



Research paper

Experimental investigation on the influence of different grades of wood chips on screw feeding performance



Michael Rackl^{*}, Willibald A. Günthner

Institute for Materials Handling, Materials Flow and Logistics, Technical University of Munich, Boltzmannstraße 15, 85748 Garching, Germany

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ABSTRACT

Although basic investigations on wood chip material properties have been carried out, only few studies deal with transport of wood chips, despite the fact that significant problems are commonly observed when feeding biomass in industrial applications. Within the work presented, basic bulk material properties were measured and experiments carried out with a system consisting of a hopper, agitator and a screw conveyor. The aim of this study was to investigate how three different wood chip grades and two blends of wood chips influence typical design parameters, such as mass flow and driving torque, of a biomass feeding system. The measured basic bulk properties are in good overall agreement with the literature. However, discrepancies were discovered between two standardized methods for determination of the bulk density. The results for the driving torque, mass flow and mass-related energy consumption showed that different grades of wood chips can alter these values considerably. Between two wood chip grades, a twice as high torque was recorded, while a third grade could not be fed due to jamming. One of the major findings of this study is that mixing a rather small amount of a high-fine content grade with the non-feedable grade of wood chips resulted in a blend which inhibited jamming during the screw feeding process.

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1. Introduction

Basic investigations on wood chip material properties were carried out in the past [1–5]. Over the past years, wood chips were increasingly investigated, focusing on different areas of application, such as rotary kilns, fixed-beds or bridging behavior (e. g. Refs. [6–8]). A recent study by Stasiak et al. [9] is one of the more comprehensive ones, which also provides a good overview on published wood chip-related research. Only few studies deal with transport of wood chips or biomass respectively, even though “(t)he probability of significant problems is 80% for biomass feeding systems according to industrial experience” [10].

Screw conveyors are amongst the most used materials handling equipment in biomass feeding. They are generally widely applied in bulk materials handling, but there exist relatively few information on design aspects in standards [11,12]. Apart from the development of theoretical models for screw feeding loads [13,14], discrete element simulations are applied to predict driving torque and critical flow states, such as blocking, for a wide range of bulk solids

(e. g. Refs. [15–17]). Nonetheless, experiments are vital for validation of all of these models, because even similar bulk solids can exhibit considerably different flow behavior and the influence of the respective handling equipment is significant.

Dai et al. [10] listed 18 energy-related biomass projects, of which most featured systems with hoppers and screw conveyors, and nine in particular used bottom-feeding screw feeders. Research on biomass screw feeding is rarely available [18–20] and as of August 2015 the authors of this work are not aware of any published content of significant interest on screw feeding of wood chip blends.

Bulk material handling equipment for wood chips is mainly designed based on experience, as the flow behavior of wood chips is intricate, due to effects, including catching of particles and particle deformation [10]. There are few experimental studies on wood chip feeding with complex bulk material handling equipment in existence [20,21] and the examined particle sizes of the wood chips were relatively small (fines to 15 mm).

The aim of this work was to study the influence of three different grades of wood chips as well as two blends for typical screw conveyor feeding-related parameters. These were the driving torque, mass flow, hopper discharge pattern and mass-related

^{*} Corresponding author.

E-mail address: rackl@fml.mw.tum.de (M. Rackl).

energy consumption of a wedge-shaped hopper with horizontal agitator and bottom-feeding screw feeder.

2. Materials and methods

Three different wood chip grades, chosen by visual inspection, were subject to several bulk material property measurements and further experimental investigation, involving a hopper/agitator/screw conveyor system.

2.1. Wood chip samples

The tested wood chips were supplied by a local company and consisted of spruce for the largest part. A more detailed description cannot be given here, since the supplier does not keep track of provenance, species and cultivar processed. The chain of custody is unknown to the authors, who believe that the samples used in this study exemplify the characteristic handling properties of softwood chips.

Sample 1 (S1, Fig. 1a) and sample 2 (S2, Fig. 1b) were good quality wood chips (stem wood), with just a small percentage of bark. Sample 3 (S3, Fig. 1c) however consisted of a considerable amount of spruce needles and fines (forest wood chips). The blends B1 and B2 were created by manually mixing wood chips from S1 and S3 according to Table 1. Mixing was carried out by separating the materials to mix into two heaps and alternately tossing them onto each other with shovels, forming a third heap. Subsequently, the third heap was divided into two heaps again and the process repeated approximately five times, until a homogeneous mixture was obtained.

2.2. Basic bulk material properties characterization methods

Five basic bulk material properties of the sample materials were measured using the following methods.

2.2.1. Particle size distribution

The particle size distribution was determined according to [22]. It was measured for the three basic samples S1, S2 and S3, using sieves of the sizes 1, 3.15, 4, 8 and 16 mm, which allowed for classification < 1 of the following particle size fractions, 1–3.15, 3.15–4, 4–8, 8–16 as well as > 16 mm.

2.2.2. Moisture content

The moisture content of the wood chip samples was measured conforming to [23]; determination of the weight loss during drying at 105 °C until a constant weight is reached. It is reported as the water mass fraction of the materials as received.

Table 1

Sample descriptions; blends are based on mass fraction (%).

Sample	Blend	Consists of
S1	no	
S2	no	
S3	no	
B1	yes	S1: 30%, S3: 70%
B2	yes	S1: 70%, S3: 30%

2.2.3. Bulk density

Bulk density was determined using an open-bottom cylindrical steel container with a diameter of 56.5 cm (custom container). Placed on concrete floor, it was filled with sample material up to a height of 58 cm (equals 145.42 dm³). Using this method, the bulk density was measured three times for each sample ($N=3$). In addition, poured and tapped bulk density was measured according to a European and a German standard [24,25].

