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Airflow resistance of two hop varieties

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Abstract. The quality of hops used in brewing is substantially reliant upon the processing step of drying. To ensure effective drying in kiln as well conveyor-belt dryers, homogeneous distribution of air is of particular importance. Uneven air distribution often results in inefficient drying and nonuniform moisture content of the hop cones. The air distribution naturally is governed by the airflow resistances in the individual floors or belts of a dryer. Hence, in order to quantify the airflow resistance of hop cones at different air velocities and bed heights, systematic measurements were carried out. In addition to determining the bulk densities of hops, the investigations included trials with fresh and dried hop samples. Clear differences were observed between hop varieties both in measured pressure drops and in bulk densities. Moreover, in the case of fresh hops, a non-linear increase in pressure drop with bed height was ascertained. Semi-empirical equations were developed to describe pressure drop as a function of air velocity. This work will contribute to the design of dryers with optimum airflow distribution and thus enhance the efficiency of drying as well as the product quality.

Key words: airflow resistance, bulk density, drying, hops, pressure drop.

INTRODUCTION

Hop provides the typical flavour to beer and thus is an essential raw material in brewing. In order to increase the shelf life of the hops, freshly harvested hop cones must be dried immediately. For this purpose, kiln dryers and conveyor-belt dryers are used which are usually operated at drying temperatures of up to 70 °C (Münsterer, 2020). Higher temperatures cannot be used to expedite the drying, as drying temperatures well below 65 °C have been proposed to reduce the loss of essential oils and other heat sensitive substances (Heřmánek et al., 2017; Rybka et al., 2018). Even though partially overdrying is commonly used as a measure against the occurrence of nests of moist hops, it adversely affects the product quality and energy consumption (Rybka et al., 2017; Heřmánek et al., 2018). Alternative approaches including technological improvements were suggested by several researchers (Rybka et al., 2019a; Rybka et al., 2019b), but the operation of conveyer-belt dryers is essentially based on experience.

Nowadays, model-based process analysis and smart control systems offer the most promising options in terms of increasing the energy efficiency of hops drying whilst improving product quality. Nevertheless, there is a lack of studies relating to the change of physicochemical properties of hops during drying. The mass and length of hop cones vary according to variety, during the growing season and also from year to year (Čeh et al., 2012). Little is known about the density or bulk density of hop cones at different moisture contents, although it is an important parameter for harvesting, processing and storage (Kumhála & Blahovec, 2014). One study investigated the relationships between the dielectric properties of bulk hops and bulk density. However the investigations were limited to freshly harvested and subsequently compressed cones, as opposed to investigating those during drying (Lev & Kumhála, 2017). With regards to hops quality, for example, investigations of a pilot scale drying system revealed that colour changes depended strongly on the bulk weight and resulting bulk thickness. The research demonstrated that the specific mass flow rate of drying air plays a critical role in determining the quality of the final product, as well as the processing time required (Sturm et al., 2016; Sturm et al., 2020). These findings have established that, therefore, it is important to consider optimum bulk and process parameters, to optimize the hop drying process and to improve process efficiency as well product quality (Raut et al., 2020).

It is well known that for any convection drying, having a better understanding and more importantly a better control over the airflow patterns is paramount. On that front, the prediction of airflow resistance is fundamental to the design of efficient drying and aeration systems. Hence, several theoretical, semi-theoretical, and empirical models have been developed which relate pressure drop to airflow (Górnicki & Kaleta, 2015). In a comprehensive fundamental work, Matthies (1956) investigated the airflow resistance of different agricultural crops and the independent variables effecting this resistance. The research included numerous grain and root crops as well as some grass and foliage crops. However, to the best of the authors' knowledge, no such studies have yet been carried out on hops. Therefore, the objective of this work was to obtain a better understanding of the bulk densities and airflow resistances of hops, particularly in relation to drying.

MATERIALS AND METHODS

The investigations described in this paper were carried out during the harvest period of the year 2020, at a drying facility located in Saxony (Saaz variety: August 26–28; Perle variety: September 07–09). The hops were dried with a three-belt dryer of Czech design (type PCHB-750). The fresh hop samples (green hops) were taken from the pile in front of the feed belt, whereas the dried hop samples were collected after continuous conditioning. In addition to the measurements to determine airflow resistance, moisture content and bulk density of the two examined hop varieties were determined.

