PRESSURE RESISTANCE DURING VENTILATION OF DIFFERENT TYPES OF WOOD CHIPS AS A FUNCTION OF PARTICLE SIZE AND PARTICLE FORM

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ABSTRACT: Pressure resistance during ventilation was measured for a high variety of wood chips (n = 95). Samples were produced using different raw materials and chipper settings. Physical fuel properties were analyzed according to European standards (bulk density, particle size distribution) but also by using a continuously measuring image analysis device (particle length, particle form). Pressure resistance (Pa m^{-1}) was measured within a custom build flow cylinder (2 m height, 0.4 m³ filling volume) and was related to volumetric flow rate. Four common models to describe pressure resistance were compared (Ramsin, Shedd, Hukill & Ives, Ergun). For all samples, pressure resistance increased exponentially with volumetric flow rate. Thereby, pressure resistance was highly variable, ranging from 11 to 190 Pa m^{-1} at 0.1 m s^{-1} and from 213 to 1240 Pa m^{-1} at 0.5 m s^{-1}. A mathematical model based on multiple linear regression analysis was created to express pressure resistance as a function of several fuel parameters. It indicates that pressure resistance strongly depends on particle size and particle form, as these factors influence the number, size and shape of air voids within wood chip piles. A simplified model version provides applicability of the results for the wood chip producing industry.
Keywords: drying, quality, wood chips, ventilation, pressure resistance

1 INTRODUCTION

Moisture content of wood chips influences the net calorific value, bulk density, combustion behavior and storability of the biofuel. Thereby, wood chips produced from recently cut material often incorporate high moisture contents > 50 m.-%. For small scale combustion units (i.e. boilers < 300 kW) optimal moisture content lies between 15 and 35 m-%. Thus, drying of wood chips is mandatory for the use in small scale systems.

Wood chips are often dried in large piles without application of external energy to the drying process. This so called "natural drying" occurs due to heating of the bulk material within the piles by respiratory processes during fungal wood decomposition. Shortcomings of "natural drying" are large dry matter losses, long storage times and the production and emission of hazardous fungal spores. Moreover, under certain conditions, "natural drying" might lead to self-ignition of the piles. "Artificial drying", i.e. drying of wood chips by ventilating using ambient or heated air through steady or moved piles may be a reasonable alternative to natural drying processes as it minimizes all above stated disadvantages. Usually, "artificial drying" utilizes an external heat source, e.g. excess heat of biogas and CHP plants during summer. With a suitable and cheap heat source given, drying efficiency is further enhanced by selecting cost and energy efficient drying fans. Thereby, dimensioning of driers depends on the desired volumetric flow rate and on the pressure resistance during ventilation. For wood chips, information on pressure resistance is scarce which often leads to oversizing of the drying fans. Correct prediction of pressure resistance is further complicated due to the high variability of physical wood chips qualities, such as bulk density, particle size or particle form.

The presented research aims at a better understanding of pressure resistance during ventilation of wood chips. Thereby, pressure resistance will be directly estimated using several other determined physical fuel properties. The results shall help to facilitate a fuel specific dimensioning of ventilation systems.

2 MATERIALS AND METHODS

2.1 Wood chip samples

Pressure resistance was measured for a high variety of wood chips samples (n = 95). Chips were collected from various production sites in Bavarian forest (n = 37), from short rotation forestry (n = 3) and from stationary chipping experiments at TFZ (n = 55). Wood chips were produced using different raw materials (e.g. stem wood, whole trees and forest residues from various tree species) and by using different chipper settings (e.g. different screen sizes, sharp and blunt knives, etc.). All samples were collected following European standard (DIN EN 14778 [1]).

2.2 Physical wood chip properties

All samples were analyzed for bulk density (*BD* in kg m^{-3}, DIN EN 15103 [2]) and moisture content (*MC* in m.-%, DIN EN 14774-2 [3]). Bulk density was calculated to a reference moisture content of 15 m.-% (BD_{15}) considering both shrinking and swelling of the particles at low *MC*. The compression behavior of wood chips during storage was estimated as the "stowage factor" (*SF* in m.-%), i.e. as the percentage difference in mass between bulk density with impact (i.e. according to DIN EN 15103 [2]) and without impact.

Particle size distribution was assessed by horizontal screening as weight fractions *F* (in m.-%) according to DIN EN 15149 [4]. For means of better comparison, all samples were dried to a reference *MC* of 15 m.-% before analysis.