2.2.4. Angle of repose

The angle of repose was determined by using the custom container and filling height as described in subsection 2.2.3. After filling with the respective sample, it was lifted vertically at a speed of 0.40 ms⁻¹. From the generated heap of material, the angle of repose was determined, following the instructions for measuring in Ref. [26] and the overall process was repeated five times for each sample ($N=5$).

2.2.5. Angle of slip

The angle of slip measurement was carried out on mild steel sheet metal and repeated ten times ($N=10$) for each of the base samples. The surface roughness of the cold-rolled sheet metal was Rz 100, according to [27].

2.3. Screw feeder experiments

The screw feeder experiments described in this subsection were carried out at room temperature. Since wood chips tend to form bridges over openings [4,8], a horizontal agitator constantly stirred the wood chips inside the hopper.

2.3.1. Test setup and procedure

The feeding experiments were carried out with a screw feeder, which was mounted underneath a wedge-shaped hopper with a horizontal agitator, as shown in Fig. 2. The base screw auger parameters are listed in Table 2. It consists of two sections with different pitches ($p(L1)=160$ mm, $p(L2)=140$ mm). Fig. 3 depicts the side view from the left of Fig. 2 and shows the hopper dimensions in addition to the rotational directions of the screw conveyor and

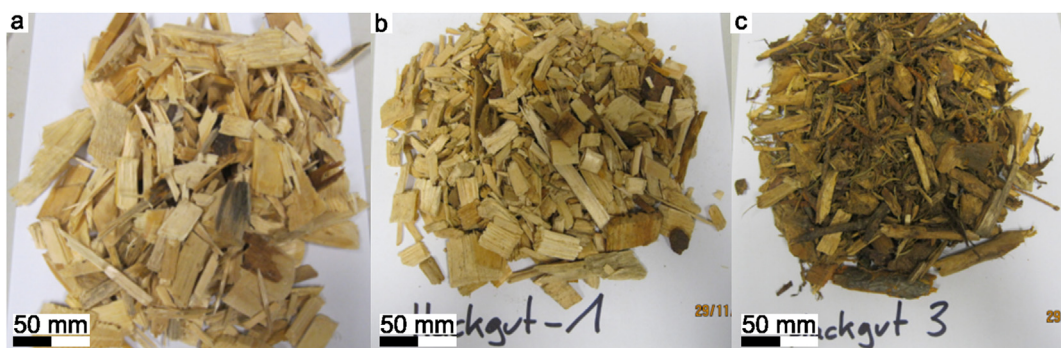


Fig. 1. Photographs of the three base wood chip samples S1 (a), S2 (b) and S3 (c).

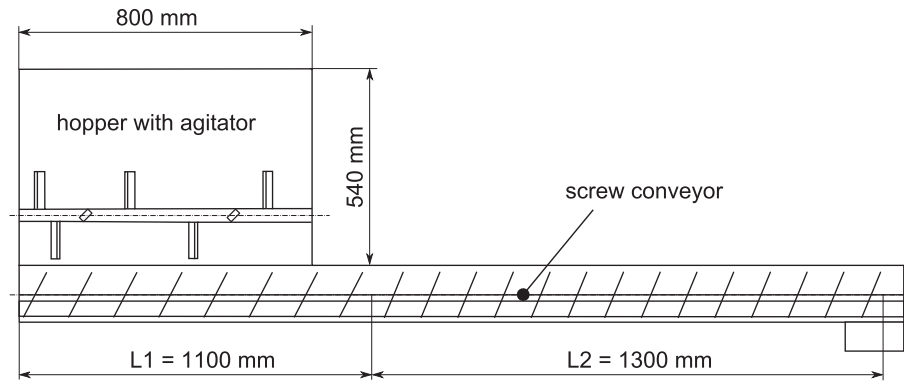


Fig. 2. Screw feeder consisting of a hopper with horizontal agitator (upper left) and screw conveyor (bottom). The auger pitch is divided into two sections with different pitches ($p(L1)=160$ mm and $p(L2)=140$ mm).

Table 2
Base screw auger properties.

Property	Specification
flight diameter	120 mm
shaft diameter	50 mm
clearance to trough	11 mm
pitch p_1^a	160 mm
pitch p_2^a	140 mm

^a See Fig. 2.

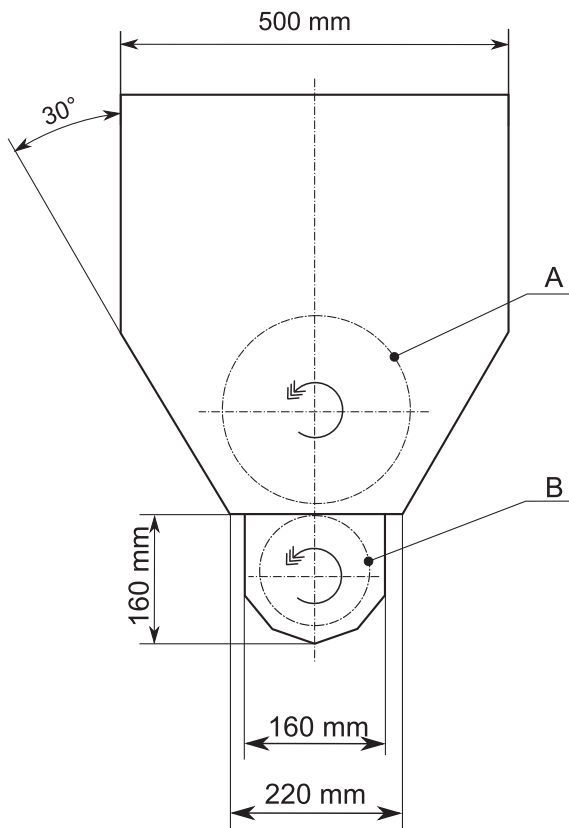


Fig. 3. Side view from the left of Fig. 2, showing the projected area covered by the agitator (A) as well as the location of the screw flights within the trough (B).

agitator. The revolution speed of the screw conveyor and the agitator were constant at $n_{screw} = 12.8$ rpm and $n_{agi} = 8.8$ rpm, respectively. All major components had been manufactured from

mild steel. The agitator rods are inclined at an angle of 45° , tending to transport the wood chips within the hopper towards the left in Fig. 2.