A simple test system was set up to determine flow resistances at different air velocities, bed heights and moisture contents (Fig. 1). Essentially, the test system consists of a radial blower equipped with a frequency converter, a measuring section for the air volume flow rate and a sample container with a sieve grate. The measuring section and the sample container were realized with ventilation pipes made of galvanized sheet steel (standard diameter: 300 mm).

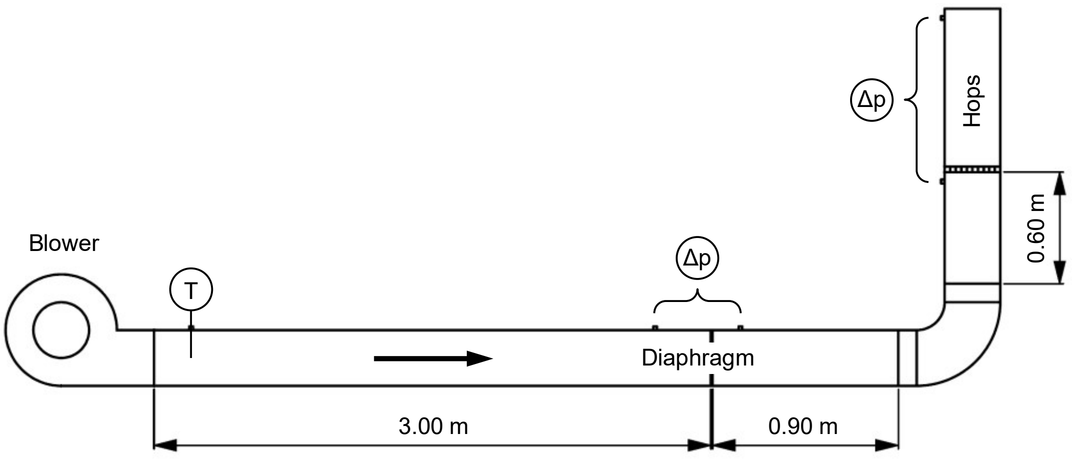

Figure 1. Simplified schematic of the test facility.

The air volume flow rate was determined by measuring the differential pressure and the air temperature on a standard diaphragm (inner diameter: 50 mm) in accordance with EN ISO 5167-2 (2003). At the same time, the pressure loss of the ventilated bed was measured (differential pressure before and after the sample container). Two differential pressure sensors (measuring range 0-1,250 Pa; Ahlborn FD A602-S1K), a temperature sensor (thermocouple type K; Ahlborn ZA 9020-FSK) and a data logger (Ahlborn Almemo 2890-9 by Ahlborn Mess- und Regelungstechnik GmbH) were used for the measurements.

At the beginning of each experiment, the sample container was filled with hop cones up to a bed height of 25 cm. During the subsequent ventilation, seven different air volume flow rates were set via the frequency converter of the fan (10–70 Hz). Each volume flow rate was held constant for about three minutes. The two differential pressures and the air temperature were measured every second and recorded as mean values every five seconds. The mean values were then used for subsequent analysis for each of the seven volume flow rates. The sample container was then filled with hop cones first to a bed height of 50 cm and finally to 75 cm. The procedure described above for varying the air volume flow was repeated for the other two bed heights as well. Each trial was carried out three times with different hop samples. With two hop varieties, three bed heights, two moisture contents and three repetitions, a total of 36 trials were conducted.

The following equation of resistance for bulk grain and bulbous crops was developed by Matthies (1956):

$$\Delta p = \frac{C_0}{2} \cdot k \cdot \frac{h}{\varepsilon^4} \cdot \eta^n \cdot \rho_a^{1-n} \cdot \frac{w^{2-n}}{d^{1+n}} \quad (1)$$

where Δp denotes pressure loss in the bed; C_0 is the drag coefficient; k is a material specific empirical constant for the respective crop; h represents the bed height; ε is the void fraction of the bed (porosity), η stands for the dynamic viscosity of the air; ρ_a denotes the density of the air; w is the air velocity through the empty sample container, and d is the diameter of an equivalent sphere with the same volume as the bulk body (equivalent diameter). Concrete values for the exponent n resulted from extensive theoretical and experimental investigations of the drag coefficient of flows through the beds as a function of the Reynolds number. By rearranging the above Eq. (1)

to express the bed-height specific pressure drop and simplifying it further by consolidating the unknown quantities C_0, k, ε and d in C_1, we get:

$$\frac{\Delta p}{h} = C_1 \cdot \eta^n \cdot \rho_a^{1-n} \cdot w^{2-n} \qquad (2)$$