In addition, particle size distribution and particle form were analyzed using a continuously measuring image analysis device (Haver-CPA 4, Haver & Boecker GmbH, Germany) allowing for highly detailed information on the size and shape of the bulk material (Fig. 1, [5]). For image analysis, wood chips were spread horizontally by means of a vibrating feed canal and a conveyor belt. After separation, each individual particle passed a light source opposite of a digital CCD camera (Fig. 1). The camera records 4096 pixels over a width of 400 mm, thus the resolution per pixel is 98 µm. From the retention time within the camera's scope and the recordings for the varying horizontal expansion, the size of each particle's two-dimensional silhouette is recorded and calculated by a computer. The image analysis determines particle size as "maximum particle length (*MaxL* in mm)" (i.e. arrow "B" in Fig. 2). In contrast, horizontal screening assesses particle size rather as particle width i.e. as the "minimal Feret Diameter" (*MinFer* in mm, see arrow "A" in Fig. 2).

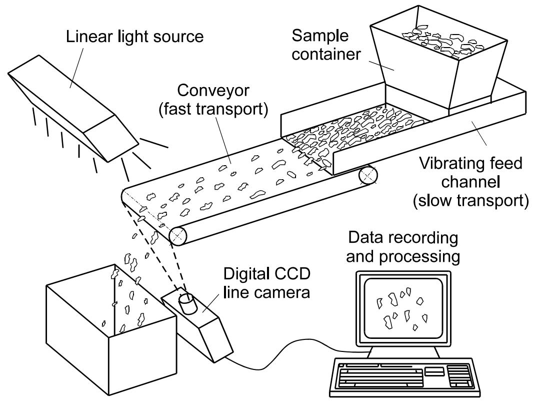

Figure 1: Schematic description of the continuously measuring image analysis device

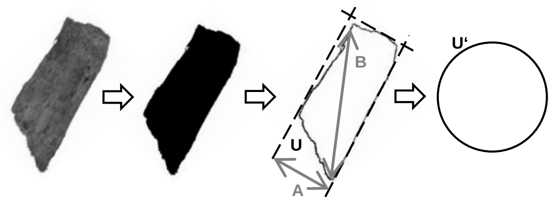

Figure 2: Measured parameters of the image analysis device (selection)

Particle size distribution by image analysis was characterized using the median particle size (*Median* in mm) and the 25 % and 75 % quartiles (Q_{25} and Q_{75} in mm, Fig. 3). Furthermore, mean values for *MaxL* and *MinFer* were calculated by weighting mean values of each particle size class to the respective particle fraction.

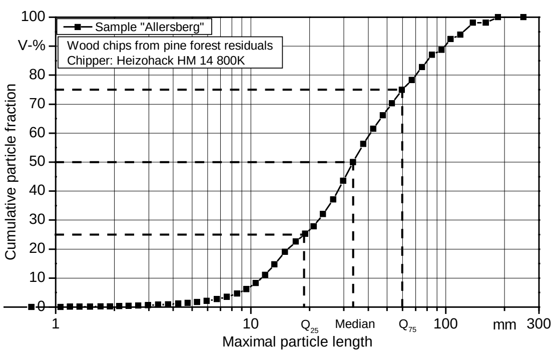

Figure 3: Example for a particle size distribution measured with the image analysis device

Particle shape was assessed as the "particle shape factor" (*PSF*, Fig. 2) and as the "length to width ratio" (*LW*). The *PSF* is defined as the quotient of the particle circumference (*U*) and the circumference of a coextensive circle (*U*'). A high *PSF* characterizes a high deviation from a perfect round shape having a shape factor of 1. In the narrow sense the *PSF* is a parameter which characterizes the degree of a particle's approximation towards an ideal sphere. However, with the here applied image analysis a three-dimensional measurement cannot be performed. Instead of a volume the calculation is thus related to the two-dimensional silhouette area (Fig. 2).

The "length to width ratio" (*LW*) is calculated as the quotient of *MaxL* and *MinFer*. Both *PSF* and *LW* were weighted to the fractions of the respective particle size classes. Table I summarized all parameters used to characterize physical fuel properties of wood chips.