The overall setup is shown in Fig. 4 and consisted of the screw feeder and hopper plus agitator, a 750 W motor (230 V, 50 Hz AC), a Watt meter ([28], accuracy: $\pm 2.5\%$ of reading), a torque sensor ([29], capacity: ± 500 Nm, accuracy: $\leq 1\%$ of full scale) and digital scales ([30], capacity: 150 kg, accuracy: 0.02 kg). The agitator shaft and screw shaft were connected by a chain gear, so the torque measured was the overall driving torque for both; effective power was measured by the Watt meter.

Prior to each run, leftover material from the previous run was removed and the hopper was filled with wood chips, which were flattened out at 5 cm below its upper edge. Table 3 shows the filling mass for each sample tested. The test procedure was repeated eight times for each wood chip sample ($N = 8$) and the discharge pattern recorded with a high-definition video camera.

2.3.2. Evaluation of the screw feeder measurements

All data were recorded and stored on a personal computer. The torque was measured at 10 Hz, while effective power and mass of the fed sample material were taken at 2 Hz and 1 Hz respectively; both of the latter measurement devices did not support higher data acquisition rates.

The courses of mass $m(t)$ and effective power consumption $P_{el,eff}$ over time were corrected for starting point offset and averaged before creating diagrams. Torque data $T(t)$ was smoothed, using the Matlab [31] smooth function (rloess option, span = 50) and averaged prior to plotting. All time-related data were interpolated in order to obtain function values for the same points in time. These values were then used to compute the standard deviation or 95% confidence interval boundaries for each of the respective points in time.

Other specific values for bulk material handling were computed from the direct measurements for fed mass $m(t)$ and torque $T(t)$ over time. The mass flow $\dot{m}(t)$ can be calculated as shown in Equation (1).

$$\dot{m}(t) = \frac{d}{dt} m(t) \Big|_t \quad (1)$$

The mechanical power P_{mech} required to drive the screw feeder and agitator was computed from the measured torque and angular velocity of the screw shaft, according to Equations (2) and (3).

$$P_{mech}(t) = T(t) \cdot \omega_{screw} \quad (2)$$

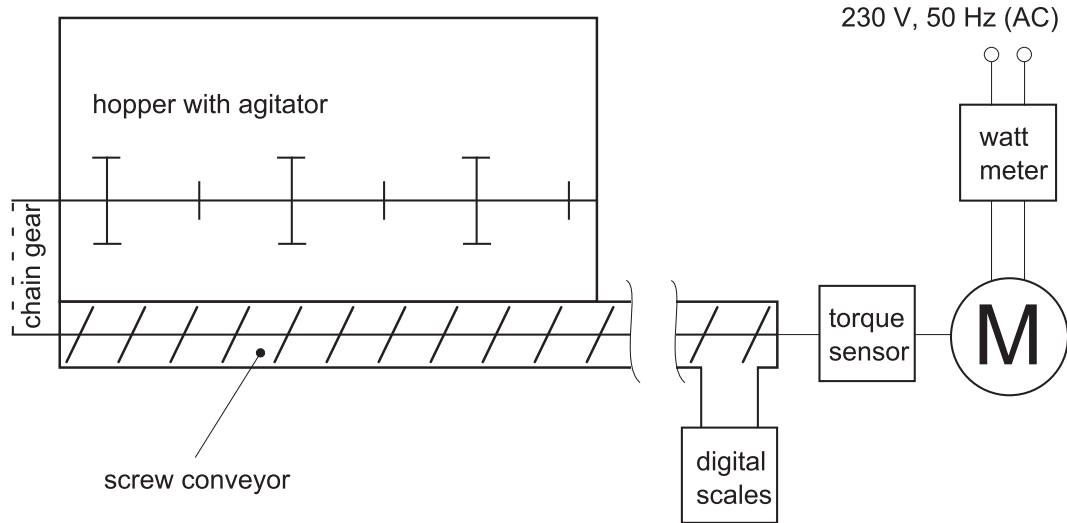


Fig. 4. Schematic setup of the screw feeder experiment setup, consisting of the hopper with agitator, screw conveyor, watt meter, electric motor (M), torque sensor and digital scales. The chain gear connected the screw conveyor shaft with the agitator.

Table 3

Mean mass used to fill the hopper up to 5 cm below its upper edge, including standard deviation.

Sample	Screw feeding sample mass (kg)
S1	28.46 ± 0.14 ^b
S2	34.85 ± 0.50
S3	46.37 ± 0.79
B1	41.66 ± 0.74
B2	34.19 ± 1.35

^b N=2.

where $\omega_{screw} = 2 \cdot \pi \cdot n_{screw}$ (3)

Preliminary tests had shown the hopper discharge behavior as depicted in Fig. 5, which was similar for all runs. The points in time, t_0 through t_5 were identified, using the measurement results and video files from the experiment runs.

