Fragmentation of fuel pellets during transport via a belt conveyor
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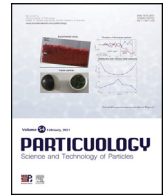Gilvari, Hamid; van Battum, Coen H.H.; Farnish, Richard; Pang, Yusong; de Jong, Wiebren; Schott, Dingena L.

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Fragmentation of fuel pellets during transport via a belt conveyor: A design of experiment study

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A B S T R A C T

This work investigates the proportion of generated fines in a pilot-scale experiment using a belt conveyor and commercial fuel pellets. For this, a belt conveyor with a length of 3.1 m was used and operated at varying conditions: speeds, percentages of material loading on the belt, two combinations of the inclination angle of the belt and the falling height, and a different number of handling steps. We considered a design of experiments approach based on response surface methodology to investigate the effect of different conditions on the potential of fines generation. Moreover, a comparison between the results of the belt conveyor and three common benchmark experimental approaches (tumbling box, rotary impact tester, and mechanical compression test) was made. Results show that the number of handling steps and the combined effect of drop height and inclination angle directly affected the fines generation. However, the tested belt speed range and the level of loading were of lower significance. A polynomial quadratic model was derived based on the regression analysis and showed a high accuracy to predict the proportion of fines. Moreover, the tumbling box method showed good potential to predict the proportion of fines in a belt conveyor when transported several times.

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Introduction

With increasing the worldwide energy demand on the one hand and increasing global warming and greenhouse emissions, on the other hand, the use of alternative energy sources to fossil fuels is becoming of vital importance. In recent years, biomass-based energy sources attracted more attention due to their low greenhouse gas (GHG) emissions and high availability (Gustavsson, Börjesson, Johansson, & Svenningsson, 1995). In 2019, more than 9% of global energy production was supplied with biomass energy sources (Enerdata, 2020).

Raw biomass has high water content and a low bulk density. To use biomass more efficiently, it is normally subjected to drying and densification processes in which the material's quality improves in terms of energy content and bulk density. Higher bulk and energy density and lower moisture content can ensure easier and econom-ical transport and storage. However, pellets are naturally fragile and may produce fine particulates due to breakage and attrition, which potentially challenge transport and storage. The increased number of fines—particles smaller than 3.15 mm according to ISO standard 17831-1 (ISO 17831-1, 2015ISO 17831-1, 2015)—may increase the risk of fire, material loss, equipment fouling, and environmental issues (Gilvari, de Jong, & Schott, 2019a; Ilic, Williams, Farnish, Webb, & Liu, 2018; Ramírez-Gómez, 2016).

The potential of pellets to produce fines depends on many factors from the feedstock to the production process and the storage conditions (Kaliyan & Vance Morey, 2009; Tumuluru, Wright, Hess, & Kenney, 2011). This potential is mainly measured using laboratory-scale experiments such as durability and impact testers (Gilvari et al., 2019a). Nevertheless, the extent of fines generation during industrial transport and storage depends on the design specifications of the transport and storage equipment and their operational conditions.

Several papers studied the effect of the operational conditions of the transport equipment and design on the extent of breakage and attrition of fuel pellets. Oveisi et al. (2013) investigated the

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Fig. 1. Wood pellets used in the experiments; a bucket of mixed pellets (left), the two different types of wood pellets in a close-up (right).

breakage of wood pellets via free fall in different scenarios and find found that for wood pellets with a durability of 97% (according to the tumbling box method), greater drop heights linearly increases the proportion of generated fines. Boac, Casada, and Maghirang (2008) investigated the effect of chain conveyor and silo loading on the breakage of pellets with 13.2% moisture content and 92.9% durability (according to tumbling box) and observed an up to 32.7% increase in the number of particles <5.6 mm. Jägers, Wirtz, Scherer, and Behr (2020) and Murtala, Zigan, Michael, and Torbjörn (2020) studied the effect of pneumatic conveying on wood pellet degradation and observed that an increase in the air inlet velocity and a decrease in pellet mass flow, increases the extent of fines generation.

Belt conveyors, amongst others, are more common to be used in pellet industries due to their high flow capacities in long distances (García Fernández, Pizarro García, Gutiérrez Lavín, Bueno de las Heras, & Pis, 2013). However, it is not yet clear to what extent pellets may degrade during transfer via a belt conveyor while operating at various conditions such as different belt speeds, belt loading, belt inclinations, and the number of handling steps. Moreover, the relationship between the results of the laboratory benchmark tests such as durability testers and the generated proportion of fines during transport via a belt conveyor has not yet been studied. Therefore, the objective of this paper is to investigate the effect of different operational conditions of a belt conveyor on the number of fines generated during transport. A design of experiment (DoE) approach based on response surface methodology (RSM) is applied to study the effect of different factors. This can contribute to a better design of transport equipment in pellet industries. Moreover, the other contribution of this research is to correlate the strength of pellets—measured via different benchmark laboratory tests — to the proportion of fines generated via a belt conveyor in order to fill the gap between benchmark tests and belt transportation.