Alternatively, to consider the void fraction (porosity) as a variable, by excluding it from the consolidation, Equation (1) reduces to:

$$\frac{\Delta p}{h} = \frac{C_2}{\varepsilon^4} \cdot \eta^n \cdot \rho_a^{1-n} \cdot w^{2-n} \qquad (3)$$

The mathematical description of the bed-height specific pressure drop $\Delta p/h$ according to Eqs (2) and (3) was essentially contingent upon the experimental determination of the factors C_1 or C_2 and the exponent n. The systematically varied air velocities were calculated from the differential pressures measured on the standard diaphragm in accordance with EN ISO 5167-2 (2003). A description of the iterative calculation method is omitted here for brevity.

RESULTS AND DISCUSSION

Table 1 shows the moisture content and bulk density of the two hop varieties. Each value in Table 1 represents the mean value from three individual measurements. The moisture contents were determined by weighing and drying in a drying cabinet (manufactured by Memmert GmbH) at 105 °C for 24 h.

Table 1. Moisture contents w.b. (wet basis) and bulk densities of the hop varieties Saaz and Perle before and after drying

	1	2	3	Mean	B/A*	P/S**
Saaz fresh						
Moisture content w.b. (%)	78.8	79.1	78.9	78.9		
Bulk density A (kg m^{-3})	81.7	78.9	82.2	80.9		
Bulk density B (kg m^{-3})	91.4	89.3	94.9	91.8	114%	
Saaz dry						
Moisture content w.b. (%)	10.8	12.0	12.4	11.8		
Bulk density A (kg m^{-3})	22.5	22.1	24.5	23.0		
Bulk density B (kg m^{-3})	25.4	24.6	27.8	25.9	113%	
Perle fresh						
Moisture content w.b. (%)	78.9	78.4	78.4	78.6		
Bulk density A (kg m^{-3})	90.8	84.1	88.9	87.9		109%
Bulk density B (kg m^{-3})	105.9	98.8	102.9	102.6	117%	112%
Perle dry						
Moisture content w.b. (%)	10.6	11.4	10.7	10.9		
Bulk density A (kg m^{-3})	22.7	23.4	23.3	23.1		101%
Bulk density B (kg m^{-3})	26.8	27.8	27.1	27.2	118%	105%

* B/A = bulk density of hops compacted by manual shaking (B) as compared to hops loosely filled (A); ** P/S = bulk density of Perle (P) as compared to Saaz (S).

The bulk densities were determined by weighing in a container with a volume of exactly 20 L. The cones were initially loosely filled (bulk density A) and then compacted by manual shaking (bulk density B). The shaking resulted in approx. 13–18% greater values. In addition, the difference in bulk density among the two investigated hop varieties was also observed. The bulk density of the freshly picked cones of the Perle variety was around 9–12% greater than that of the Saaz variety.