After the initial state ($t = 0$ s), the hopper fill level first decreased at the transport direction side. It took about 50 s for the screw feeder trough to be filled and first wood chips to fall on the digital scales (t_0). t_1 was identified when the mass flow became quasi-

static. t_2 was reached, when more than half of the length of the agitator had lost contact with the wood chips inside the hopper. This moment was identified by using the video data. At t_3 , the torque and power consumption dropped sharply, followed by the mass flow at t_4 . t_{end} marked the end of the measurement, when the hopper and trough were empty in addition, besides from non-feedable material in corners or in the gaps between screw flights and trough (Fig. 5, a–f). The interval between t_1 and t_2 was considered the main feeding period (MFP), with the screw feeder and agitator engaged with the wood chips.

Further evaluation involved the energy consumption per transported mass, E'_{mech} and E'_{eff} [19], which was computed for the main feeding period. In Equation (4) and Equation (5), P_{mech} is the mechanical power, whereas $P_{el,eff}$ is the effective power consumption as measured by the Watt meter.

$$E'_{mech} = \frac{\int_{t_1}^{t_2} P_{mech}(t) dt}{\int_{t_1}^{t_2} \dot{m}(t) dt} \quad (4)$$

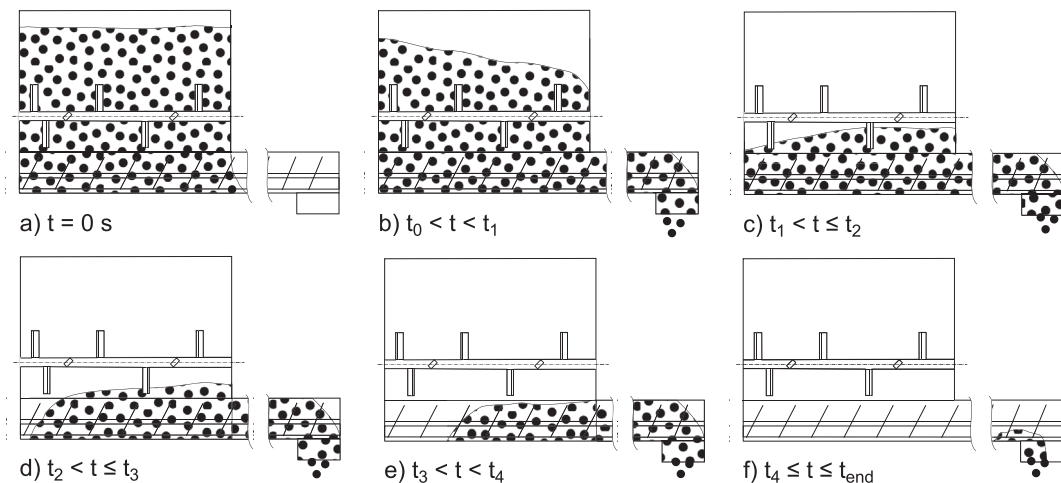


Fig. 5. Discharge pattern during the experimental runs. The figure shows a cross section trough the axes of the agitator and screw conveyor.

$$E'_{eff} = \frac{\int_{t_1}^{t_2} P_{el.,eff}(t) dt}{\int_{t_1}^{t_2} \dot{m}(t) dt} \quad (5)$$

3. Results

The presentation of results is divided into a section on the bulk material properties of the wood chip samples on the one hand, and a section on the screw feeding experiments on the other hand.

3.1. Basic wood chip sample properties

The samples' bulk densities, angles of repose, angles of slip, moisture contents and particle size distribution are shown in Table 4 and Fig. 6, respectively.

The particle size distribution shows that S1 contained a enormous share of 62% of particles larger than 16 mm, whereas S2 and S3 consisted primarily of wood chip particles sized between 1 and 16 mm. S2 contained a higher fraction of particles sized 4 mm–16 mm than S3, while S3 features a higher percentage of wood chips measuring 1 mm–4 mm. During handling the wood chip samples between tests, it was noticeable that S2 and S3 could be managed more easily, since the particles of S1 tended to get tangled with each other.

Bulk densities increase from S1 to S3 (with decreasing mean particle size), when measured according to the DIN standard [24] and with the custom container. This is in agreement with expected decreased voidage (at constant material density) and results by Littlefield et al. [32], obtained for pecan shells. Nevertheless, considerable differences exist between the absolute results of the three distinct measurement methods. For S1, the bulk density measured according to the European standard [25] was 58% higher than the one resulting from the DIN standard [24]. These discrepancies clearly relate to the different measuring methods, but the results demonstrate that mentioning the exact measuring method is crucial, when reporting values for bulk density.

The bulk densities of the blends B1 and B2 lie between the values for S1 and S3 and closer to the more prevalent base sample, as one would expect. The overall bulk density values determined within this study are in good agreement with literature [2–5], yet somewhat lower than those reported by Stasiak et al. [9].

The mean angle of repose for all samples is around 31° and does not seem to depend on the wood chip grade, which is supported by literature [2,3]. Nevertheless, the method of measuring the angle of repose used in this work yields smaller values than known from literature, e. g. 31° in this study, compared to 37° ... 46° (also [4,5]).

Measured values for the angle of slip on mild steel are consistent with existing results for mild and stainless steel [2,4]. It appears that there is no significant difference between the angle of slip being measured on mild or stainless steel, for wood chips.