Materials

Fuel pellets used in this study were commercial wood pellets produced in Canada and transported to Europe via an ocean vessel for energy production purposes. The vessel contained around 30,000 metric tons pellets of which around 400 kg were randomly chosen and transported to the laboratories to perform experiments in this study. The samples contained two different types of wood pellets with different colors (white and brown) and appearances with a share of 30–70% for white and brown pellets, respectively. Pellets were well mixed in the whole batch as shown in Fig. 1. Table 1 shows the physical properties of the pellets. The mois-

Table 1
Properties of the pellets used in this study.

Pellet properties	White	Brown
Diameter (mm)	6.6 ± 0.1	6.7 ± 0.1
Length distribution (mm)	5–40	
Bulk density (kg/m^3)	700 ± 7.9	
Moisture content (%)	6.2 ± 0.3	

ture content was measured according to ISO standard 18134 (ISO 18134-2, 2017ISO 18134-2, 2017) by placing 300 g of materials inside an oven at the temperature of 105 °C for 24 h. The bulk density was measured using a 5 L steel cylinder according to EN standard 15210 (EN 15103, 2010). For that purpose, the cylinder was filled with pellets using the tap method and then the mass of pellets inside the cylinder was weighted. The bulk density was measured by dividing the mass of pellets over the volume of the cylinder. The moisture content and the bulk density were measured twice based on their standards and the reported values are the mean of repetitions. The pellet lengths and diameters were measured using a digital caliper according to EN standard 16137 (EN 16127, 2012).

In a previous study (Gilvari, de Jong, & Schott, 2020a), we concluded that the length of pellets can play a major role in generating fines—with shorter pellets produced more fines in a benchmark test. Therefore, for the laboratory tests in this study, the effect of pellet length distributions (PLD) was considered. For that, pellets with different length distributions were manually selected and their length distributions were measured using an in-house image processing tool using MATLAB scripts. Details of the image processing tool can be found in our previous study (Gilvari, de Jong et al., 2020a).

Methods to measure fines generation

In this section, first, the benchmark test methods to measure the pellet strength, including the tumbling box, rotary impact tester, and compression test, are introduced. Then, the belt conveyor setup, which was used to measure the fines generation during the transportation is presented. Finally, the applied DoE method is given.

Mechanical durability

The mechanical durability tester used in this study was a tumbling box operating at 50 rpm for 10 min based on ISO standard 17831-1 (ISO 17831-1, 2015ISO 17831-1, 2015). Different tests

Fig. 2. Rotary impact tester.

have been performed on mixed pellets, separated pellets, and size-classified separated pellets. To execute the tests, more than 1 kg of pellets were manually sieved with a round hole screen with a mesh size of 3.15 mm, and subsequently, 500 g of that was placed into the device and tumbled. For size-classified pellets, pellets were manually classified into different groups and using the image processing tool described in (Gilvari, de Jong, & Schott, 2019b), the PLDs were captured and then introduced to the tumbling box. For separated pellets i.e. brown and white, pellets were manually selected with mixed sizes and then placed into the tumbling box. After the test, all samples were sieved with the same sieve (3.15 mm screen) and the mass of the remaining particles was weighed using a laboratory balance. The mechanical durability was calculated according to Eq. (1):

$$DU = \frac{m_a}{m_i} \times 100\% \tag{1}$$

where DU is the mechanical durability, m_a is the mass of pellets after tumbling, and m_i is the mass of initial samples. All tests have been performed in two repetitions, except size-classified pellets which have been carried out once.

Rotary impact tester

The impact tester is an in-house developed device at the Wolfson center of the University of Greenwich, the UK, to study the breakage behavior of different materials at high impact velocities. This is a closed cylindrical device with a diameter of 900 mm and a height of 350 mm with a small hole at the center of the top surface. A hole is designed at the bottom surface to collect the materials after the test. Inside the device, there are two discs: one over the other with a diameter of 480 mm with 35 mm vertical separation. The upper disc has a hole with a diameter of 60 mm at the center and the lower disc is plain to enable keeping the materials on it. Around the inner discs, there are 24 plates attached to the cylinder. Upon rotation of the discs, pellets are fired from the discs and collide with these plates (Fig. 2). In our experiments, the discs were rotating at an angular velocity of 28 Hz, giving a theoretical speed up to 25 m/s to the pellets upon impact. Pellets were gradually fed into the disc to discharge 500 g of pellets in less than two minutes. The resulting impact velocity was considered to mimic the highest impact velocity of pellets during transport and storage. A detailed working principle can be found elsewhere (Abdulmumini, Bradley, & Zigan, 2016; Wu, Schott, & Lodewijks, 2011). Due to the high velocity of pellets at impact, pellets break down and produce fines. After each test, all the pellets and fragments including fines were collected for further analysis.

Compression test

Individual pellets were subjected to compression tests for the determination of their mechanical strength. This is a common test to predict the internal strength of biomass pellets (Gilvari, de Jong, & Schott, 2020b; Larsson & Samuelsson, 2017; Williams et al., 2018) and has been used to measure the strength of other materials such as granules (Rahmanian, Ghadiri, Jia, & Stepanek, 2009). Due to the jagged ends, the pellet ends were manually polished using sandpapers to place the pellets vertically on the compression plate. At each run, one pellet was placed on the lower plate of the compression device. The compression tests were conducted using a Zwick compression bench equipped with a 2 kN load cell. Each test ran at a velocity of 1 mm/min until the pellet was broken. After each test, the force–displacement data were extracted from the device, using Eqs. (2) and (3), the stress–strain data were calculated.

$$\sigma_a = \frac{F}{\pi r^2}, \tag{2}$$

$$\varepsilon_a = \frac{l_0 - l}{l_0}, \tag{3}$$

where σ_a is the stress, ε_a is the strain, F is the force, r is the pellet radius, l_0 is the initial pellet length, and l is the corresponding pellet length.