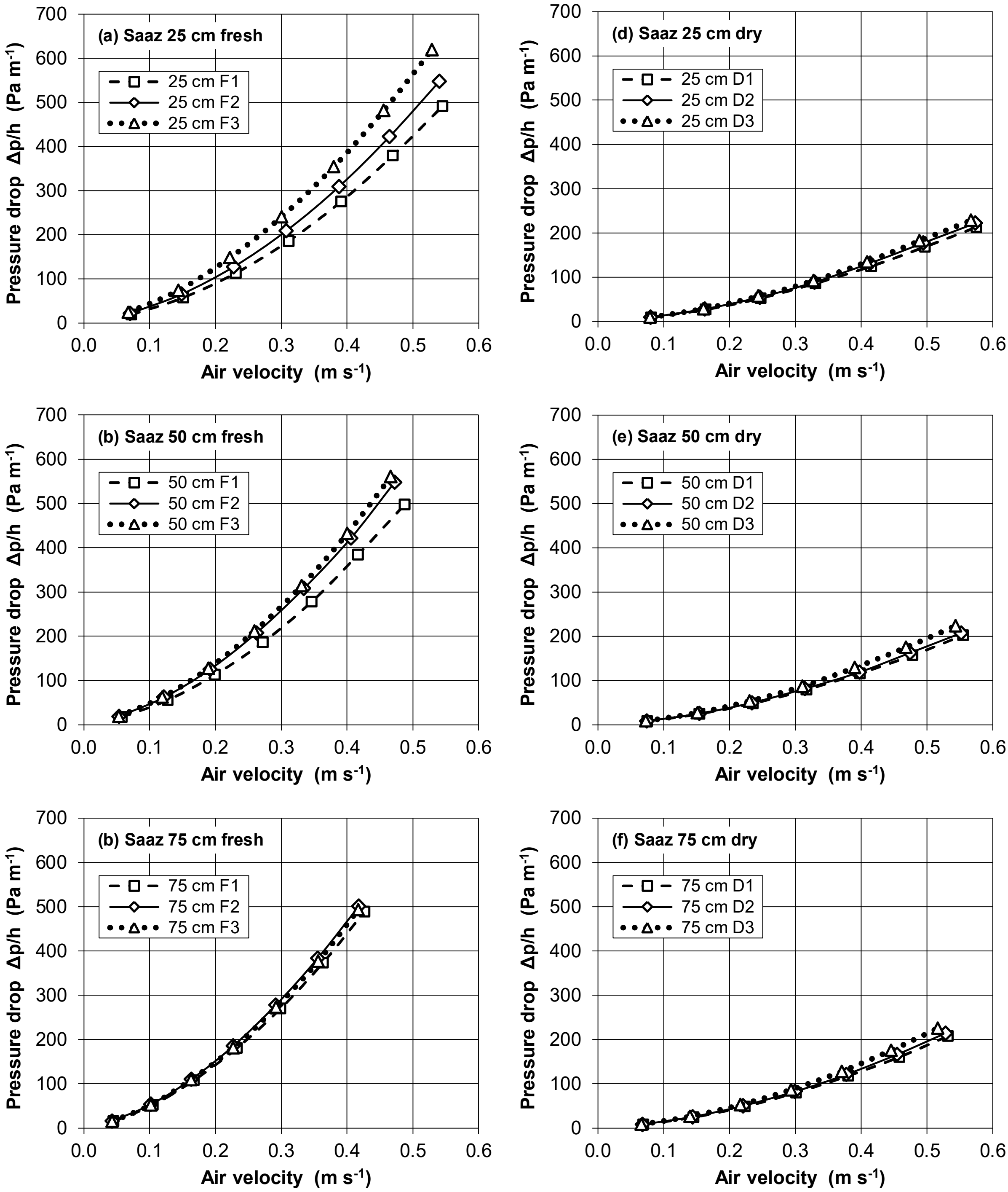

Figure 2. Pressure drop of the hop variety Saaz, measured at different air velocities, bed heights, and moisture contents.

The pressure losses of Saaz and Perle hops as a function of air velocity are shown in Fig. 2 and Fig. 3 respectively, both before and after drying ('fresh' und 'dry'). The values measured in the individual tests were related to the respective bed height and grouped accordingly. As already mentioned, each measurement was repeated three times. In Fig. 2 and Fig. 3, F1, F2, F3 denote measurements with fresh hop cones and D1, D2, D3 measurements with previously dried samples.

