

Effect of bulk material particle size on the energy consumption of a tubular drag conveyor

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ABSTRACT

Tubular drag conveyors are an excellent means of transporting powdery and granular materials in many industries. The operating principle of such a conveyor is to transport bulk material using discs attached to a chain or cable moving inside a tube. The key advantages of tubular conveyors include simple design, quiet operation, easy route geometry configuration, and dust and gas tightness. The developed mathematical models incorporate certain simplified assumptions that prove insufficient for granular and coarse materials. This is due to the complex interactions between the conveyor components and the conveyed material. The key parameter, which is omitted in theoretical models, is the grain composition of the material being conveyed. The particle size, combined with the clearance between the disc and the pipe, determines the so-called gap effect, which significantly impacts the conveyor's energy consumption. The gap is the clearance between the inner diameter of the pipe and the outer diameter of the disc. During transport, particles of the bulk material enter the gap, causing a significant increase in resistance to motion. These interactions are influenced by many factors, including random ones, making this issue challenging to solve theoretically and experimentally. The aim of the research in this paper was to investigate the effect of grain composition on the power consumption of a conveyor drive. Coal fines specimens with different particle-size distributions were tested. The results demonstrated a strong correlation between the power consumption and the grain composition of the transported material. The experimental results were compared with the theoretical model, and correction factors accounting for the gap effect were determined.

Keywords: tubular drag conveyor, gap effect, coal fines transport, particle jamming.

INTRODUCTION

Tubular drag conveyors are a versatile means of continuous transport of bulk materials. Their numerous design variations allow for use in many industries for transporting an extremely wide range of dusty and granular materials. The key advantages of tubular conveyors include simple design, quiet operation, easy route geometry configuration, and dust and gas tightness. A significant disadvantage of these conveyors is their relatively high resistance to motion. This is due to the friction of the discs and the conveyed material against the inner surface of the tube. It leads to significant abrasive wear of tubes and scrapers. Nevertheless, tubular drag conveyors are widely

used in the agricultural, food-processing, chemical, power-generation, and steel industries [1,2].

Theoretical and experimental investigations of tubular drag conveyors were presented in works [3–5]. These papers present calculation and design methods confirmed by experimental studies. However, the theoretical models do not account for certain phenomena related to the interaction of bulk material with conveyor components – specifically, the behavior of bulk material particles in the gap between the disc and the tube – the so-called gap effect. The significance of the gap effect depends on the grain size to the gap size ratio. In the paper [3], the author included the effect of the gap in the theoretical model, assuming a passive stress state in the gap according to

Rankine's theory. However, experimental studies revealed a significant discrepancy with the theoretical model. In paper [6], the authors presented theoretical considerations regarding the rational selection of the disc pitch for a horizontal conveyor, while the authors in [7] presented a similar analysis of the selection of the disc pitch for a vertical conveyor. The considerations above also do not take into account the phenomena related to the gap effect.

A significant knowledge gap remains in the theory of tubular drag conveyors regarding the gap effect. The gap effect is a phenomenon occurring in the space between the disc and tube in the presence of bulk material particles. As discussed in [2,4] the gap effect was taken into account in theoretical considerations, however experimental studies have shown that these assumptions are invalid for coarse-grained materials.

The gap effect manifests itself through the jamming (wedging) of bulk solid particles in the gap and causes attrition, crushing, or deformation. The gap effect strongly depends on the bulk material grain size to gap size ratio. Crushing and deformation require additional energy, which increases motion resistance, abrasive wear, and ultimately power consumption. In extreme cases, this can lead to serious damage or blockage of the conveyor. On the one hand, it is an undesirable phenomenon, and on the other, it is difficult to avoid. The gap size is chosen as a compromise: too small increases the likelihood of material jamming, too large reduces performance. The reason for this is the complex interaction between conveyor components and the bulk material.

The first of these is the conveyor components geometry. As mentioned above, the key parameter is the gap (clearance), defined as the difference between the inner diameter of the tube and the outer diameter of the disc: $c = D - d$ [m], which is shown in Figure 1. Considering c as a design parameter, it has a constant value. However, the actual clearance between the disc and the tube depends on the position of the disc relative to the tube, and it is variable. The parameter that determines this is the deviation of the disk axis from the pipe axis – e (Figure 1).

Disc position depends on the tube's inclination angle. A simplified assumption can be made that for a horizontal tube, the gap changes from 0 to c , while for vertical tube, the disc is concentric, so the c value is uniformly equal $0,5c$. Therefore, the actual clearance c_A depends on the position of the disc determined by a deviation e . Its value at any point on the circumference can be calculated from the formula:

$$c_A(\delta) = \frac{D}{2} - e \cdot \cos\delta - \sqrt{\frac{d}{2} - e^2 \cdot \sin\delta} \quad (1)$$

In further considerations in this article, the clearance is assumed to be a constant value defined as $c = D - d$ [m].