Belt conveyor setup and experiments

For this research, a pilot-scale belt conveyor setup was developed to investigate the generated number of fines when pellets are being transported. The setup, as shown in Fig. 3, consists of a wedge-shaped hopper, a troughed (20 °) belt conveyor, and a collecting bin. The size of the hopper outlet and the inclination of the belt is adjustable. The belt width is 0.4 m and its length is 3.1 m of which 2.6 m was used for conveying the pellets in this study. To prevent material spillage, a chute is attached to the frame of the belt conveyor.

The experimental procedure was as follows. To remove fines before starting the experiments, all pellets were manually sieved with a round-hole sieve with a screen size of 3.15 mm, according to the ISO standard 17831-1 (ISO 17831-1, 2015ISO 17831-1, 2015). For each experiment, 10 kg of the sieved samples were gently fed into the hopper. The speed of the belt varied from zero to 1.5 m/s. The speed was manually monitored with a tachometer (model: DT-30LK) to confirm the target speed. At each run, after the belt was up to speed, the hopper outlet was opened rapidly to discharge pellets onto the belt. At the end of each run, pellets were collected in the collecting bin—which was covered with a Polyvinyl Chloride (PVC) sheet with approximately 1 mm thickness. This plastic sheet was used to empty the bin while preventing loss and extra degradation of pellets in collecting and recirculating the material into the hopper. After each run, pellets were manually sieved again to determine the generated number of fines. The weight percentage of generated fines (F_g) was calculated using Eq. (4):

$$F_g = \frac{m_S}{m_i} \times 100, \tag{4}$$

where m_S represents the mass of particles passing through the sieve and m_i represents the mass of the initial sample.

The experiments were conducted over six days and every day the temperature and relative humidity of the laboratory were recorded with a thermocouple of National Instruments (model: PT-100) and an analog humidity gauge, respectively. This is important as it has been shown previously in Cutz et al. (2021), Gilvari, Cutz
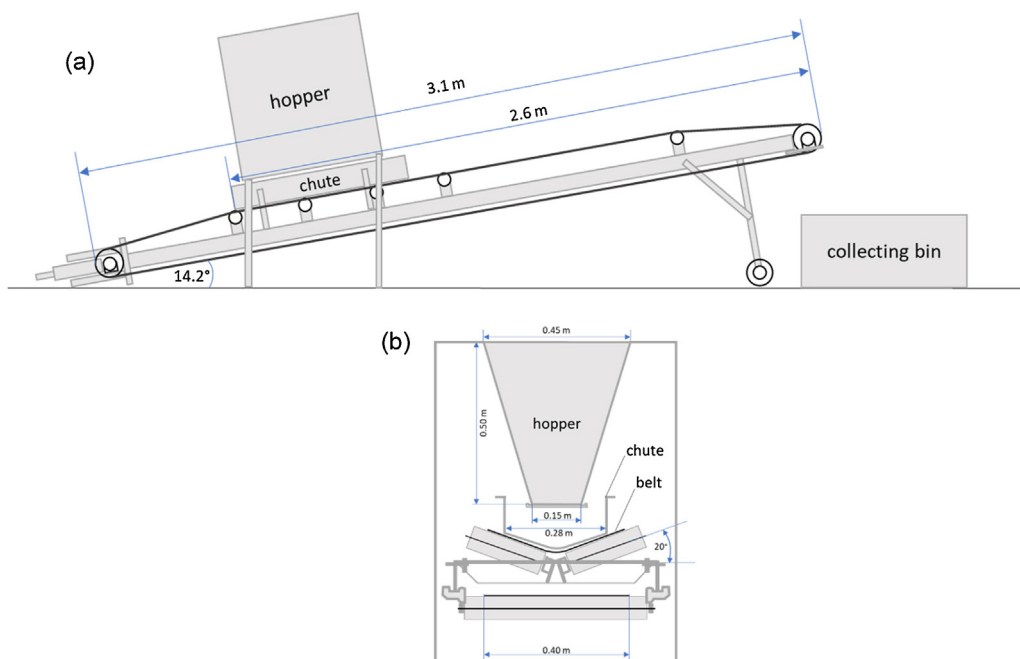
Fig. 3. The inclined belt conveyor setup including the wedge-shaped hopper to load and a collecting bin to collect the materials, (a) side view, and (b) cross-sectional view.

et al. (2020), and Graham, Eastwick, Snape, and Quick (2017) that a prominent change in both temperature and relative humidity significantly influences the mechanical degradation of wood pellets. During our experiments, the temperature and the relative humidity were $20.1 \pm 1.3\,°C$ and $60.3 \pm 3.8\%$, respectively. These results show that the temperature and relative humidity were approximately constant and there was no effect on the mechanical degradation of pellets.