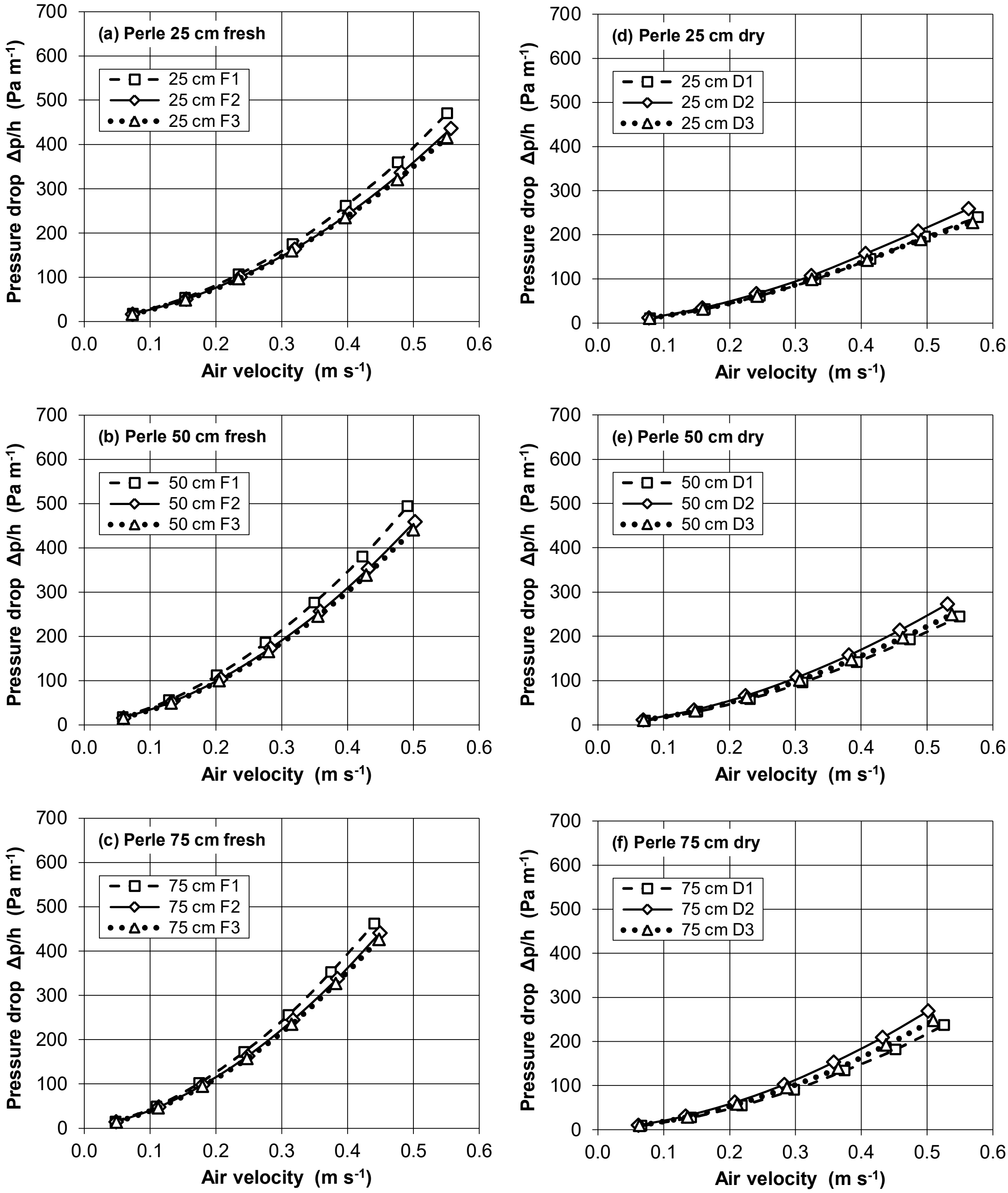

Figure 3. Pressure drop of the hop variety Perle, measured at different air velocities, bed heights, and moisture contents.

With a few exceptions (e.g. Fig. 2, a), the pressure loss curves lie generally very close to one another. The measurements with previously dried cones also give quantitatively very similar values (see Fig. 2, d–f and Fig. 3, d–f). In contrast, measurements with the fresh cones show quantitative differences in bed-height specific pressure drops (see Fig. 2, a–c and Fig. 3, a–c). In a double-logarithmic plot, pressure losses as a function of air velocity appear as virtual straight lines. Fig. 4 shows mean values formed from the individual measurements for the two hop varieties. The bed-height specific pressure drops recorded for fresh cones were significantly greater than that for previously dried cones. The values for fresh cones of both hop varieties increased with the height of the bed.