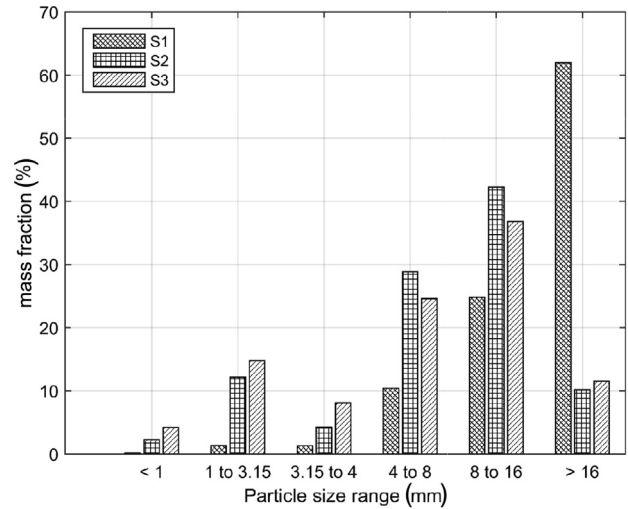


Fig. 6. Mass percentages of the different particle size fractions for the base samples S1, S2 and S3.

3.2. Screw feeder experiments

The torque measurements for S1 exceeded the maximum admissible torque of the torque sensor by a factor of two. In addition to that, the trough cover deformed near the choke section due to jamming wood chips. In order to protect the overall system from damage, S1 screw feeder experiments were canceled after two attempts, the torque sensor was sent for recalibration and the hutch cover repaired; respective results for S1 were not considered in this work.

3.2.1. General findings

Mass flow, driving torque and effective as well as mechanical power measurement results and respective 95% confidence interval boundaries for S2 (Fig. 7) S3 (Fig. 8), B1 (Fig. 9) and B2 (Fig. 10) are displayed in the corresponding figures.

The results for each of the four samples show similar behavior. The hopper fill level decreased on the right side (Fig. 2) first, which indicates the agitator transported wood chips within the hopper, due to its inclined stirring rods. As soon as the first wood chips fall out of the trough (t_0), the mass flow rises sharply and becomes quasi-static for the most time of the measurement period. It only drops at the end (t_4), since the system is emptied. The driving torque increases as the trough is filled with sample material and peaks shortly after the mass flow is fully established (t_1). For the remainder of the measurement, the torque requirement constantly decreases. It is evident that this results from the hopper fill level lowering over time and hence, the agitator to stir less wood chips. Once the fill level becomes so low that most of the agitator loses contact with the wood chips (t_2), the driving torque stays at a constant level ($t_2 < t < t_3$), and gradually decreases as soon as no

Table 4
Bulk material properties as means, where \pm indicates standard deviation.

Sample	Bulk densities (kgm ⁻³)			Angle of repose (°)	Angle of slip (°)	Moisture (mass-%)
	DIN [24]	EN [25]	Custom container			
S1	145	229	175 ± 5	33 ± 1	27 ± 2	8.5
S2	198	226	200 ± 9	29 ± 2	26 ± 1	14.8
S3	229	274	254 ± 2	31 ± 1	27 ± 1	11.8
B1	–	–	238 ± 5	31 ± 2	–	–
B2	–	–	191 ± 4	29 ± 1	–	–

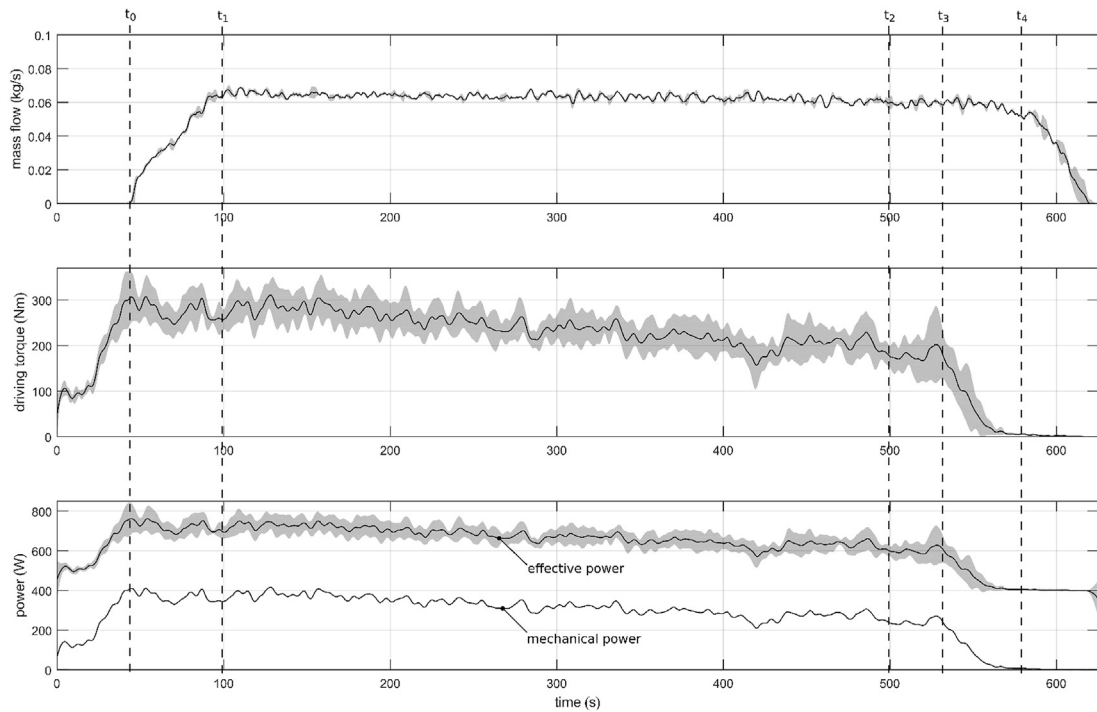


Fig. 7. Screw feeder experiment results for S2 with 95% confidence interval band.