Design of experiments (DoE)

The RSM with Box–Behnken experimental design (Minitab 18, 2019) was used to analyze the influence of four operational factors—three continuous and one categorical factor—on the proportion of fines generation. This design was chosen because first, it enables to design experiments with four factors having three levels for three of the factors and two levels for one factor, and second, as previously shown by Ferreira et al. (2007) that it is more efficient than the other DoE methods such as central composite design and full factorial design. In this type of design, three factors with three levels at different blocks are being studied, therefore, enabling the estimation of the parameters of the quadratic model.

Four operational factors suspecting to influence the pellet breakage were investigated in this study. These factors include three operational conditions of the belt conveyor including the belt speed (X_1), level of loading on the belt (X_2), the drop height from the belt conveyor (X_3), and the number of handling steps (X_4) as the independent variable. X_1, X_2, and X_4 were chosen as continuous factors and X_3 was chosen as a categorical factor.

In this study, the belt speed (X_1) could be varied between 0 to 1.6 m/s; therefore, the chosen speed range was between 0.5 to 1.5 m/s.

The level of loading (X_2) was a percentage of the nominal belt load that can be fed to the belt without causing spillage (see Fig. 4). The nominal load can be calculated based on Eq. (5):

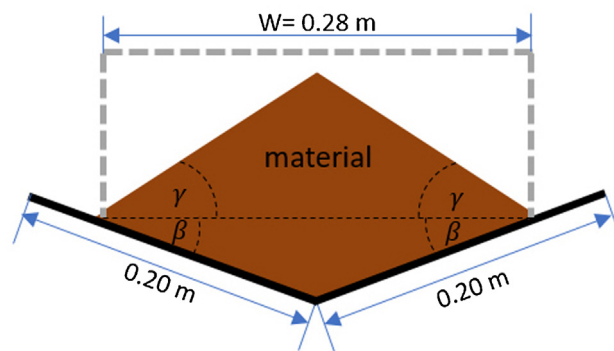$$C_N = \frac{1}{4}\left(\tan(\gamma) + \tan(\beta)\right) W^2 v_{belt}, \tag{5}$$

Fig. 4. Cross-section of the belt conveyor behind the chute. The chute is represented in grey dashed line and the belt in black solid line. Angle γ represents the surcharge angle of the material, angle β represents the trough angle of the belt, W is the width of the loading chute.

where C_N is the nominal capacity or load of the belt, γ is the surcharge angle of the material, β is the trough angle of the belt, W is the width of the loading chute, and v_{belt} is the speed of the belt, as shown in Fig. 4. From our experiments, the maximum loading factor without materials spillage is 50% of the nominal load. Therefore, here we considered 50, 40, and 30% of the nominal load for the variation of the belt load.

The categorical factor (X_3) is a combination of the inclination of the belt and the dropping height of the material at the discharge point of the belt; however, as the inclination angle and correspondingly the discharge trajectory has a negligible effect on the number of generated fines, this factor is hereafter reffered to as the drop height. At the inclination of $0\,°$, the discharge height was 0.51 m and at the inclination of $14.2\,°$, it was 0.72 m.

The number of handling steps represents the number of transfer points for pellets in which belt conveyors are used. This depends on the transport journey that pellets take (from the production site to the end-user location) and the design specifications across a transport chain. Here, each transport loop from loading the belt to discharge into the collecting bin is considered as one handling step. According to Boac et al. (2008) and Oveisi et al. (2013), pellets

Table 2
Factors and their corresponding levels used in the design of experiments.