Table I: Parameters to describe physical fuel properties of wood chips

Parameter	Abbreviation	Unit
EU Standard parameters		
Bulk density (15% *MC*)	BD_{15}	kg m^{-3}
Moisture content	*MC*	m.-%
Stowage factor	*SF*	m.-%
Particle fractions x – y mm	*F*(x-y)	m.-%
Image analysis parameters		
Median	*Median*	*mm*
25%-Quartile	Q_{25}	mm
75%-Quartile	Q_{75}	mm
Maximal length (weighted)	*MaxL*	mm
Minimal Feret Diameter (weighted)	*MinFer*	mm
Particle shape factor (weighted)	*PSF*	-
Length to width ratio (weighted)	*LW*	-

2.3 Pressure resistance measurement

Pressure resistance during ventilation of wood chips (ΔP in Pa m^{-1} bulk material) was measured in a specially designed flow cylinder of 2 m height and 0.4 m³ filling volume (Fig. 4). For each measurement, the cylinder was filled completely with bulk material. The cylinder was attached to a wooden basis of 1000 x 1500 x 500 mm. A blower (TLR, Himel Maschinen GmbH & Co. KG, Germany) ventilated ambient air through the cylinder at adjustable air flow rates. Thereby, air flow (*V* in m s^{-1}) was continuously measured by a flow meter (TERZ 94, RMG Messtechnik GmbH, Germany, Fig. 4).

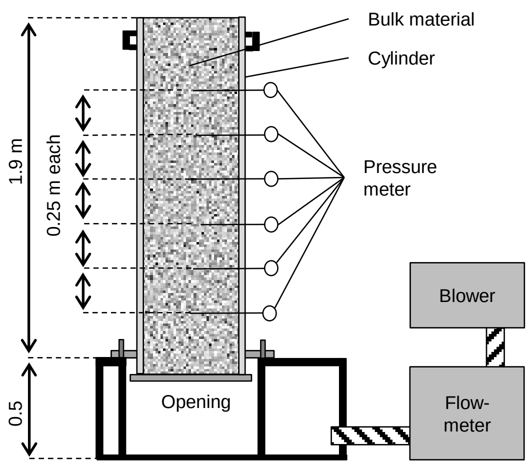

Figure 4: Schematic design to measure pressure resistance of wood chips

Pressure resistance ΔP was assessed for each wood chip sample by measuring static pressure at 6 heights within the cylinder at a constant air flow. A metal tube was injected into the cylinder at 1 of 6 openings (Ø = 5 mm, distance = 25 cm, Fig. 4). Total height of the wood chip column above the lowest opening was 1.6 m. The metal tube was connected to 1 of 3 pressure meters by a PVC tube. Pressure meters covered the range of 0 to 2500 Pa (P26, Halstrup-Walcher GmbH, Germany). Pressure resistance (ΔP) was then calculated at a given blower speed as the slope of a linear regression between the height of the wood chip column and the static pressure (see Fig. 5).

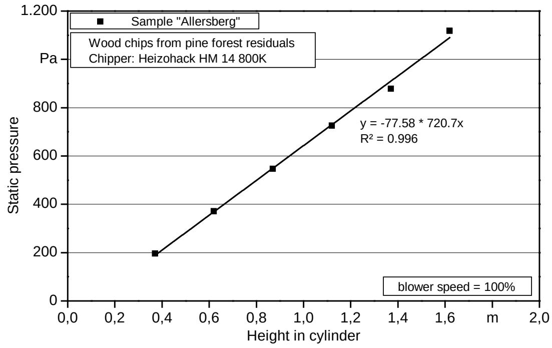

Figure 5: Example for the calculation of pressure resistance using a linear regression between the height of the wood chip column and static pressure

For each wood chip sample, ΔP was measured at 11 different air flow rates (0 to 100 % blower speed in 10 % intervals) and related to volumetric flow rate V (see Fig. 6). For each wood chip sample, the measurement was performed twice, whereby the cylinder was emptied and refilled between the experiments.

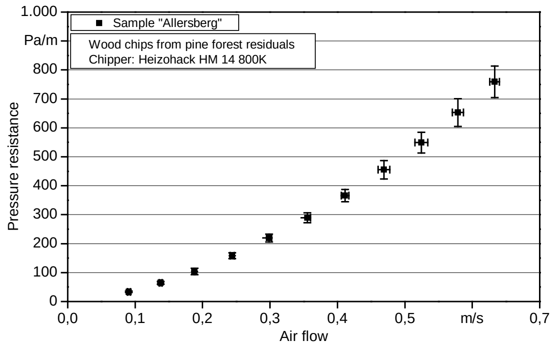

Figure 6: Example for the relationship between pressure resistance and air flow

2.4 Modeling of pressure resistance

Throughout literature, four equations are commonly used to relate ΔP to V. The equations are referred to as the models according to "Ramsin", "Shedd", "Hukill & Ives" and "Ergun". Each equation defines the relationship between ΔP and V using two material specific parameters a and b:

(I) Ramsin $\Delta P = a_1 V^{b_1}$

(II) Shedd $V = a_2 \Delta P^{b_2}$

(III) Hukill & Ives $\Delta P = \frac{a_3 V^2}{\ln(1 + b_2 V)}$

(IV) Ergun $\Delta P = a_4 V + b_4 V^2$

The common procedure to report pressure resistance is to fit the experimental data with one of the four equations. Afterwards, parameters a and b are simply reported for the measured bulk material (e.g. ASAE D272 [6]). Selection of one equation is often done randomly and an evaluation between different models is seldom done [7]. In the present study, experimental data of each wood chip sample (n = 95) was fitted using all four equations and the precision of the regressions was compared.