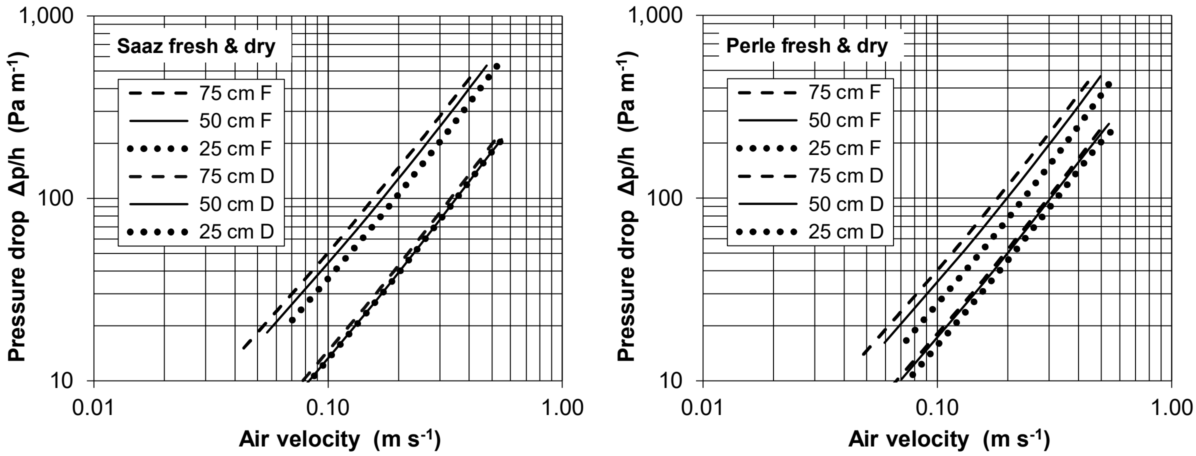

Figure 4. Pressure drop of the hop varieties Saaz and Perle, mean values at different air velocities, bed heights, and moisture contents.

In practice, the air velocity used for drying freshly harvested hops lies in the range of 0.3–0.4 m s^{-1}, although the actual values are subject to strong fluctuations (Münsterer, 2020). The cause of these fluctuations are ultimately differences in the structure of the packing and thus in the airflow resistance of the beds. Even within one hop variety, individual cones differ considerably in terms of size, shape and surface properties. Added to this are the size distribution of cones, the proportion of voids in the bed, as well as leaves and stems. In addition, changes in moisture content and bulk density during the drying process affect the effective airflow resistance. Hence, airflow resistance remains a dynamic variable throughout the course of drying.

In order to determine the parameters of Eqs (2) and (3), the slopes of the straight line in Fig. 4 were first calculated. The slopes in the double-logarithmic representation correspond to the exponent of air velocity, as shown below:

$$2 - n = \frac{\ln{(\Delta p/h)_6} - \ln{(\Delta p/h)_2}}{\ln{(w)_6} - \ln{(w)_2}} \tag{4}$$

The indices 2 and 6 denote the values of the corresponding height specific pressure drop and air velocity measured at 20 Hz and 60 Hz, respectively. The exponents calculated according to Eq. (4) are listed in Table 2. The mean value of the exponents was used for all further calculations ($2 - n = 1.63$).

The air temperature fluctuated only slightly around 22 °C in all measurements. Therefore, constant values for the dynamic viscosity ($\eta = 18.5 \cdot 10^{-6}$) N s m^{-2} and the density of the air ($\rho_a = 1.18$) kg m^{-3} were used, as opposed to temperature dependent ones. However, it must be noted that at higher temperatures, the temperature dependence of η and ρ_a must be considered. With the factors C_1 given in Table 2, all measured pressure losses could be predicted satisfactorily based on Eq. (2). The calculated pressure loss depends on air density and thus on temperature. Temperature deviations of less than 5 K lead to deviations in pressure loss of less than 1.1 % under the test conditions described. The freshly picked cones of the Perle variety caused significantly lower pressure loss values than the Saaz variety. On the other hand, the measured bulk density exhibited the opposite trend (see Table 1). Hence, the correlation between the pressure loss and the bulk density suggested by Matthies (1956) for stalk and leaf-shaped crops could not be satisfied.

