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Red clover drying coefficient dependences on air velocity at constant drying temperature

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Abstract. The clover is widely used as feed of animals and preservation of fodder is an important problem. This paper informs about the experimental and theoretical investigations of red clover (*Trifolium pratense*) drying by forced convection. This research is focused on verification of influence of different air velocities on the drying process of red clover in thin layer in mild temperatures (22 °C) and rather high relative humidity of air (70%). The initial moisture content of clover was determined by gravimetric method using the hot air drying in the electric oven. Special device for convection drying with air flow passing through material from the bottom through supporting trays with a sieve (dimensions of mesh 3 x 4 mm) by constant temperature was used for drying when the air velocity 0.7 m s^{-1}, 1.0 m s^{-1}, 1.2 m s^{-1} and 2.0 m s^{-1}. These results was compared with drying by free convection. Changes of clover samples were determined from the measured values of weight using the gravimetric method. The function of drying coefficient *K(t)* is determined (using thin layer theory) and theoretical results are compared with experimental results. Using experimental results were determined relationships between air velocity and parameters included in function of drying coefficient. This allows theoretically to predict the drying process depending on the air velocity.

Key words: clover, conservation, drying theory, fodder, forced drying, natural drying.

INTRODUCTION

Red clover (*Trifolium pratense*) is important forage plant grown mostly on temperate clime throughout the world. This kind of plant is easily adaptable to many natural factors as soil type, climate conditions and others. Last but not the least reason is that is excellent nitrogen fixer and also is free from many disease and insect pests, has versatile uses, and is suitable for use in crop rotations. Mostly is used for silage, hay, haylage and is especially valuable in adding nitrogen and organic matter to the soil (Riday, 2010).

Nowadays red clover improves agro-ecosystem. The main idea is that red clover is used as under-seeding plant to wheat or corn in the system strip-tillage. This results in improvements as reduction of erosion, runoff and leaching; soil temperature and moisture regulation; weed suppression; interruption of pest and disease cycles and others (Wyngaarden et al., 2015).

One of the best way to process red clover is haylage or silage system. The next popular way haw to process this plant is into round bales. During drying matter of hay, it could be problem with moisture and rain. These problems can be associated with large losses and other losses can arise if we store insufficiently dried hay. For decrease drying time it should be used a mower-conditioner for cut (Rayburn, 2002). Hay bales losses are functions of hay moisture, temperature and how long the hay is exposed to these conditions (Holmes, 2004).

To develop recommendations for cutting fodder crops and drying, based on forecasts weather conditions, it can be useful a mathematical model. Important problems for future conservation of crops are related to the energy saving in drying process (Jokiniemi, et al., 2012).

A drying model can estimate the moisture content of fodder crops as a function of time for given weather conditions. Predictive model and uses the air temperature, wind speed, global radiation is shown (Atzema, 1992). The drying process of harvested grass was evaluated using numerical approaches in (Bartzanas et al., 2010).

The drying of lemon grass plant (*Cymbopogon citratus Stapt*) at different air temperatures and drying speed is decribed in (Coradi et al., 2014), thin-layer total drying time of some herbal leaves at different drying temperatures and velocities are determined by (Kaya & Aydin, 2009). The results of low temperature drying of hops are shown in (Hermanek et al., 2017 and Rybka et al., 2017).

The aim of this study is to determine the function of drying coefficient K(t) and to compare the theoretical results with the results of experimental measurement. The measurements were made for five air velocities, and for each situation a suitable mathematical representation of the course of the equation was found.

MATERIALS AND METHODS

In July and August 2016, red clover drying was carried out at the Faculty of Engineering of the Czech University of Life Sciences Prague. Fig. 1 shown that for the laboratory measurements were used own design of convection system. The system is consisted from four vertical drying chambers in each of which air flows at different velocity. The velocities for each chambers were 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 0.0 m s^{-1} air velocity.

Each chamber is independent and allows for a different flow rates of air velocities. Samples for each measurement were inserted into chambers on sieve tray with mesh 3 x 4 mm of total area approximately 204 cm^2. The airflow for drying of sample is delivered by the fan of diameter 120 mm and controlled by fan revolutions.