The second is bulk material properties. Its influence is complex and random. It depends on grain composition, particle shape, grain compressive strength, anisotropic properties (brittle, elastic-plastic), friction coefficient, moisture, origin (mineral, biological, chemical), and others. The effect of the gap combines the conveyor geometry

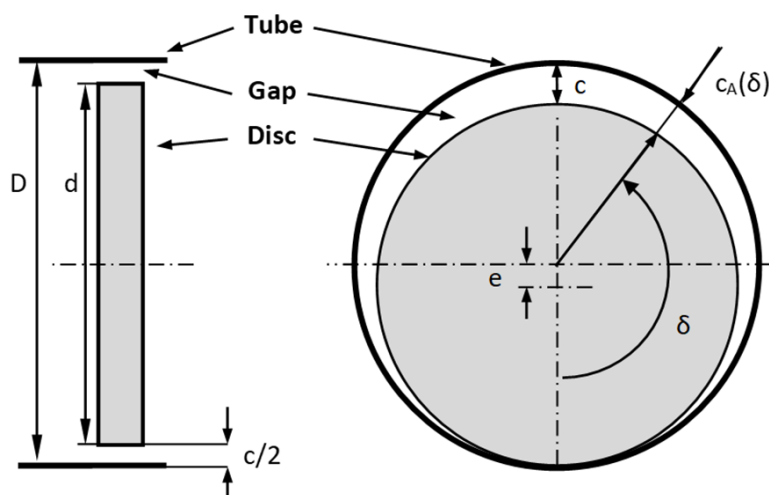


Figure 1. Diagram of the disc position in the tube: concentric (left), eccentric (right)

and the bulk material properties, making this problem largely random and extremely difficult to describe by a general theoretical model. The empirical model also poses a challenge.

The preliminary tests of energy consumption of tubular drag conveyor conducted by the author confirmed a strong influence of grain particle size on energy consumption [8]. The tests were conducted for a conveyor with an internal pipe diameter of $D = 106$ mm and a clearance value of $c = 4$ mm for fine sand, and polyamide granulate of 4 mm. Tests were conducted for fill factor 0.85. The results are shown in Figure 2.

When analyzing the graph in Figure 2, it can be seen that the theoretical model's assumptions are valid for the materials with grain sizes much smaller than the gap size (fine sand). For granular materials (polyamide granulate), with grain sizes close to the clearance value c , the theoretical model is no longer valid. For polyamide granulate, the discrepancy in results is significant, which may be due to the uniform size and elastic-plastic properties. In the paper [9], the authors conducted experimental studies of the transport of selected plant-based materials using a tubular scraper conveyor. The studies focused on curved sections. The authors, among other things, found a significant effect of the grain size of the transported material on the transport efficiency, which is related to the entry of grains into the gap between the disc and the tube.

The analysis of the state of knowledge indicates that the analytical calculation models do not fully represent the real transportation processes in tubular drag conveyors [2–5,8,9]. The reason for that is the theoretical model of the gap influence does not cover the effects of particle attrition, like deformation and destruction, and particle attrition is especially important for bulk solids with particle sizes equal to or larger than the average gap

between disk and tube. It can be highlighted that the general assumption for the calculation theory was proven for light fine-grained bulk material. It could also be recognised that the calculation theory does not describe the gap influence for coarse-grained material properly [4,8].

To sum up, there is a need to conduct further theoretical and experimental research on tubular drag conveyors in order to understand the phenomena in the interaction of conveyor elements with bulk material, in particular, the effect of the gap.

The aim of the study was to determine the bulk material granulation on the energy consumption of a tubular scraper conveyor for transporting coal fines. Material granulation combined with gap size has a significant impact on the operation of the entire system. Its significance mostly depends on the type of material being conveyed – particularly particle size. Thus, the gap effect is closely related to bulk material granulation. One of the key parameters is the relation between gap size and particle size.

MATERIALS AND METHODS

Coal fines were selected for the study. Coal fines are widely used in power plants (combustion of pulverized coal), in coke production (after blending), or in briquette production. The standard fraction of coal fines typically ranges from 0 to 30 mm. For investigations, a grade 0–20 mm was selected. This is type 32 (gas-flame) steam coal. Sieve analysis was performed for the selected sample, results are shown in Figure 3. The largest percentage by weight is in the 2–5 mm fraction, which corresponds to the gap size of the test conveyor.

The independent variable in the study was the particle-size distribution of the bulk material.

