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Effect of different air velocities on convective thin-layer drying of alfalfa for livestock feeding

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Abstract. Alfalfa (*Medicago sativa*) is widely used as forage which has very high feeding value. The aim of this paper is to inform about the experimental and theoretical investigations of alfalfa drying in thin layer. Special device for convection drying with air flow passing through material from bottom through supporting trays with sieve by constant temperature was used for drying when air velocity was 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2.0 m s^{-1}. The results were compared with natural convection drying by the same temperature, but with the 0 m s^{-1} air velocity. The increased air velocity for convection influenced drying process positively. The results show that the differences between the drying with air velocities 1.2 m s^{-1} and 2 m s^{-1} are very small, therefore 1.2 m s^{-1} could be realised as an optimum. The evaluation of measurement results was focused on curves of drying rate, changes in water content and changes of moisture depending on the time and their mutual relations. Experimental data create the background for calculation of main parameters useful for description and modelling of the drying process, which can be helpful e.g. for decision of optimum drying time. Drying alfalfa for hay by forced convection shortened the drying time as compared with natural convection two and a half times. Drying alfalfa for haylage by forced convection shortened the drying time as compared with natural convection even four times.

Key words: air, drying time, forced drying, moisture, natural drying.

INTRODUCTION

Alfalfa (*Medicago sativa*) is used because of its high protein content and highly digestible fibre for high-producing dairy cows, beef cattle, horses, sheep, and goats. Alfalfa is most often harvested and conserved as hay, but can also be made into haylage or silage. The differences are according to the moisture (dry matter DM content).

DM is one of fundamental characteristics in conservation of alfalfa (Bebb, 1990; Maloun, 2001). The DM content in fresh plants varies depending on the weather and on phenophases (age) in a wide range from 11 to 25%. At the younger vegetation DM content of alfalfa is lower, which requires long drying, but there is also a lower fibre content and improved digestibility of forage. During the conservation it is necessary to increase the amount of dry matter at least 35% (preferably 40%) for the production of silage (suitable technological process using horizontal or tower silos).

For the production of haylage (silage with higher DM) it is necessary to increase DM content to 45% (in horizontal or tower silos), for production of round bale wrapped in foil to DM content from 45 to 65%. DM content of 75–85% allows storage of forage in round bales without using the packaging film (under shelter) or in hayloft for longer periods. In the production of uncoated hay bales it is needed to prevent mould growth by increased DM content at least to 75%.

For the production of quality hay should be achieved DM 75–85%, which requires drying time 2–4 days of favourable weather. High-quality alfalfa hay should be green, soft to the touch, with a high proportion of leaves, smelling well and without admixtures. Moisture level should not be higher than 15%.

Drying time and temperature together with the moisture influences the quality of the final dry fodder. Low temperatures have positive influence on quality of biological materials, but require longer processing time. There are many different applications of drying for the agricultural (Jokiniemi et al., 2012; Aboltins & Palabinskis, 2013; Jokiniemi et al., 2014) purposes. Problems of natural drying applied to drying of special plants are solved also in some scientific publications, e.g. (Aboltins & Kic, 2016).

The increased air velocity for convection or suitable material preparation can influence the drying process positively. But too high air velocity, needed to accelerate the drying process, can cause problems with losses of light particles particularly at the final stage of drying when forage has low water content and thus low density of small particles. In practice, sometimes DM is not sufficient in the production or storage of hay, haylage or silage, or on the contrary, DM is too high which can cause higher losses of fodder. DM is an important determinant of intake by animals (Pond & Pond, 2000). The attention of alfalfa drying under artificial conditions is paid in different scientific publications, e.g. (Adapa et al., 2004; Osorno & Hensel, 2012).

The aim of this work is to bring some new experimental and theoretical investigations of alfalfa drying by forced convection with air flows of different air velocities going from bottom through trays with layer of fodder up.

MATERIALS AND METHODS

The laboratory measurements were carried out at the Faculty of Engineering CULS Prague during summer weather conditions in August. The technical equipment used for the experiments was forced convection system of own design (Fig. 1) (Kic & Liska, 2012; Kic & Aboltins, 2013), which consists of four vertical drying chambers.