Multiple linear regression analysis was performed to estimate parameters a and b of the Ramsin (I) and the Ergun (IV) equation by physical fuel parameters, directly (Table II). Pressure resistance models were developed on basis of the modeled parameters a and b. Thus, one pressure resistance model incorporated the results of two multiple linear regression analyses, one for parameter a and one for parameter b. Two sets of variables were used for multiple linear regression, providing a "scientific" and a "simplified" approach (Table II). All parameters were used as single values (X), squared values (X^2) and as the cross product between values (X*Y). In short, the "scientific" models use bulk density and all image analysis parameters, i.e. they utilize detailed information on particle size and particle form. In contrast, the "simplified" models aims at easy measures for the wood chip producing industry, using only bulk density, the stowage factor and two particle fractions from horizontal screening, one for the amount of small particles (< 3.15 mm) and one for larger particles (> 16 mm).

Table II: Sets of parameters for multiple linear regression analysis

Model	Parameters
Scientific	BD_{15}, *Median*, Q_{25}, Q_{75}, *MaxL*, *MinFer*, *PSF*, *LW*
Simplified	BD_{15}, SF *F*(<3), *F*(>16)

In addition to the distinction between "scientific" and "simplified", models were developed for two sets of wood chips, (i) using all experimental data ("wood chip models") and (ii) using a subset of wood chips produced from coniferous wood ("conifer chips models"). The latter was performed because artificial drying of wood chips was deemed more relevant for boreal areas with high abundance of coniferous wood. Thus, a total of 8 pressure resistance models were developed, incorporating two multiple linear regression analyses for each model.

Sensitivity analysis was performed for each model to uncover the influence of individual fuel parameters on ΔP. For sensitivity analysis, ΔP was calculated for the respective model using mean values of all model parameters. In the next step, each individual variable was varied from 50 to 150 % while all other parameters were kept constant. The respective change in ΔP was evaluated graphically.

3 RESULTS & DISCUSSION

3.1 Physical fuel quality

Physical wood chip parameters were highly variable among samples, covering a wide range of different fuel qualities (Table III). Mean bulk density BD_{15} was 214 kg m^{-3}, ranging from 125 for Norway spruce stems chipped with blunt knives to 311 kg m^{-3} for chips produced from forest residues of European beech. The high variety of fuel qualities can be related to the high variety of different raw materials and chipper settings. Thereby, the collected samples were considered to cover the whole range of possible wood chip qualities from Bavarian production sites.

Table III: Range of physical fuel parameters of all wood chip samples

Parameter	deciduous	conifers
BD_{15}	171 – 311	125 - 239
MC	12.5 – 56.0	13.3 – 64.0
SF	7.1 – 14.6	7.3 – 15.4
Median	11 – 104	21 - 55
Q_{25}	7 – 53	13 – 30
Q_{75}	15 – 169	29 – 102
PSF	1.3 – 4.0	1.4 – 3.4
LW	2.0 – 6.9	2.2 – 7.9
MaxL	12 – 120	25 – 75
MinFer	5 – 30	7 - 27

3.2 Pressure resistance of wood chips

In accordance with the high variety in wood chip quality, pressure resistance ΔP varied strongly among individual wood chip samples (Fig. 7) ranging from 11 to 106 Pa m^{-1} at 0.1 m s^{-1} and from 213 to 1240 Pa m^{-1} at 0.5 m s^{-1}, respectively (Table IV).

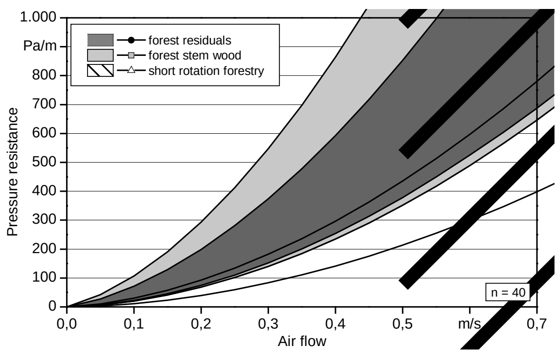

Figure 7: Pressure resistance of wood chips from forest residuals, forest stem wood and short rotation forestry

