has a high share of fine particles. According to the previous literature review this causes higher pressure drop than for coarse wood chips.

Experimental Setup and Procedure

The experiment takes place in a vertically ventilated drying bin with a perforated floor. The bin has a square base with 0.6 x 0.6 m dimensions and 2 m sides. The floor of the bin consists of a honeycomb layer with 0.01 m holes. The schematic representation of the experimental set-up is displayed in Fig. 3.

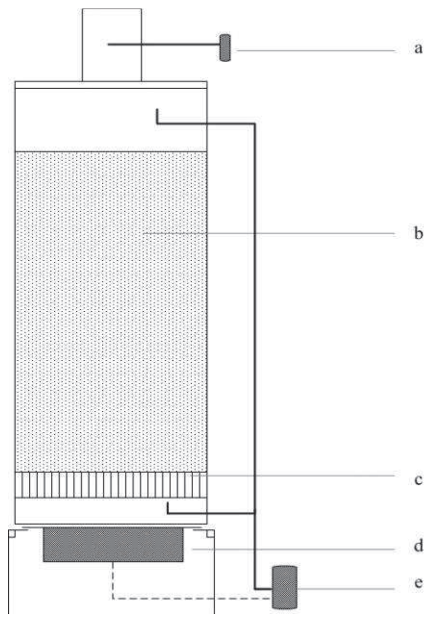

Figure 3. Experimental set-up (a – hot-wire anemometer; b – wood chips; c – honeycomb layer for flow stabilization; d – fan; e – pressure and flow speed gauges).

The wood chips are loaded manually in to the experimental dryer bin from the top, the material falls naturally, and no additional compaction is applied.

RESULTS AND DISCUSSION

Statistical model has been applied to the response variable. The model P-value below 0.05 indicates that the selected model is statistically significant at the 5.0% significance level. The R-squared of the model equals 99.155%. The adjusted R-squared equals 99.105%, this indicator is used for the comparison with other models that have a different number of independent variables. The Durbin-Watson statistic test shows no indication of autocorrelation in the residuals at the 5.0% significance level.

The Pareto chart in Fig. 4 presents the effects of the factors on the pressure drop.

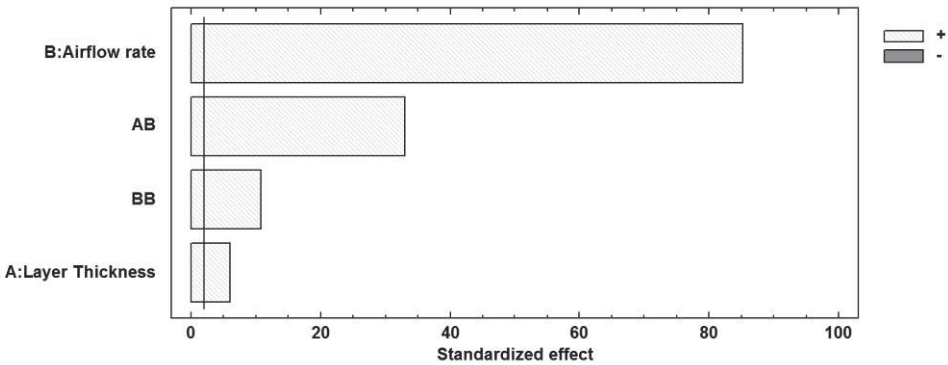

Figure 4. Pareto chart for pressure drop.

The bar fill shows weather the effect is positive or negative, it can be seen that both analysed factors have a positive effect – increasing the wood chip layer thickness, and airflow rate increases the pressure drop.

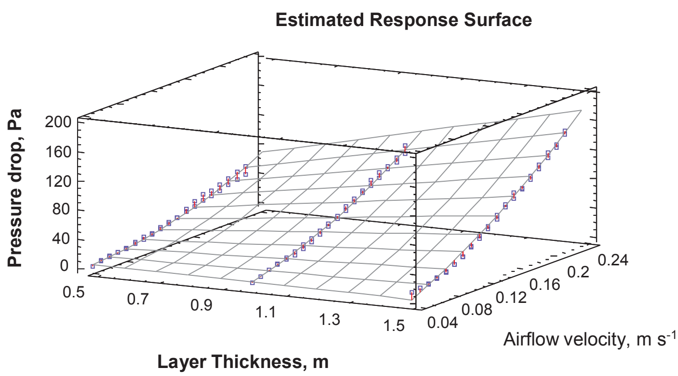

Figure 5. Estimated response surface for pressure drop.

The quadratic regression equation (2) is fitted to the experimental data, and the equation for the analysed model is retrieved as follows:

$$\Delta P = 17.4532 - 24.1817 \cdot H - 341.178 \cdot v + 530.515 \cdot H \cdot v + 1478.27 \cdot v^2 \qquad (3)$$

where ΔP is the pressure drop (Pa); H – the wood chip layer thickness (m) and v – the airflow velocity (m s^{-1}). The Fig. 5 displays the experimental equation (3) in a surface plot.

The statistical mesh in Fig. 5. has three rows of dots representing the three series of experimental point values at different layer thicknesses. It is visible that the equation has a good representation of the real data. At low airflow velocities the influence of increasing wood chip layer thickness is very weak, while with increasing airflow velocities the influence of layer thickness becomes more and more significant. This is consistent with the Ergun equation (1).

CONCLUSIONS

The air exchange in the layer of dried biofuels, and the removal of evaporated moisture is one of the key mechanisms affecting the efficiency of drying process. However, higher air velocities will cause higher pressure drop and higher parasitic energy consumption as a result. Increase of the layer thickness should not be considered as a stand-alone solution for reduction of construction expenses, because it also has a significant negative effect on the pressure drop. These aspects cannot be ignored during the designing process of wood chip dryers. The optimum thickness of drying bed, and airflow speed, together with the drying time, has to be obtained in every case to balance capital, and operational costs.

The set of experiments were planned, and carried out to evaluate the aerodynamic pressure drop in function of the air velocity, and thickness of the wood chip layer. A non-linear empirical model was developed, and validated using the experimental results. Data analysis shows a statistically very high significance between the independent variables, and the pressure drop. This model can be used for planning, designing, and optimisation of the wood chip drying process.

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