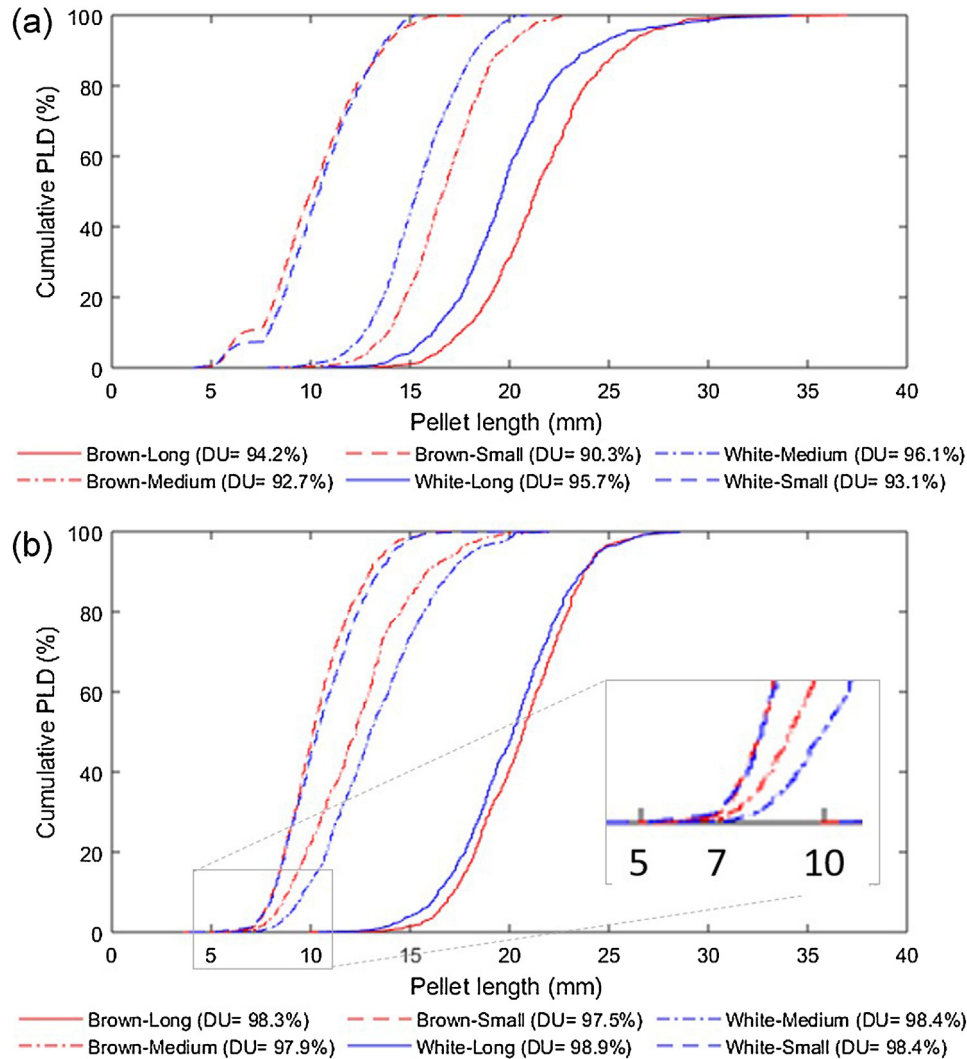| Factor	Low level (−1)	Medium level (0)	Low level (+1)
X_1: Belt speed (m/s)	0.5	1.0	1.5
X_2: Level of loading (%)	30	40	50
X_3: Drop height (m)	0.51	–	0.72
X_4: Number of handling steps	1	5	9

Fig. 5. Pellet length distributions of samples tested in (a) impact tester and (b) tumbling box. (DU = durability value).

may drop approximately 10 times during their transport journey; therefore, a maximum of nine steps is considered here.

A multiple regression analysis using a polynomial quadratic equation for the number of fines was performed using Minitab® 18.1 software (Minitab 18 Statistical Software, 2021), as shown in Eq. (6):

$$Y = c_0 + \sum c_i X_i + \sum c_{ii} X_i^2 + \sum c_{ij} X_i X_j + \varepsilon, \qquad (6)$$

where Y is the measured response, c_0 is the intercept coefficient, c_i, c_{ii}, and c_{ij} are the regression coefficients, and X_j are the factors used in the regression analysis, and ε is the error of the model.

For the continuous independent variables, i.e. X_1, X_2, and X_4, a range of interest is established based on preliminary tests and corresponds to three discrete levels: minimum (−1), medium (0), and maximum (+1). The independent factors and their corresponding levels are shown in Table 2. The categorical independent factor (X_3), which is the drop height of the pellets consists of two levels (−1 and +1). An experimental design was created in Minitab® 18.1 consisting of 30 experiments (Table S1, see the supplementary material) For each of the experiments, one replication was performed.

Analysis of variance (ANOVA) and regression analysis were performed to investigate the statistical significance of the regression coefficients at a confidence level of 95%. Only statistically significant terms have been included in the result of the multiple regression analysis. The model accuracy was evaluated using the coefficient of determination (R^2 value).

Results and discussion

The PLD of the samples used in the tumbling box and the rotary impact testers show that the PLD of the classified samples is roughly
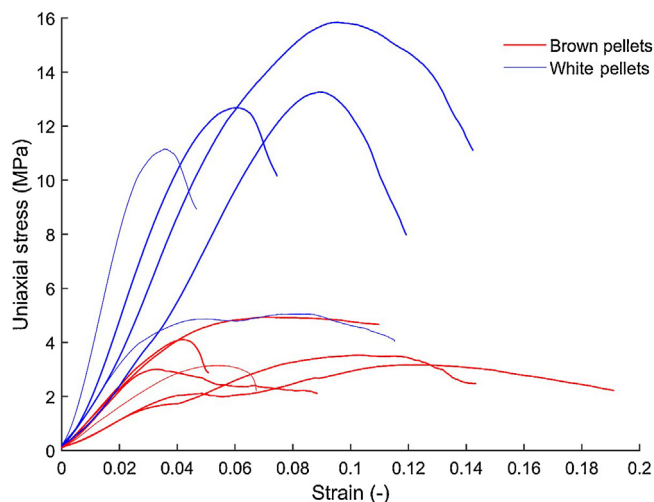
Fig. 6. Axial compression test results for brown and white pellets.

similar except for the medium-sized pellets, which show a small deviation (Fig. 5(a) and (b)). In general, the proportion of generated fines in the rotary impact tester is higher than in the tumbling test. This is due to the high impact velocity of pellets in the rotary impact tester. Moreover, as previously reported by other researchers such as Murtala et al. (2020), in the tumbling method pellets are usually subjected to attrition forces while in the rotary impact tester the impact forces play a major role in the breakage of pellets.