Table IV: Range of pressure resistance in Pa m^{-1} for wood chips produced from different raw materials

Data set	V = 0.1 m s^{-1}	V = 0.5 m s^{-1}
Stem wood	20 – 106	350 - 1240
Forest residuals	22 – 71	380 – 850
Short rotation forestry	11 – 30	213 – 435

Pressure resistance was minimal for willow chips from short rotation forestry and maximal for chips from Norway spruce stem wood chipped with small screen sizes (30 x 30 mm). In total, the variety in ΔP was highest for wood chips produced from stem wood, followed by chips from forest residuals and from short rotation forestry (Table IV). Variation was also high using the same raw material (e.g. spruce stem wood = 24 to 106 Pa m^{-1} at 0.1 m s^{-1}). Thus, the variation is also strongly related to the high amount of different chipper settings used during production. Consequently, general predictions on pressure resistance are complicated even for wood chips produced from the same raw material.

3.3 Mathematical description of pressure resistance

All four equations (Ramsin, Shedd, Hukill & Ives and Ergun) described the relationship between ΔP and V precisely (Table V). Coefficients of determination (R^2) were always > 0.998 for all calculations. Moreover, deviations between predicted and measured ΔP were constantly within the range of ± 0.3 % of the measured value (Fig. 8). The equation according to Shedd was not used for further investigation, as it relates V to ΔP, whereas all other equations relate ΔP to V.

Table V: Mean coefficient of determination (R^2) for the regressions between air flow and pressure resistance

Equation	Mean R^2
Ramsin	0.9997
Shedd	0.9997
Hukill & Ives	0.9998
Ergun	0.9997

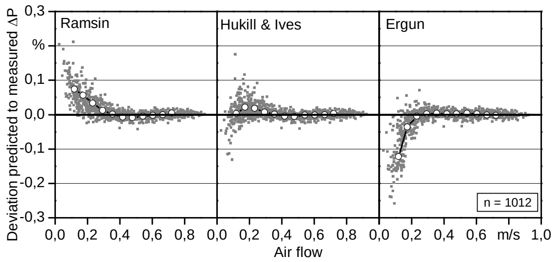

Figure 8: Deviation between measured and predicted pressure resistance

Overall, best results were obtained with the equation according to Hukill & Ives (Fig. 8). However, due to the high precision of each equation, this improvement was negligible and all commonly used equations were deemed suitable to describe experimental results on pressure resistance of wood chips.

Table VI: Range of model parameters a and b for wood chips

Equation parameter	observed range
Ramsin a	683 - 3580
Ramsin b	1.55 – 1.93
Hukill & Ives a	3657 - 12158
Hukill & Ives b	19 - 15648
Ergun a	35 - 764
Ergun b	603 - 3460

Parameters a and b are not interchangeable in between equations as they cover completely different ranges (see Table VI). Thus, comparison of studies on pressure resistance are complicated by the use of different model equations. Moreover, data reported in the literature usually comprise only a small number of samples and may not cover the whole range of different fuel qualities (Table VI). This may be especially true in case of wood chips, as general presentations of absolute or mean values for a and b cannot provide enough information to cover the variability of ΔP. Thus, instead of reporting absolute but overgeneralized values for a and b, multiple linear regressions analysis was performed to calculate a and b directly from physical fuel properties.

3.4 Scientific model

The "scientific" model approach aimed at a comprehensive understanding of ΔP, incorporating values for bulk density, particle size and particle form. Only Ramsin's and Ergun's equations were used for model development, since multiple linear regressions could not be applied to the parameters a and b of Hukill & Ives' equation, successfully ($R^2 < 0.5$).

The "scientific" model was able to estimate the parameters a and b of Ramsin's and Ergun's equation with high precision. Coefficients of determination (R^2) were always > 0.831 (Table VII).

Table VII: Coefficient of determination (R^2) of multiple linear regression for parameters a and b

Model parameter	R^2 (a)	R^2 (b)
Ramsin (wood chips)	0.837	0.842
Ramsin (conifer chips)	0.894	0.918
Ergun (wood chips)	0.867	0.831
Ergun (conifer chips)	0.912	0.865

Estimations provided higher R^2 when using samples from coniferous wood compared to analyses using the whole range of all wood chip samples. Individual fuel parameters, such as *SF*, Q_{75}, *MaxL* and (in case of the conifer model) *Median* could be omitted from the models, as they didn't provide an improvement of R^2. Equations (V) and (VI) give modeling results for parameters a and b of the "scientific wood chip" model according to Ergun's equation.