Each of the drying chambers – a space in which was placed perforated tray with sample – allows independent measurements during drying at different flow rates of drying air. The airflow delivered by fan of 120 mm diameter is controlled by fan revolutions.

To research the drying kinetics, alfalfa samples which were cut up into a particle length from 2 to 5 cm, were placed in a thin layer about 50 mm on sieve tray with mesh 3 x 4 mm of total area approximately 20,400 mm^2. Initial weight of one sample on one tray was approximately 120 g. The forced drying was with air velocity in drying chambers 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2.0 m s^{-1}. The results were compared with natural convection drying by the same temperature, but with the 0 m s^{-1} air velocity.

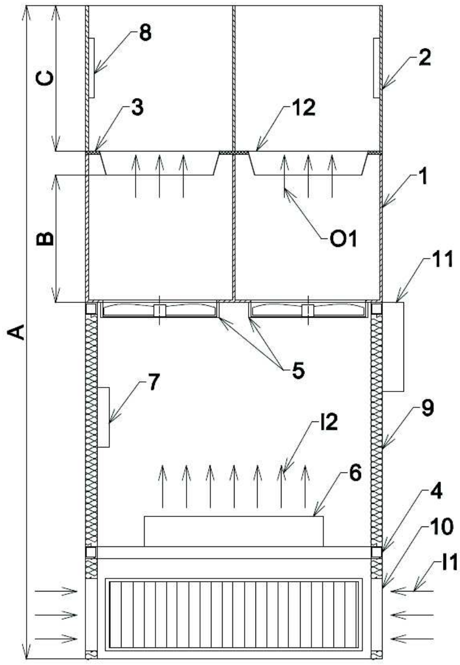

Figure 1. Apparatus used for alfalfa drying: 1 – lower drying chamber; 2 – upper drying chamber; 3 – underlay; 4 – structure; 5 – fans; 6 – air heating; 7 – sensors; 8 – sensors; 9 – thermal insulation; 10 – inlet air; 11 – control panel; 12 – perforated tray with measured alfalfa; I1 – inlet of fresh air; O1 – air passing through perforated tray with measured alfalfa; A – overall height, B – height of the lower chamber; C – height of the upper chamber.

Air speed was measured by anemometer CFM 8901 Master with resolution 0.01 m s^{-1} and accuracy ± 2% of final value. Air temperature and humidity was measured by the sensor FHA646-E1C connected to the data logger ALMEMO 2690-8. The average temperature of drying air was 27 ± 0.6 °C and relative humidity 49 ± 1.8%.

The moisture content in the alfalfa samples was identified by gravimetric measurement in regular time intervals. Samples were weighed during the drying on the digital laboratory balance KERN-440-35N with maximum load weight 400 g and with resolution 0.01 g and values were recorded. Each measuring tray was weighed during the first 1 hour every 15 min, later during the next 2.5 hours every 30 min and after that every 60 min. The total drying time 144 h was adapted to the need for a determination of lowest moisture content, which can be achieved by convective drying. An example of alfalfa samples before and after forced drying is on the Fig. 2.

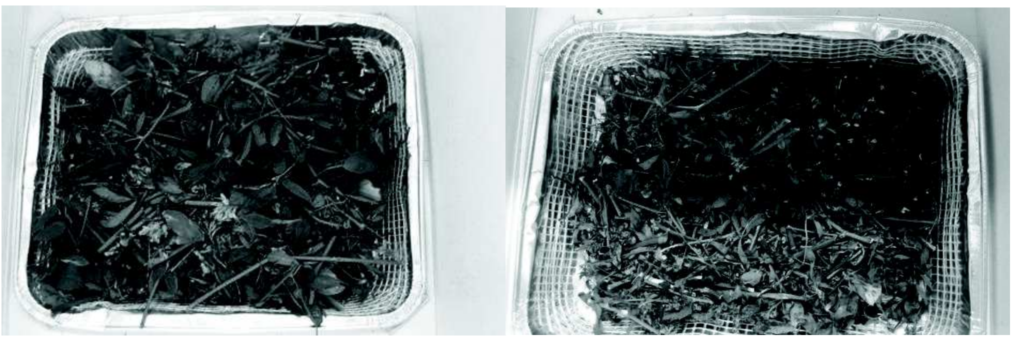

Figure 2. Alfalfa samples on sieve tray before (left) and after (right) drying by forced convection.