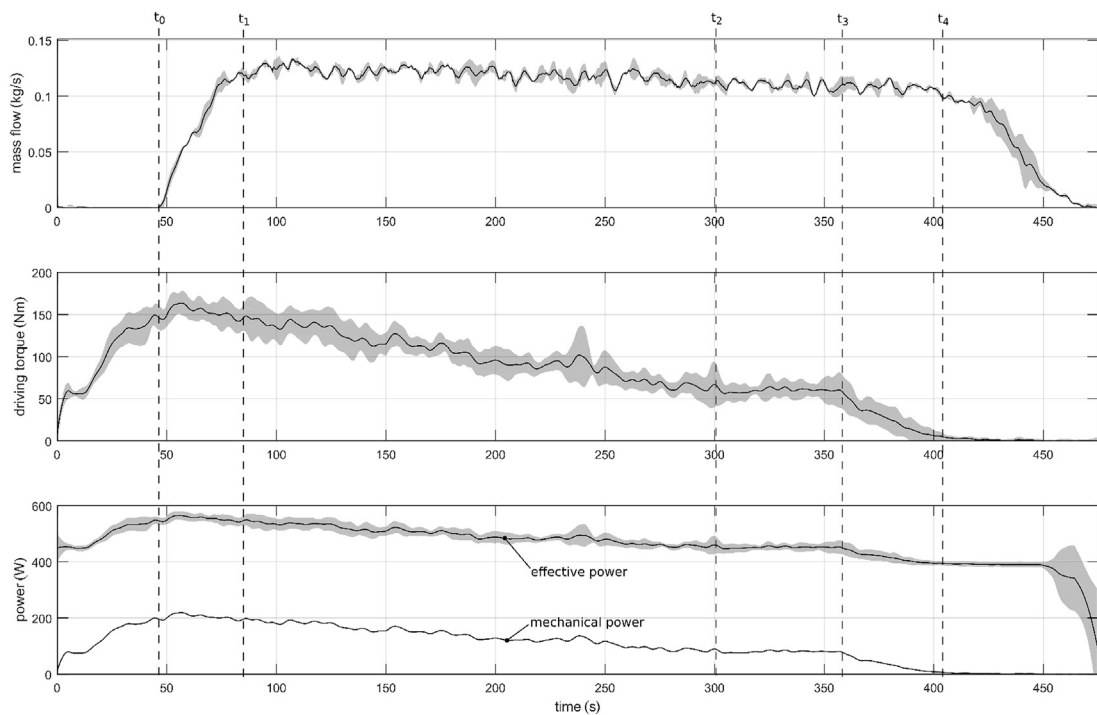


Fig. 8. Screw feeder experiment results for S3 with 95% confidence interval band.

material is left inside the hopper and the trough is emptied. This effect is most evident in S3 results.

Interpretation of the torque data would have been impossible if no averaging and smoothing had been applied to the raw data, since many peaks were recorded. These peaks result from effects, such as the granular nature of wood chips as a bulk material and particle breakage.

The mechanical power was calculated from the driving torque and revolution speed of the screw shaft and its course perfectly corresponds with the effective power measured. From preliminary measurement, the motor's mean idle power consumption and standard deviation were determined and are (394 ± 2) W.

At the end of the measurement periods, there is a rapid growth of the 95% confidence interval. This is due to the different durations

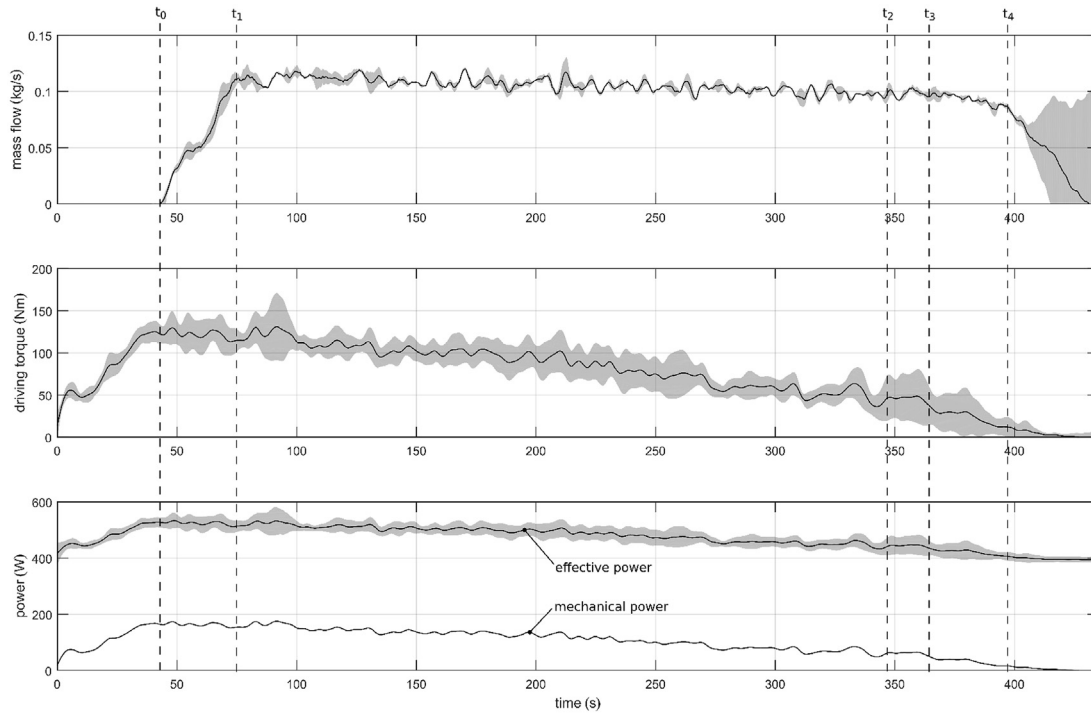


Fig. 9. Screw feeder experiment results for B1 with 95% confidence interval band.