$$
\begin{aligned}
\text{(V)}\quad \text{Ergun a} = {} & 58.7 \\
& + 88.1 \times LW \\
& + 1.65 \times MinFer^2 \\
& + 0.08 \times BD_{15} \times Median \\
& - 0.15 \times BD_{15} \times MinFer \\
& + 0.26 \times Q_{25} \times Median \\
& - 10.9 \times Q_{25} \times PSF \\
& + 8.4 \times Median \times KFF \\
& - 4.1 \times Median \times LW \\
& - 1.13 \times Median \times MinFer \\
& + 16.9 \times PSF \times LW
\end{aligned}
$$

$$
\begin{aligned}
\text{(VI)}\quad \text{Ergun b} = {} & 685{,}6 \\
& - 438 \times PSF \\
& + 523 \times LW \\
& - 3.2 \times Q_{25}^2 \\
& + 7.8 \times MinFer^2 \\
& + 0.25 \times BD_{15} \times Median \\
& - 0.36 \times BD_{15} \times MinFer \\
& + 2.76 \times Q_{25} \times Median \\
& + 21.9 \times Median \times PSF \\
& - 15.3 \times Median \times LW \\
& - 5.78 \times Median \times MinFer
\end{aligned}
$$

Equations (VII) and (VIII) give modeling results for parameters a and b of the "scientific conifer chip" model according to Ergun's equation.

$$
\begin{aligned}
\text{(VII)}\quad \text{Ergun a} = {} & -68.89 \\
& - 38.2 \times Q_{25} \\
& + 156.8 \times LW \\
& + 32.8 \times MinFer \\
& - 0.01 \times BD_{15}^2 \\
& - 229.9 \times PSF^2 \\
& + 4.22 \times LW^2 \\
& + 4.92 \times BD_{15} \times PSF \\
& - 0.58 \times BD_{15} \times LW \\
& + 11.9 \times Q_{25} \times PSF \\
& - 8.76 \times LW \times MinFer
\end{aligned}
$$

$$
\begin{aligned}
\text{(VIII)}\quad \text{Ergun b} = {} & 2991 \\
& - 289.9 \times Q_{25} \\
& - 3917.7 \times PSF \\
& + 1378.9 \times LW \\
& + 297 \times MinFer \\
& + 1.30 \times BD_{15} \times Q_{25} \\
& + 11.5 \times BD_{15} \times PSF \\
& - 3.59 \times BD_{15} \times LW \\
& - 2.07 \times BD_{15} \times MinFer \\
& + 143.7 \times PSF \times MinFer \\
& - 50.9 \times LW \times MinFer
\end{aligned}
$$

Linear regressions between measured and predicted ΔP were calculated for air flow rates of 0.1 to 0.5 m s^{-1}. Air flow rates > 0.5 m s^{-1} may lead to emission of fine material from the dryer and also increase energy costs. Thus, they were deemed irrelevant for the calculations on model precision (Fig. 9). Standard error of performance (SEP), i.e. the standard deviation of the residuals, was 40.6 and 33.1 Pa m^{-1}, respectively. Maximal difference between measured and predicted ΔP was ± 203 Pa m^{-1}.

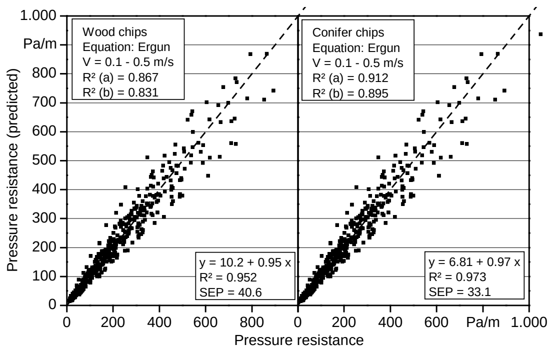

Figure 9: Linear regression of predicted to measured pressure resistance (scientific model using Ergun's equation).

A sensitivity analysis of the scientific model provided detailed insight into the dependence of ΔP on individual fuel properties. Results were similar between the "wood chips" and "conifer chips" model (Fig. 10 and 11). In both cases, increasing values for BD_{15} and *PSF* led to strong increases in ΔP. In contrast, increasing Q_{25}, *LW* and *MinFer* decreased ΔP.

High bulk densities may lead to a stronger compression of the loose material during the filling of the storage room when the fuel is being dropped down from an outlet and is thus having a higher kinetic energy than a low bulk density fuel. The higher weight of high bulk density fuels might therefore minimize the size of air voids within the wood chip pile. Smaller air voids might provide higher barriers for air flow compared to bigger voids, leading to an overall higher ΔP during ventilation.