The DM content in alfalfa samples was identified by gravimetric measurement using an MEMERT UNB-200 air oven under temperature 105 °C. Samples were weighed on a Kern 440-35N laboratory balance in regular time intervals. The total drying time was adapted to the need for a determination of the equilibrium moisture.

The following main parameters are calculated from the measured values of all alfalfa samples. Water content u is defined as the ration of the weight of water m_W contained in a solid to the weight of dry solid m_S, expressed in the equation (1):

$$u = \frac{m_W}{m_S} \tag{1}$$

where: u – water content, g g^{-1}; m_W – weight of water, g; m_S – weight of dry matter, g.

Moisture w is the ratio of the weight of water m_W contained in a solid to the mass of the humid solid $m = m_S + m_W$, expressed in the equation (2):

$$w = \frac{m_W}{m} 100 \tag{2}$$

where: w – moisture, %.

Changes of water content du during the time difference dt describe the drying rate N expressed in the equation (3):

$$N = \frac{du}{dt} \tag{3}$$

where: N – drying rate, g g^{-1}min^{-1}; t – time, min.

The obtained results of drying rate N were processed by Excel software and some suitable parameters have been verified by statistical software Statistica 12 (*ANOVA* and *TUKEY HSD Test*).

Different superscript letters (a, b) mean values in common are significantly different from each other in the rows of the tables (*ANOVA; Tukey HSD Test;* $P \leq 0.05$), e.g. if there are the same superscript letters in all the rows it means the differences between the values are not statistically significant at the significance level of 0.05.

RESULTS AND DISCUSSION

The kinetics of alfalfa drying process caused by forced and natural convection with air velocities (0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1}and 2 m s^{-1}) is described by the curves calculated according to the equations (1), (2) and (3) in the Figs 3–8. The whole convection drying time 144 h was sufficient to the maximal drop of water content which can be achieved by convection of air temperature 27 °C and relative humidity 49%.

The Fig. 3 shows that all air velocities of forced drying including the smallest one (v = 0.7 m s^{-1}) in comparison with natural convection (v = 0 m s^{-1}) reduced the time of drying considerably. The small differences between the drying courses of forced drying with air velocities (0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1}, 2 m s^{-1}) during the first 5 drying hours are more obvious if the curves are presented on the Fig. 4.

The course of moisture w during the first 100 h of convection drying is presented on the Fig. 5. The decrease of moisture is significantly slower in the case of natural convection (v = 0 m s^{-1}) than with forced convection. The differences between the drying courses of forced drying with air velocities (0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1}, 2 m s^{-1}) are very small.

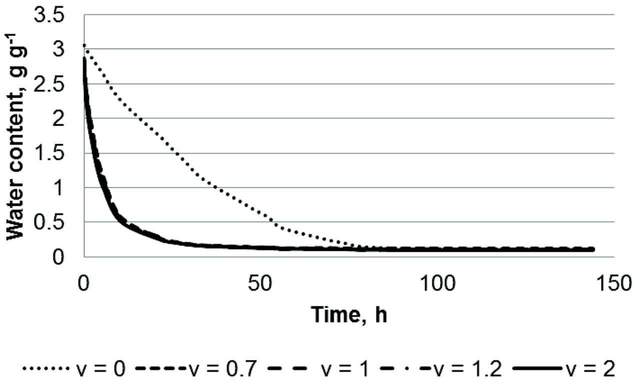

Figure 3. Water content u of all 5 alfalfa samples during 144 h of convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}.