Table 2. Parameters for calculating the pressure drop according to Eq. (2) and Eq. (3)

Hop variety		Saaz fresh	Perle fresh	Saaz dry	Perle dry
Exponent of air velocity					
$2-n$ at 25 cm		1.64	1.67	1.66	1.62
$2-n$ at 50 cm		1.61	1.63	1.65	1.62
$2-n$ at 75 cm		1.58	1.60	1.64	1.63
Mean of exponents	Ø 1.63	1.61	1.63	1.65	1.62
Factor C_1 in Eq. (2) *					
C_1 at 25 cm		$76.1 \cdot 10^3$	$56.4 \cdot 10^3$	$27.9 \cdot 10^3$	$32.2 \cdot 10^3$
C_1 at 50 cm		$93.5 \cdot 10^3$	$73.2 \cdot 10^3$	$28.2 \cdot 10^3$	$35.9 \cdot 10^3$
C_1 at 75 cm		$106.6 \cdot 10^3$	$85.1 \cdot 10^3$	$30.9 \cdot 10^3$	$37.9 \cdot 10^3$
Porosity ε (assumed)					
ε at 25 cm		0.420	0.420	0.420	0.420
ε at 50 cm		0.405	0.405	0.415	0.415
ε at 75 cm		0.390	0.390	0.410	0.410
Factor C_2 in Eq. (3) *					
C_2 at 25 cm		2,369	1,755	870	1,003
C_2 at 50 cm		2,490	1,970	836	1,066
C_2 at 75 cm		2,466	1,970	874	1,071

* Factors C_1 and C_2 calculated with mean of exponents $2 - n = 1.63$.

Matthies (1956) pointed out in particular that airflow resistance is inversely proportional to the fourth power of porosity. Since the porosity of hop beds is unknown, an attempt was made to estimate the influence. For this purpose, it was assumed that the volume of the void decreased proportionally to the height of the bed when the bed settled, more so for the fresh samples than for the dried ones. The assumed values for porosity ε and the resulting factors C_2 for Eq. (3) are given in Table 2. The factors C_2 were found to lie close to each other for the different bed heights investigated, albeit with differences between the two hop varieties. The absolute values depend strongly on the assumed porosity.

CONCLUSIONS

Knowledge of physical product properties is an important basis for both the design and the operation of dryers. The physicochemical properties of most agricultural products change considerably in the course of drying and hops are no exception to this. The airflow resistance of the material to be dried is not only a decisive factor for the choice of blowers, but also determines the distribution and utilization of the airflow inside the dryer, and thus the uniformity of the drying process. The throughput of conveyor-belt dryers, for example, is often controlled by monitoring the bed height. Consideration of the bulk density of different hop varieties facilitates an improved adjustment of belt speed. However, the different physical properties of hops depend not only on the variety. In addition, the growing conditions, ripening time, weather conditions and moisture contents also markedly affect the physical properties.

In this work, the airflow resistance of hop cones at different air velocities and bed heights was investigated experimentally. The key findings obtained from the measurements carried out with the varieties Saaz and Perle can be summarized as follows:

- The fresh samples of the two varieties showed markedly different bulk density. In contrast, only minor differences were observed among the dry samples.
- The airflow resistances of beds consisting of two hop varieties differed considerably. However, differences in pressure drop did not positively correlate with differences in bulk density.
- No linear relationship was ascertained between bed height and airflow resistance.
- The void fraction of a packed bed generally has a major influence on its airflow resistance. However, it would hardly be possible to experimentally establish the porosity of hops beds. The calculation of pressure loss curves with estimated porosity values confirmed that moist hop cones are presumably compressed, so that the void fraction decreases and the airflow resistance increases.

For modelling and simulation of hops drying, especially with computational fluid dynamics (CFD), sound knowledge of airflow resistance and bulk density is essential. This work has shown how targeted experiments can lead to valuable insights into predicting the dynamic airflow resistance of a hops bed. However, further systematic investigations are required to gain better understanding of the changes in bulk density during the course of drying, and to achieve an accurate model to reflect the reality within reasonable tolerance.

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