High *PSF* represents very heterogeneous particles that strongly deviate from the prefect round shape. Thus, high *PSF* indicates rough surface structures which may provide additional barriers for air flow and increase the turbulences of the air flow in the bulk material.

A high Q_{25} represents a low amount of fine material, indicating that average air void size is bigger compared to samples with small Q_{25}. Similarly, a high "length to width ratio" (*LW*) and large particle diameters (*MinFer*) might increase the size of air voids in piles and thus facilitate the passage of ventilation air.

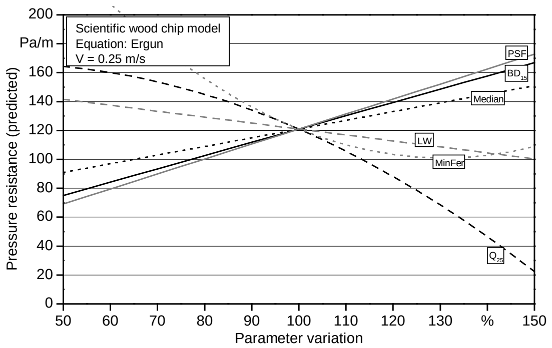

Figure 10: Sensitivity analysis of the scientific model (Ergun's equation) for pressure resistance of wood chips

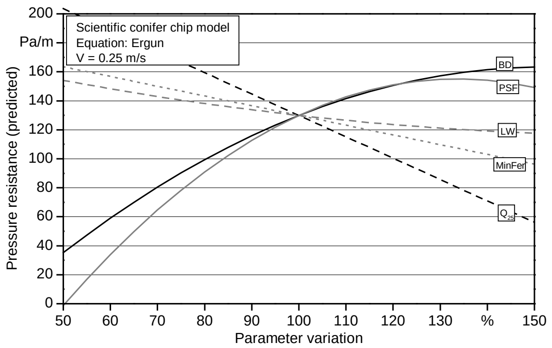

Figure 11: Sensitivity analysis of the scientific model (Ergun's equation) for pressure resistance of conifer wood chips

3.5 Simplified model

In contrast to the "scientific" models, the "simplified" models for wood chips and conifer chips didn't aim at a detailed understanding of pressure resistance, but at a practical applicability of these models for the wood chip producing industry. Producers should be able to measure the required model parameters with simple and cost efficient methods. Parameter selected were BD_{15}, *SF* and the particle size fraction provided by two screens, i.e. the particle size fraction < 3.15 mm and > 16 mm.

Coefficients of determination of the simplified models were lower than for the scientific models but still quite high ($R^2 > 0.683$, Table VIII). A lower model precision was deemed acceptable, as it makes use of parameters which are determined by broadly available measuring devices. Maximal deviation between predicted and modeled ΔP of the simplified models was $< \pm 310$ Pa m^{-1} for air flow rates from 0.1 to 0.5 m s^{-1} (Fig. 11).

Table VIII: Coefficient of variation (R^2) of multiple linear regression for parameters a and b of Ramsin and Ergun's equation

Model parameter	R² (a)	R² (b)
Ramsin (wood chips)	0.703	0.750
Ramsin (conifer chips)	0.774	0.841
Ergun (wood chips)	0.764	0.683
Ergun (conifer chips)	0.848	0.765

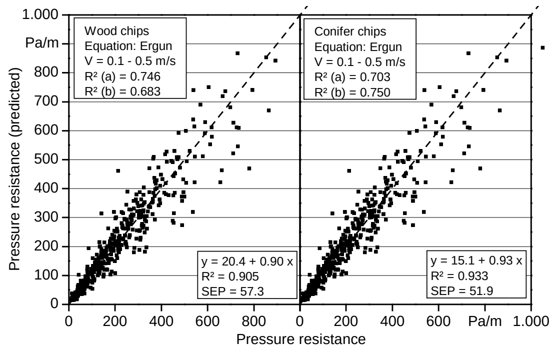

Figure 12: Linear regression of predicted to measured pressure resistance (simplified model using Ergun's equation).