Red clover was cut up into pieces of 20–50 mm length. Sample of an approximate initial weight of 45 g was placed on every tray. On the sieves was placed only layer just about 50 mm which is important for our research because it is assumed that there is no moisture sharing between the layers of material.

For measured air velocity was used equipment: Anemometer CFM 8901 Master (Hygrotec Messentechnik GmbH, Germany) with resolution 0.01 m s^{-1} and accuracy ± 2% of final value. The sensor FHA646-E1C was used for measure humidity and air temperature. This sensor sent data to the data logger ALMEMO 2690-8 (Ahlborn GmbH, Germany). The measured average temperature of drying air was 22 ± 0.2 °C and relative humidity 70 ± 0.4%.

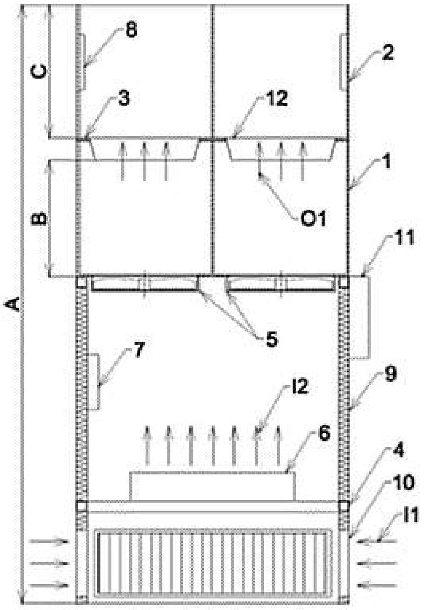

Figure 1. Apparatus used for drying: 1 – lower drying chamber; 2 – upper drying chamber; 3 – underlay; 4 – structure; 5 – fans; 6 – air heating; 7 – sensors; 8 – sensors; 9 – thermal insulation; 10 – inlet air; 11 – control panel; 12 – perforated tray with measured material; I1 – inlet of fresh air;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

The total drying time was 164.5 h. After this time was achieved the lowest moisture content for the convective drying. During the first 0.5 hour of drying were samples measured every 10 min, the next until the 1.5 hours every 15 min, the next 2 hours every 30 min and then every 60 min. For measuring weight in regular intervals was used the laboratory weight KERN-440-35N (KERN and SOHN GmbH, Germany) with maximum load weight 400 g and with resolution 0.01 g.

The dry matter (DM) content in red clover was detected by gravimetric measurement using an MEMERT UNB-200 (MEMMERT GmbH + Co. KG, Germany) air oven under temperature 105 °C. During regular time intervals samples were weighed on a Kern 440-35N laboratory balance. The total drying time was adjusted to the need for a determination of the equilibrium moisture.

RESULTS AND DISCUSSION

The experiment at red clover drying was made in the laboratory. Based on the results of the measurements there are calculated water loses and dry weight of original sample volume for each air velocities. The partial goal is to determine the drying coefficient *K(t)* that obtained by fitting the values of each measurement into the Eq. (1).

$$K(t) = \frac{-ln\left|\frac{m - m_d}{m_s - m_d}\right|}{t}, \qquad (1)$$

where $K(t)$ – drying coefficient; m – weight of samples during drying, g; m_d – weight of dry matter, g; m_s – samples weight at the beginning of drying, g; t – time, h.

According (Aboltins, 2013) drying coefficient *K(t)* values are determined and approximated. For the best approximation of this data is chosen function (2).

$$K(t) = at^b, \tag{2}$$

where *a, b* – constants that characterize experimental conditions.

For each drying air velocity are determined *a* and *b* values from (2). These results are shown in the Table 1.

Table 1. The coefficients a, b values dependence from air velocity

Air velocity, m s^{-1}		a	b	R^2
v_1	0.70	0.1446	-0.2522	0.9700
v_2	1.00	0.1536	-0.2757	0.9859
v_3	1.20	0.1690	-0.3093	0.9930
v_4	2.00	0.1719	-0.3037	0.9912
v_0	0.00	0.0338	-0.0018	0.0008

In the Table 1 is shown that the coefficient of determination for air velocities that are not equal to v_0 is high. Unfortunately, Eq. (2) is not suitable for speed v_0, it is for free convention, without forced drying. The best approximation for velocity v_0 is polynomial equation of second order but coefficient of determination is still less than 0.35. From this equation were obtained the coefficients *a*, *b*, for different velocities, which can also be seen in the Table 1.