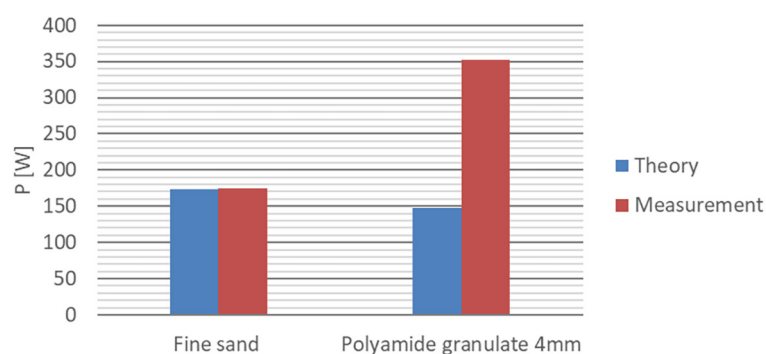


Figure 2. Comparison of theoretical and experimental results for sand and polyamide granulate

The dependent variable was the conveyor drive power consumption. Gap size was assumed as a constant $c=4$ [mm].

Out of 0–20 mm grade, three grades were sieved: 5–10 mm, 2–5 mm, and 0–2 mm. For each size grade, basic properties were determined, which are shown in Table 1.

The angle of internal friction and the coefficient of external friction were determined using a Jenike direct shear apparatus. The values in Table 1 were used to analyze the results later in this paper.

The test rig consisted of a laboratory-scale tubular drag conveyor with horizontal, inclined, and bent routing. Figure 4 shows a general view

of the conveyor. The basic parameters of the conveyor are shown in Table 2.

The test program was carried out on an inclined section, the distance between the inlet and outlet was 2.8 m as shown in Figure 5. This section was chosen to avoid the influence of the direction station on the measurement results, which manifests itself through jamming of the material between the rim and the housing.

The measurement equipment included a Metrix PX 120 wattmeter and a laptop for data logging. The measured quantity was active power with an accuracy of $\pm 1.5\%$. The test program included measuring the conveyor's active power

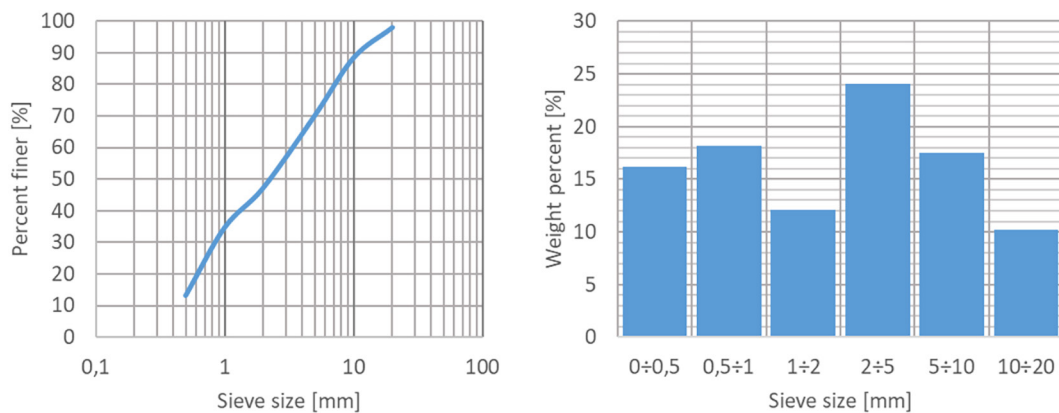


Figure 3. Sieve analysis of a coal fines specimen

Table 1. Coal fines properties

Size grade [mm]	Bulk weight [N/m ³]	Angle of internal friction [°]	External friction coefficient
5–10	7926.5	66.4	0.5
2–5	8625.1	53.6	0.5
0–2	10045.4	47.1	0.5