Equations (IX) and (X) give modeling results for parameters a and b of the "simplified wood chip" model according to Ergun's equation:

(VIII) Ergun a =112
$+ 4.19 \times BD_{15}$
$- 29.4 \times SF$
$- 9.5 \times F(>16)$
$- 0.01 \times BD_{15}^2$
$- 0.51 \times F(<3)^2$
$+ 0.03 \times F(>16)^2$
$+ 0.14 \times BD_{15} \times F(<3)$
$+ 0.56 \times SF \times F(>16)$
$- 0.14 \times F(<3) \times F(>16)$

(IX) Ergun b = 3648
$- 172 \times SF$
$- 59.3 \times F(>16)$
$- 1.01 \times F(<3)2$
$+ 0.22 \times F(>16)2$
$+ 0.30 \times BD_{15} \times F(<3)$
$+ 2.85 \times SF \times F(>16)$

Equations (XI) and (XII) give modeling results for parameters a and b of the "simplified conifer chip" model according to Ergun's equation:

(X) Ergun a = 480
$- 44.86 \times SF$
$- 8.23 \times F(>16)$
$+ 0.0025 \times BD_{15}^2$
$- 0.556 \times F(<3)^2$
$+ 0.170 \times BD_{15} \times F(<3)$
$+ 0.835 \times SF \times F(>16)$
$- 0.248 \times F(<3) \times F(>16)$

(XI) Ergun b = 1755
- 22.2 x $F(>16)$
+ 0.095 x BD_{15}^{2}
- 2.66 x $F(<3)^{2}$
- 2.136 x BD_{15} x SF
- 0.149 x BD_{15} x $F(>16)$
+ 11.5 x SF x $F(>3)$
+ 4.78 x SF x $F(>16)$
- 0.847 x $F(<3)$ x $F(>16)$

Sensitivity analyses of the simplified models provide similar results compared to the scientific models (Fig. 13 and 14). For both, the simplified "wood chips" and "conifer chips" model, increases in BD_{15} and $F(<3)$ lead to an increase in ΔP, while the opposite is observed for *SF* and $F(>16)$. The results confirm results from the scientific model in that a high amount of fine particles ($F(<3)$) lead to smaller air voids and high amount of large particles ($F(>16)$) lead to bigger voids in the piles, thereby increasing and decreasing barriers for air flow, respectively. Moreover, a high *SF* indicates a high amount of large voids before compression. Thus, wood chip piles with high *SF* may have overall larger air voids and fewer barriers for air flow.

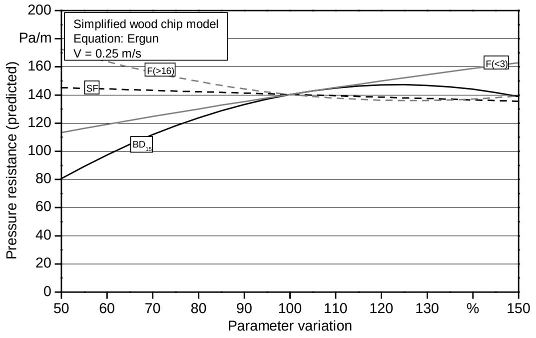

Figure 13: Sensitivity analysis of the simplified model for pressure resistance of wood chips

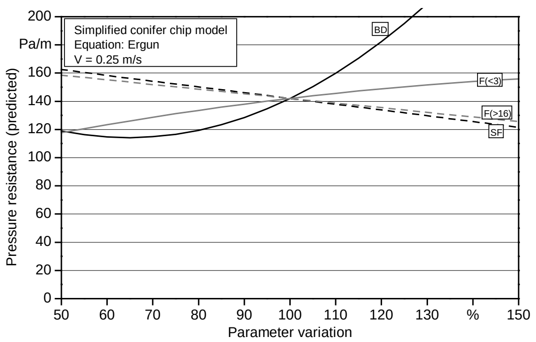

Figure 14: Sensitivity analysis of the simplified model for pressure resistance of coniferous wood chips

Interestingly, the influence of BD_{15} on ΔP was more pronounced in the conifer chips model compared to the wood chips model. In the present study, conifer chips were mainly produced from spruce and pine wood. Since spruce and pine have rather similar particle densities, bulk density increases in the "conifer model" manly due to higher amounts of dry matter per m³. Consequently, compared to the "wood chip" model, a high bulk density in the simplified conifer model clearly indicates a further decrease of open voids, resulting in overall higher ΔP.

4 CONCLUSION

Pressure resistance ΔP was strongly related to particle size and particle form. Changes in ΔP most likely result from differences in the amount, size and structure of air voids within wood chip piles. Air voids are directly affected by particle size distribution, particle shape and particle form. Modeling of ΔP using the Ramsin equation led to similar results as with the here presented Ergun's equation. Moreover, sensitivity analysis showed similar dependencies of ΔP for air flow ranges from 0.1 to 0.7 m s^{-1}. Thus, model equations were deemed suitable for a wide range of different air flow rates.

Overall, the scientific model provides a detailed insight into the dependence of ΔP on fuel specific properties, whereas the simplified model provides an easy and rapid measure to estimate ΔP for a wide range of wood chip qualities.

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7 LOGO SPACE

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