Using (1) was calculated theoretically red clover during process using equation (3):

$$m_t = (m - m_d) \cdot exp^{\left[-\left(\frac{a}{b+1}\right)\cdot t^b\right]} + m_d, \tag{3}$$

where m_t – theoretical weight of material at the time *t*, g.

The comparison of theoretical and experimental data is shown in the Fig. 2. The most preferable form of red clover drying coefficient with forced air was power expression: $K(t) = at^b$. As it can be seen in the Fig. 2, the theoretical model of the drying process well describes the values obtained in the experiment. The greatest difference was observed at the beginning of the process and at the highest air velocity (Table 2), which could be explained by the uneven distribution of moisture in the layer.

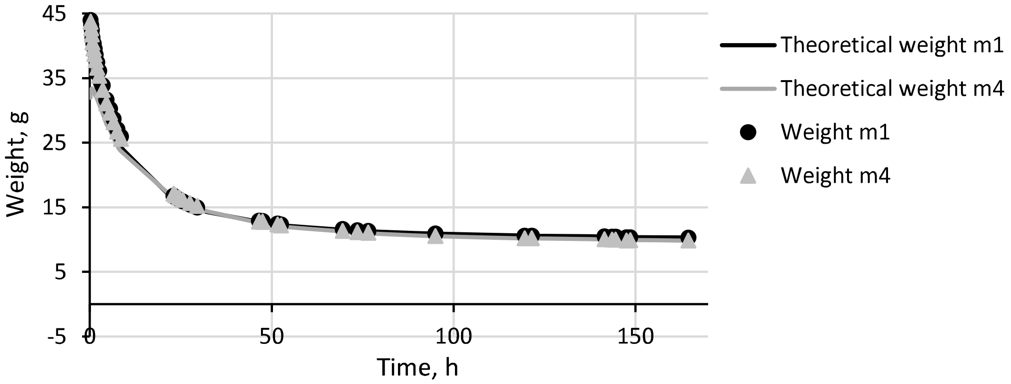

Figure 2. Comparison of the experimental and theoretical data: m_1 ($v_1 = 0.70$ m s^{-1}) and m_4 ($v_4 = 2.00$ m s^{-1}).

Table 2. The absolute average differences between the experimental and the theoretically calculated weight at different drying air velocity

Air velocity, m s^{-1}		Average, g	Standard deviation, g
v_1	0.70	1.856	2.472
v_2	1.00	1.923	2.583
v_3	1.20	2.348	3.199
v_4	2.00	2.288	3.146
v_0	0.00	0.471	0.393

Differences between the experimentally measured weight and the theoretically calculated weight values are plotted in the Fig. 3, where the intervals are divided into groups of 2 g. In the Fig. 3 we can also see the frequency of differences for each air velocities. The air velocity v_0 is not included in the graph, for which, as already mentioned, this mathematical equation is not appropriate.