The durability of brown and white pellets measured with the tumbling box was 96.8% and 98.2%, respectively, with the standard deviation of 0.05 for brown and 0.1 for white pellets. Similar to this, the durability of brown pellets in all the PLDs was lower than that of the white pellets (Fig. 5). This is also confirmed with the results of the compression tests (Fig. 6) where the average maximum stress at failure for the brown pellets was 3.65 MPa (standard deviation = 0.75) and for the white pellets was 11.60 MPa (standard deviation = 4.03), although Larsson et al. (Larsson & Samuelsson, 2017) observed weak correlations between the mechanical strength of individual pellets and bulk.

In addition to the type and size-classified pellets, two other tests have been conducted using randomly chosen pellets from the initial 400 kg samples with the tumbling box. The results show 96.5% durability (fines = 3.5%) with a standard deviation of 0.05. Therefore, the durability value of the mixed pellets in the tumbling box is lower than the durability value of other tested pellets i.e. white and brown pellets of each category. This is probably due to the existence of the particles smaller than 7 mm and bigger than 3.15 mm in the randomly chosen mixed pellets. As shown in the subplot of Fig. 5(b), the pellets used in the tumbling method were bigger than 7 mm, therefore, the number of particles in the test was lower, and consequently, this resulted in fewer interactions between the pellets. However, in the mixed pellet sample, the presence of particles with a size between 3.15 and 7 mm increases the number of particles in the sample and therefore, increases the number of collisions between particles resulting in a higher generation of fines.

The results of the belt conveyor experiments based on the Box–Behnken experimental design and those of the benchmark tests are shown in Fig. 7. The maximum proportion of generated fine particulates via the belt conveyor was 3.6% and it was observed at the maximum number of handling steps (nine steps), drop height of 0.72 m, 50% level of loading, and a belt speed of 1 m/s. Comparing this proportion of generated fines with the results of the benchmark tests showing in Fig. 7, it is concluded that the result of the tumbling box testing is closer to the belt conveyor experiments that
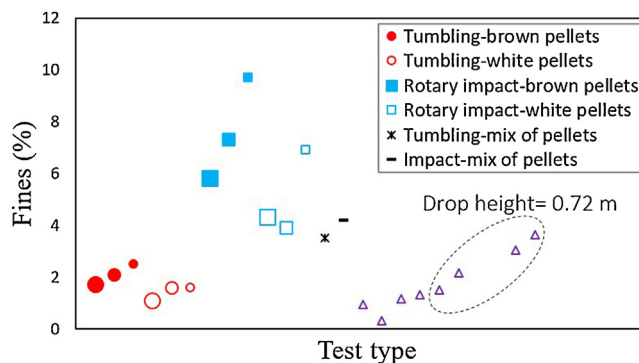

Fig. 7. Proportion of fines in laboratory experiments and transport via the belt conveyor. The marker size represent the PLD: the bigger the size, the longer the PLD is.
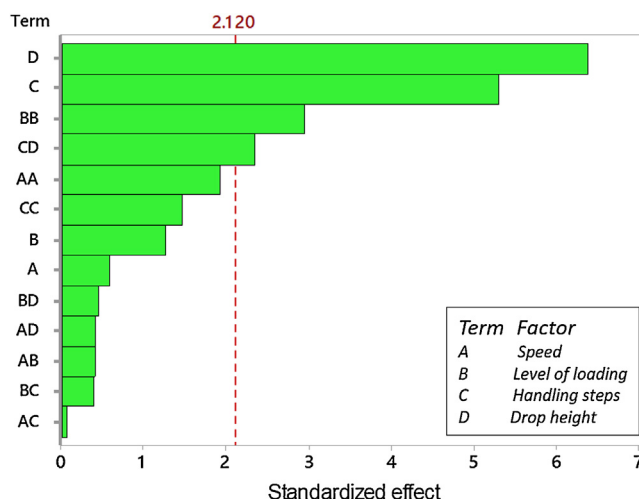

Fig. 8. Pareto chart of the standardized effect ($\alpha = 0.05$). Any term with a value more than the reference absolute value (2.120) is considered significant.

consisted of several handling steps. Moreover, it is shown that the higher drop heights generate a higher number of fine particulates.

Fig. 8 shows the absolute values of the standardized effects of the (in)dependent factors on the generated fines from high to low including a reference line (dashed line) to indicate the statistical significance. The Pareto chart shows that the drop height (X_3), the number of handling steps (X_4), the level of loading squared (X_2^2), and the interaction between the number of handling steps and the drop height ($X_3 * X_4$) are statistically significant. With multiple regression analysis, relations between the factors and the response were found, as given in Eq. (7):

$$\begin{cases} F_f = 0.0691 - 0.00476X_3 - 0.00055X_4 + 0.000047X_2^2 \\ \quad +0.000632X_3X_4 \qquad X_3 = 0.51\,\text{m} \\ F_f = 0.0691 + 0.00476X_3 - 0.00055X_4 + 0.000047X_2^2 \\ \quad +0.000632X_3X_4 \qquad X_3 = 0.72\,\text{m} \end{cases} \tag{7}$$

where F_f represents the fines fraction in the batch of pellets. The R^2 value for this regression analysis is 0.852, which is considered an acceptable value for such a regression in engineering fields (Lommen, 2016).