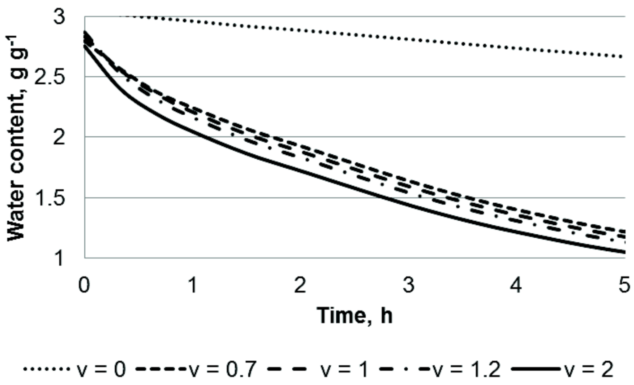

Figure 4. Water content u of all 5 alfalfa samples during the first 5 h of convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}.

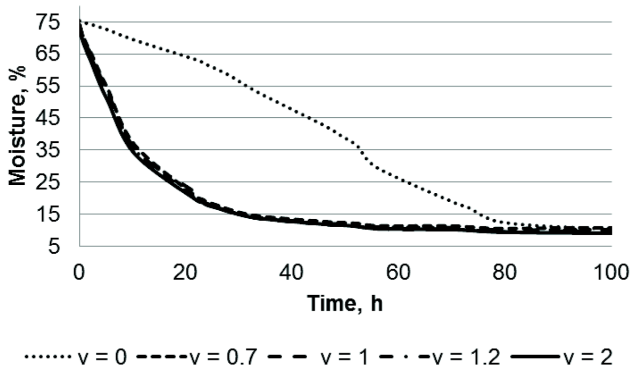

Figure 5. Moisture w of all 5 alfalfa samples during 100 h of convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}.

The course of drying rate N during the first 5 h of convection drying is presented on the Fig. 6. The highest drying rate of all 5 alfalfa samples is during the first hour. To see better the differences influenced by the air velocity, the drying rate only from the first 60 minutes is presented on the Fig. 7.

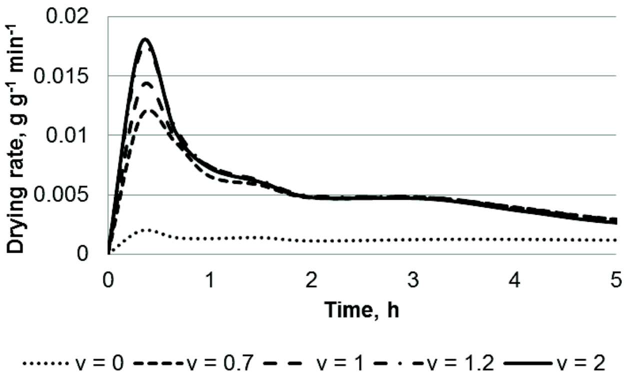

Figure 6. Drying rate N of all 5 alfalfa samples during 5 h of convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}.

The biggest drying rate was achieved during the first 30 min. According to the Fig. 7 the difference between the drying rate with air velocity 1.2 m s^{-1} (N = 0.0172 g g^{-1} min^{-1}) and 2 m s^{-1} (N = 0.0178 g $g^{-1}min^{-1}$) is rather small. It is obvious that the drying rate with natural convection (N = 0.0019 g $g^{-1}min^{-1}$) is very low also during the first hour.

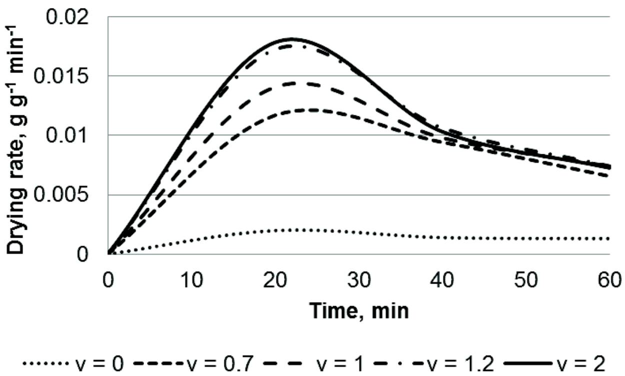

Figure 7. Drying rate N of all 5 alfalfa samples during 1 h of convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}.

Calculated results of drying rate N were evaluated statistically. The big difference between the initial drying rate during the first 30 minutes and subsequent drying phases strongly affects and distorts the results of mean values, standard deviations and statistical assessment of the mutual differences between them.