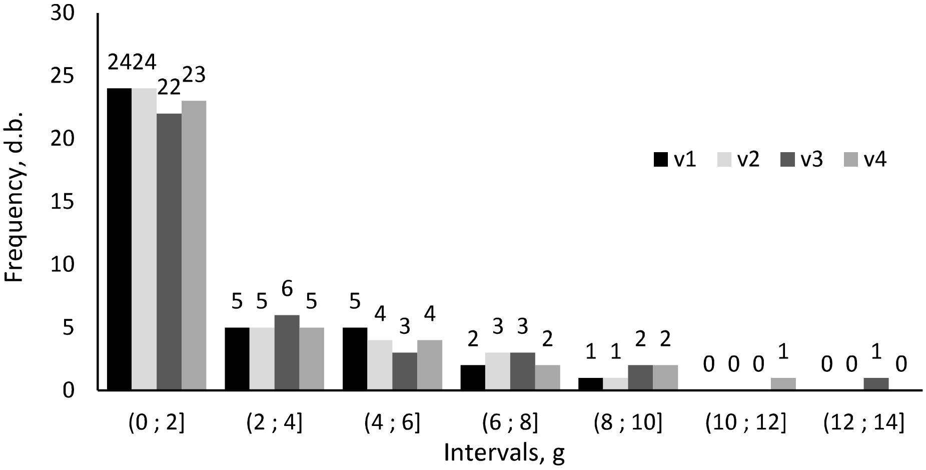

Figure 3. Frequency of differences between the experimental and theoretical results divided into intervals with step 2 grams.

In the Fig. 3 we can see that the most of theoretical and experimental data are the same in the first interval. The second, third and fourth intervals have a much lower frequency. The fifth, sixth, and seventh intervals, which contain only individual data and include differences greater than 8 g, can be considered as a measurement error.

As seen in Fig. 2 the highest differences are achieved by drying during the first drying hours. It can be explained with moisture on the material surface.

Assuming that the Eq. (2) which was chosen is the most appropriate mathematical expression for the type of red clover drying. A graph of coefficients *a*, *b* from the Table 1 depending on the air velocities was created.

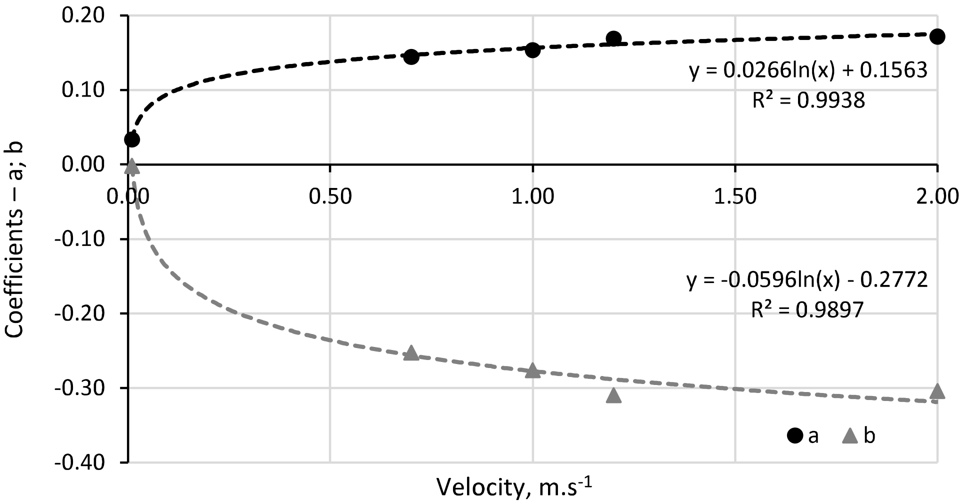

Figure 4. Coefficients *a*, *b* dependence on the drying air velocity.

It was again found the mathematical equation of the dependencies of these two parameters in the form (4, 5). High coefficients of determination are obvious in the Fig. 4. Changes of coefficients *a*, *b* can be counted from equations:

$$a = 0.0266 \cdot \ln(v) + 0.1563, \tag{4}$$

$$b = -0.0596 \cdot \ln(v) - 0.2772, \tag{5}$$

where v – velocity of drying air, m s^{-1}.

If the velocity of drying air is known, it is possible to expect *a*, *b* and after that calculate drying coefficient *K(t)*.

CONCLUSIONS

1. The most preferable form of red clover drying coefficient with forced air was power expression. Using the experimental data and the mathematical model of the drying process, it is possible to determine the unknown parameters at each speed of drying agent.
2. The max average differences of experimental and theoretical weight values were lower than 5%.
3. The obtained relationships which connect the parameters of the drying coefficient depending on the drying agent speed allow to predict the process of drying at various speeds of unheated air. Drying time is one of main parameters which could be determined as a practical result.
4. The theoretical background solved in this paper can be used for practical information about the suitable drying process of red clover for different conservation applications with economic benefits. The principles of drying coefficient determination and optimization of drying process can be applied on another type of fodder similar to the red clover.

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