With a normal distribution of the residuals, the assumption that the data are normally distributed was checked as described by Antony (2014). The histogram and the normality plot shown in Fig. 9 confirm that the residuals are normally distributed and we can see that the experimental data points are closely aligned to the reference line.
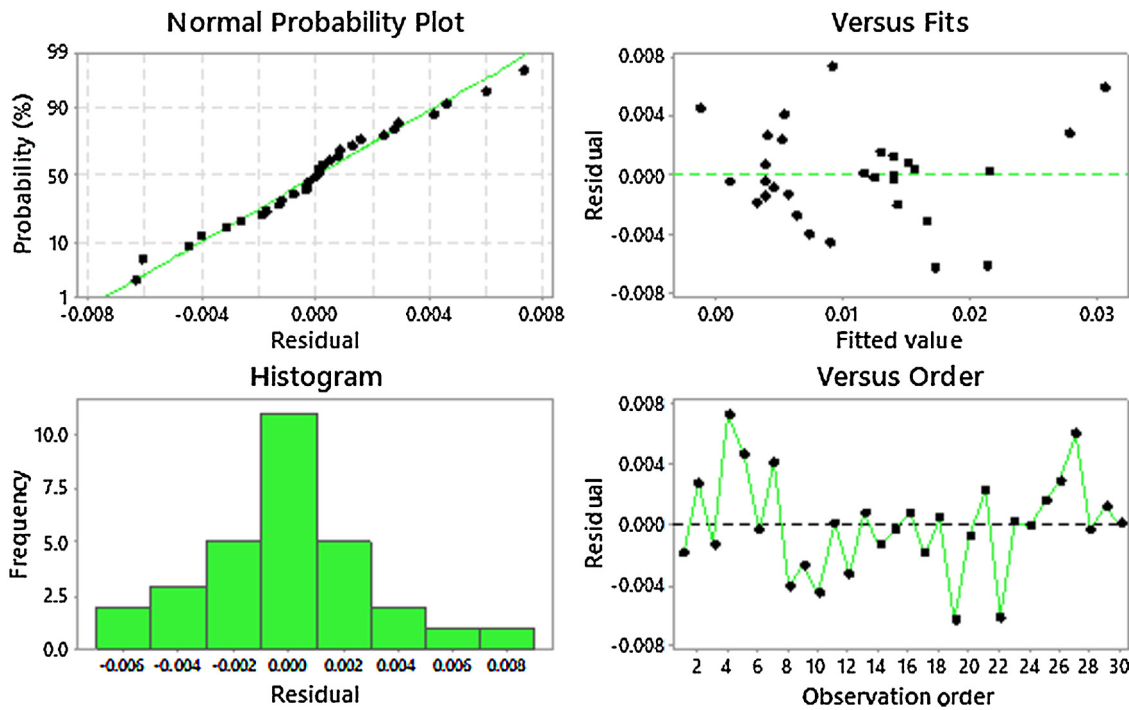
Fig. 9. Residual plot for fines generated in the experiments of the conveyor belt. The top left shows the normal probability vs residual, top right fitted values vs residues, bottom left residual vs frequency, and bottom right shows order number vs residual.
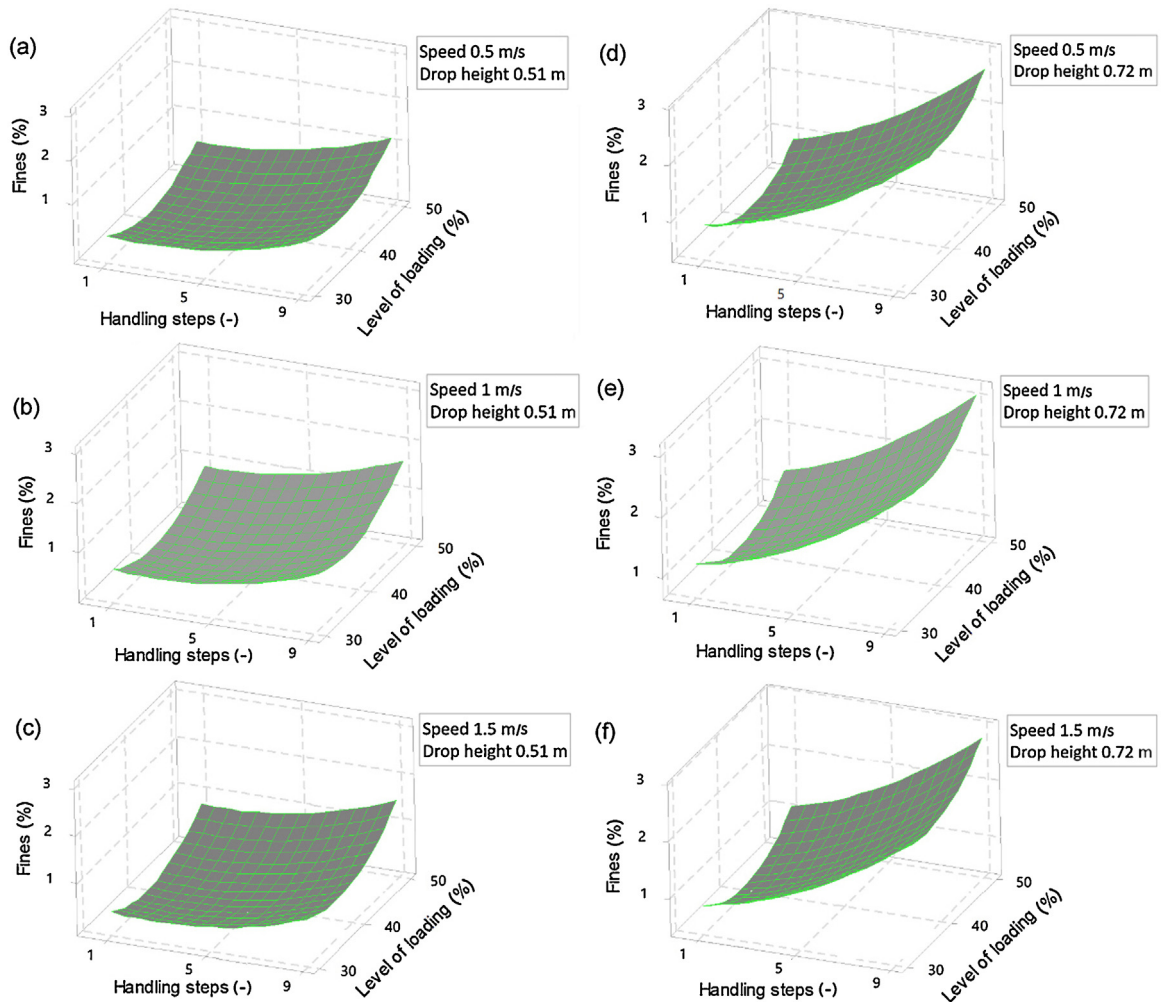