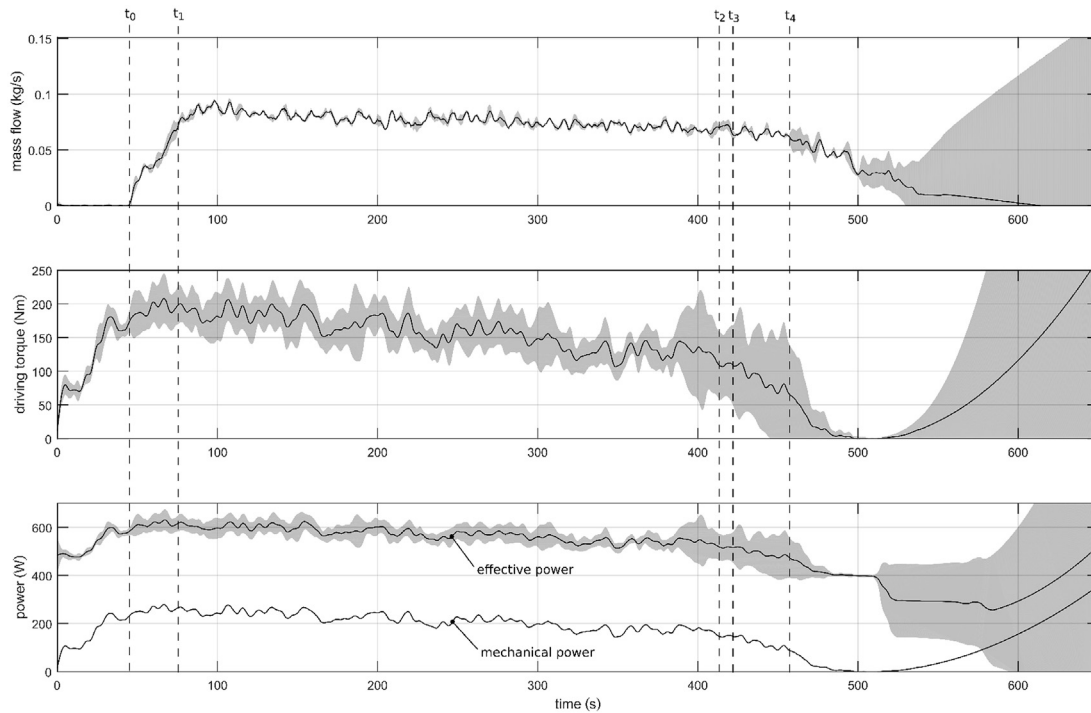


Fig. 10. Screw feeder experiment results for B2 with 95% confidence interval band.

it took for the system to be emptied. It is most obvious in the results for blend B2. Differences in the durations it took to empty the hopper may be for different reasons. Two of them are minor differences in the bulk density or single over-sized particles among the wood chips, blocking flow for a short while. For further comparison of the samples, only the main feeding period (MFP)

between t_1 and t_2 is considered.

3.2.2. Screw feeder results comparison

The mass flow during the main feeding period (MFP, Fig. 11) between t_1 and t_2 corresponds well with the bulk densities of the samples. Not as a surprise, the mass flow generally increases with

the respective bulk density of the sample.

Boxplots of the driving torques during the MFP are displayed in Fig. 12. Clearly visible from Fig. 12, the driving torque was highest when feeding S2. When comparing S2 to S3 and recalling that S1 could not be fed due to exceeding the torque sensor's maximum torque, it becomes obvious the required driving torque strongly depends on the mean particle size of the wood chips. The median of S2 is more than twice as high as the one for S3- a striking difference! These results consolidate the findings from Gil et al. [33], which state that larger mean particle size leads to worse flow.

Even though B2 consisted of 70% of the non-feedable sample S1, its median torque is lower than that of S2. A possible explanation for this observation is that fines within S3 act as a solid lubricant for the larger S1 particles, stopping them from getting tangled with each other and preventing jams by lowering S1's effective inter-particle friction. Concordant to this, Zulfiqar et al. [34] reported that mixing coal with wood chips can significantly affect the flow behavior of the resulting blend and Guo et al. [35] found that needle-shaped biomass reduced adherence and transitioned flow pattern to coal.

Interestingly enough, the torque for B1 is slightly lower than the one from S3. However, this might be due to statistical effects. The authors believe there is a tendency, according to which the flow-ability of the blends increases with the percentage of S3.

Effective power consumption measurements and calculated mechanical power are in agreement with these findings, as shown in Fig. 13. Furthermore, it is obvious the motor used for the experiments only provides limited efficiency, as its idle power consumption is already around 400 W (cf. subsection 3.2.1).

The mass-related energy consumption, as calculated according to Equation (4) and Equation (5), is depicted in Fig. 14. Net values for the specific energy consumption for augering biomass were reported by Miao et al. [19]. They range from approximately 0.2 kJ kg⁻¹ for corn to about 16 kJ kg⁻¹ for switchgrass. The values from this study are between 1.09 and 5.06 kJ kg⁻¹ for the mechanical power and 4.14–10.6 kJ kg⁻¹ when taking the effective power consumption into account. Even though the mass-related mechanical power in this study and those from Miao et al. [19] for screw conveyors are in the same range, it shall not be left unmentioned that experimental setups were different and the values from Miao et al. [19] were given with respect to the dry mass.

Similar to the driving torque, the values for the mass-related energy consumption of B1 and B2 are considerably lower than from S2. Fig. 14 shows a tendency, where the mass-related energy decreases with increasing percentage of S3.