The results of the statistical evaluation of drying rate N during the first hour and 5 hours are presented in the Tab. 1. The positive effect of forced convection is obvious during the first hour of drying. The difference between the drying rate of natural convection (v = 0 m s^{-1}) and the other drying rates by forced convection is statistically significant.

Differences between the drying rates of two highest velocities (1.2 m s^{-1}, 2 m s^{-1}) and other drying rates are statistically significant during the first 5 hours of drying. According to the statistic evaluation of drying rates for longer time, the differences between all drying rates of all velocities in this respect are not statistically significant; therefore they are not presented in the Table 1.

Table 1. The drying rates N of all 5 alfalfa samples during 1 hour and 5 hours of convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}. Different letters (a, b) in the superscript are the sign of high significant difference (*ANOVA; Tukey HSD Test;* $P \leq 0.05$)

Air velocity	N (1 hour)	N (5 hours)
	g g min^{-3} ± SD	g g min^{-3} ± SD
v = 0 m s^{-1}	0.0014 ± 0.0004^{a}	0.0014 ± 0.0002^{a}
v = 0.7 m s^{-1}	0.009 ± 0.002^{b}	0.0062 ± 0.002^{a}
v = 1 m s^{-1}	0.01 ± 0.002^{b}	0.0068 ± 0.003^{a}
v = 1.2 m s^{-1}	0.012 ± 0.004^{b}	0.007 ± 0.003^{b}
v = 2 m s^{-1}	0.012 ± 0.004^{b}	0.007 ± 0.004^{b}

SD – Standard deviation.

Rather interesting is the dependence of drying rate N on water content u presented in the Fig. 8, describing both very important parameters of drying process. The best relation between the drying rate and water content is achieved if the water content is high and with higher air velocity of forced drying. The difference between the drying with air velocities 1.2 m s^{-1} and 2 m s^{-1} is rather small.

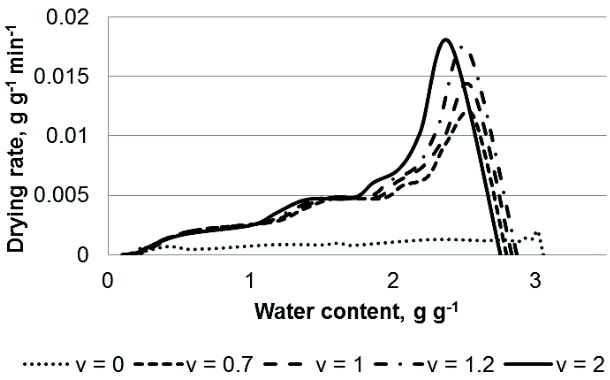

Figure 8. Drying rate N of all 5 alfalfa samples as a function of water content u during convection drying with air velocities 0 m s^{-1}, 0.7 m s^{-1}, 1 m s^{-1}, 1.2 m s^{-1} and 2 m s^{-1}.

From a practical perspective, it is possible determine from the measured and calculated results that to achieve relative humidity 15% (appropriate for hay) by forced convection drying of alfalfa in air of 27 °C the drying time is about 30 h. The achievement of these parameters by forced convection is in all cases of tested air flow velocities. In the case of natural convection with zero velocity it would be required drying time approximately 75 h.

To achieve relative humidity 55%, which corresponds to a request for storage in the form of alfalfa haylage (DM 45%), it is sufficient 8 hours of drying by forced convection; in the case of drying by natural convection with zero velocity it would require 30 h.

CONCLUSIONS

This research is useful for verification of influence of different air velocities on the drying process of alfalfa in thin layer.

It has been found that the forced convection has a strong and positive influence on drying time in comparison with free drying by natural convection. The differences between the results of drying with air velocities 1.2 m s^{-1} and 2 m s^{-1} are very small, therefore 1.2 m s^{-1} could be realised as an optimum. Higher air velocity could cause losses of small dry particles especially at the end of drying process.

In order to achieve the suitable moisture of alfalfa for different conservation applications with economic benefits, the optimization of drying time should be provided and respected.

Future research in this area of research should be focused on the study of other factors influencing the drying process especially in different air temperatures, partly described and expressed by drying coefficient.

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