Fig. 10. Surface plot of the proportion of fines at different operational conditions of the belt.

Comparing surface plots a, b, and c (drop height of 0.51 m) with the plots in d, e, and f (drop height of 0.72 m) in Fig. 10, the drop height significantly influences the proportion of generated fines. Oveisi et al. (2013) found that a greater drop height induces more pellet breakage resulting in more fines generation. Our results are in accordance with their findings. However, in our study, the inclination is varied too. Because we did not observe a change in the drop height from the level of discharge point by changing the inclination angle from 0 to 14.2 °, we consider that the effect of inclination angle is negligible. Nonetheless, future studies can focus on the effect of discharge trajectory and angle of impact on the number of the generated fines.

It is already proven that a higher impact velocity increases the impact forces on pellets (Grima & Wypych, 2011). Although an increased falling height (0.21 m) increases the speed of the pellets upon impact and so increases the impact velocity, a belt speed in the range of 0.5 and 1.5 m/s does not seem to play a significant role in the generation of fines. Jägers et al. (2020) found that higher pellet velocities (7.5–15.7 m/s) induce progressive particle size reduction of wood pellets when transported by pneumatic conveying. However, our findings are in contrast with this, most probably because the speed of the belt in our study is in a range between 0.5 and 1.5 m/s and this speed range does not significantly influence the number of generated fines.

According to the study by Oveisi et al. (2013), the number of generated fines depends on the bedding material. When pellets impact a bed covered by pellets (not the button surface of the collecting equipment), the number of generated fines is lower. Jägers et al. (2020) also found a larger pellet mass flow (a higher level of loading) reduces the comminution effects. In contrast, in this study, the Pareto chart analysis (Fig. 8) shows that only the level of loading squared is statistically significant for the number of generated fines.

The number of handling steps significantly influences the number of generated fines. This can be found in any of the surface plots shown in Fig. 10. These results are following the findings of Oveisi et al. (2013) who concluded that the pellets become increasingly weaker after repeated impact. Cracks and tears upon the next impact can evolve into breakage of the pellets resulting in a higher number of generated fines.

Looking at Table S1 (see the Supplementary material), the proportion of produced fines at the drop height of 0.71 m and nine handling steps is 2.2–3.6%, which is close to the generated proportion of fines of the randomly chosen sample in the tumbling method (3.5%), and a slightly different from that of rotary impact tester (4.2%), as shown in Fig. 7. Therefore, the tumbling box method could successfully predict the proportion of fines in a transport system of pellets with nine handling steps and discharge height of 0.72 m each. The rotary impact tester, however, can probably predict the fines at higher impact velocities. Although Murtala et al. (2020) concluded that for the predictions of the number of fines particulate in transferring pellets via pneumatic conveying system a combination of both tumbling box and rotary impact tester should be used, our observations show that the tumbling box is capable of predicting the fines generation in gentle transport (a low-speed and small drop height) with several transfer points.

Conclusions

Using a Box–Behnken response surface design, the number of fines generated during the transport of fuel pellets by a pilot-scale belt conveyor was studied. It was shown that the number of handling steps and the drop height are the most influential parameters on the generation of fines; however, the level of loading and the speed of the belt in a range between 0.5 and 1.5 m/s were not affecting the fines generation. Moreover, using a regression model,

a polynomial quadratic model (R^2 = 0.852) to predict the number of fines generation via a belt conveyor was introduced. It is concluded that for gentle transport of pellets, the falling height and the number of handling steps should be carefully considered. It is also concluded that the tumbling box method can predict the proportion of generated fines with high accuracy for the pellets that are transported and discharged via a belt conveyor nine times.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

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