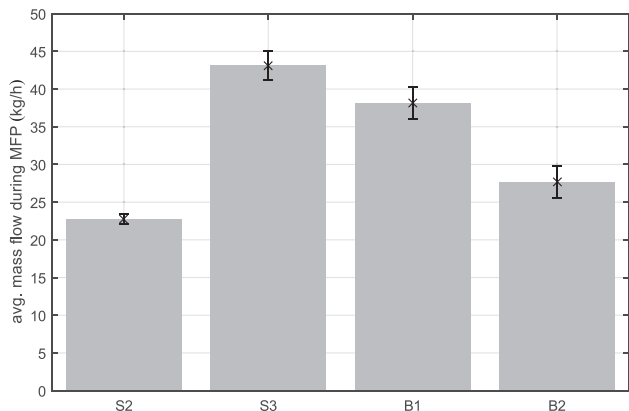


Fig. 11. Mass flow and corresponding standard deviation during the main feeding period (MFP).

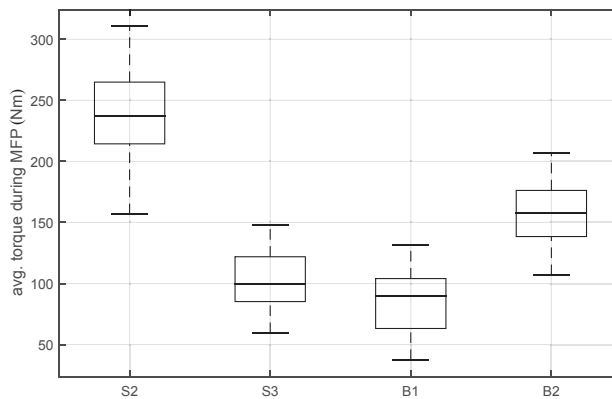


Fig. 12. Boxplots of the driving torque during the MFP.

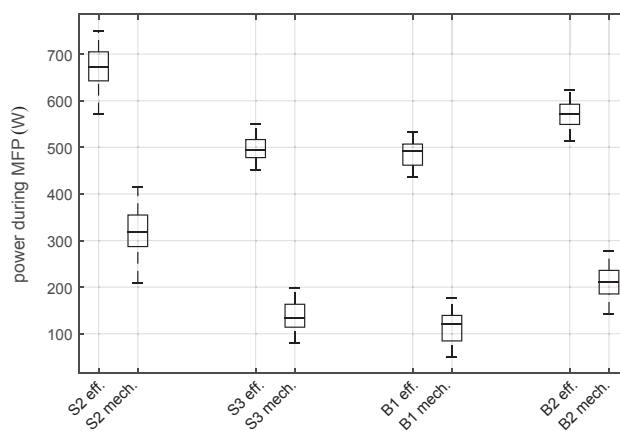


Fig. 13. Boxplots of the effective power consumption (eff.) and mechanical power (mech.).

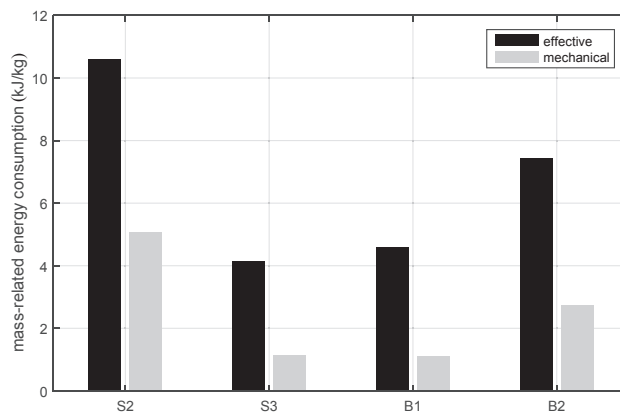


Fig. 14. Mass-related energy consumption per sample for effective power and mechanical power.

4. Outlook

Even though the findings from this work showed how to achieve significant improvements in feedability, they require further consolidation with respect to other wood chip feeding applications. In addition, mixing blends from different wood chip grades almost certainly changes the (net) calorific value of the transported bulk

material. It is of vital importance to investigate to which extent this value is altered, since the described hopper/agitator/screw conveyor system is typically applied as a device for transporting wood chips to a furnace, and the subsequent combustion process can be affected.

5. Conclusions

The target of this study was to investigate the influence of three different wood chip grades and two blends on typical parameters for screw conveyor materials handling. As a side result, three different methods of measuring the bulk density of wood chips were compared and it was revealed there can be differences of up to 58%. Also taking into account the systematic differences from the angle of repose results, the findings from this study underline how important it is to report the measuring method as precisely as possible, whenever values for the angle of repose and the bulk density are reported.

Wood chips can be a bulk material which is hard to feed with screw conveyors. Sample S1, which mostly consisted of wood chip particles larger than 16 mm, caused problems when augered with the screw conveyor used in this study. It was shown that mass flow, driving torque and therefore the mass-related transport energy vary significantly between different wood chip grades and respective blends. The mechanical mass-related energy to feed wood chips was reported to be in between approximately 1 and 5 kJ kg⁻¹. The mean particle size of the wood chips has a strong influence on the driving torque, as larger particles may get tangled with each other or equipment parts and cause increased driving power demand or even blockage.

One of the main findings is that considerate blending of two wood chip grades can resolve the problems of excessive driving torque and thus significantly lower the energy demand for the screw conveyor/agitator. Mixing a blend from a 70% share of hard-to-feed wood chip grade with 30% of a high-fines, bark and needle content, grade significantly influenced the feeding behavior and mass-related energy consumption, while only slightly altering the bulk density and expected mass flow.

The results also indicate that improving or deteriorating flow-ability of blends made from wood chips and other bulk materials might not just depend the amount of wood chips, but also on the mean particle size, which the wood chips consist of.

Conflict of interest

There is no conflict of interest.

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