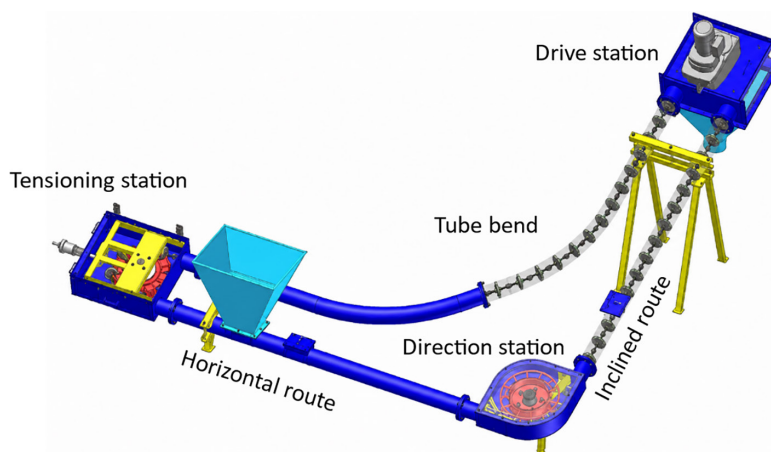


Figure 4. General view of test rig

Table 2. Test conveyor data

Motor power	$N = 0.37$ [kW]
Rope speed	$v = 0.06$ [m/s]
Inner tube diameter	$D = 0.106$ [m]
Outer disc diameter	$d = 0.102$ [m]
Inclined route angle	$\alpha = 18$ [°]
Horizontal route length	$L_h = 2$ [m]
Inclined route length	$L_i = 3$ [m]
Disc pitch	$h = 0.155$ [m]

at idle and under load. Each measurement was repeated three times. Before the main tests, the tube fill factor for each fraction was experimentally estimated by measuring the time it took to empty the hopper from a known volume of coal fines. The estimated fill factor ranged from 0.88 to 0.9. An average of 0.89 was assumed.

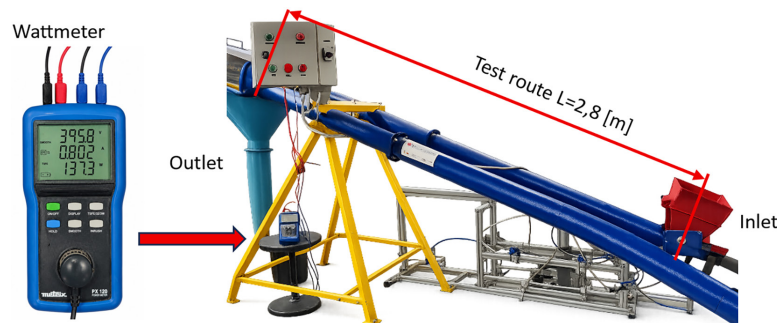
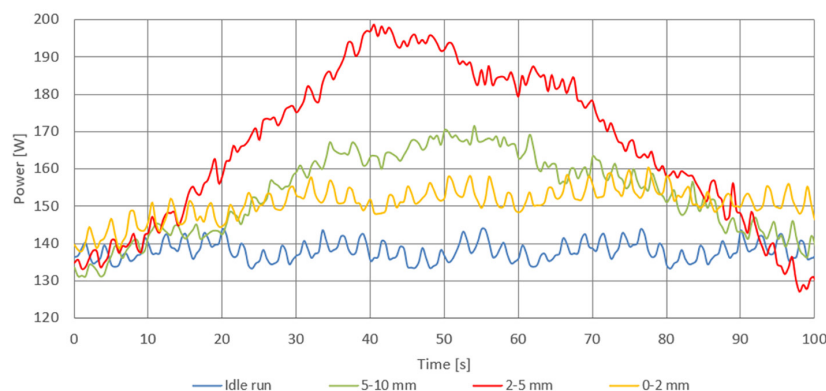
At least 40 kg of each fraction of coal fines were prepared for the tests, which ensured steady operation of the conveyor under load for a minimum of 18 seconds. The measurement for each fraction was repeated three times using the same portion of material. Finally, the power consumption during the conveyor's idle run was recorded.

RESULTS

The results of the tests carried out are the records of the active power P vs. time t . The active power is the part of the electrical power that is actually converted into useful conveyor motor work. Figure 6 presents a summary chart of selected active power waveform records for each of the tested size grades and idle run-empty.

The power waveform records $P(t)$ represent the whole work cycle, which covers three phases of conveyor operation (except idle run). The first is filling, the second is operating under load (fill factor 0.89), and the third is emptying. Summary graphs in Figure 6 show a comparison of the power waveforms for the idle run and loaded conveyor. Significant differences in power consumption can be observed for individual coal fines fractions.

Further analysis of the results was performed for the conveyor's operating ranges under load and at idle. From the power records, a data range corresponding to the conveyor's operation at full load on the measurement section of the route was selected. The raw data were subjected to statistical analysis.


Figure 5. View of test route with inlet and outlet

Figure 6. $P(t)$ summary graph for the entire cycle, including idle conveyor operation

Figures 7 to 10 show three power records over time and corresponding box plots illustrating the distribution of the tested quantities.

For the 5–10 mm and 2–5 mm fractions (Figure 7 and Figure 8), a downward trend in power consumption can be observed with each subsequent run. This may be due to the use of the same material portion for each run, which resulted in

the degradation of a certain number of grains and a slight reduction in the wedging effect. Measurements for the 0–2 mm fraction (Figure 9) demonstrate better repeatability, which can be explained by the minimal impact of the material's grain wedging effect.

The graph in Figure 11 presents box plots for each experiment for comparison. Differences

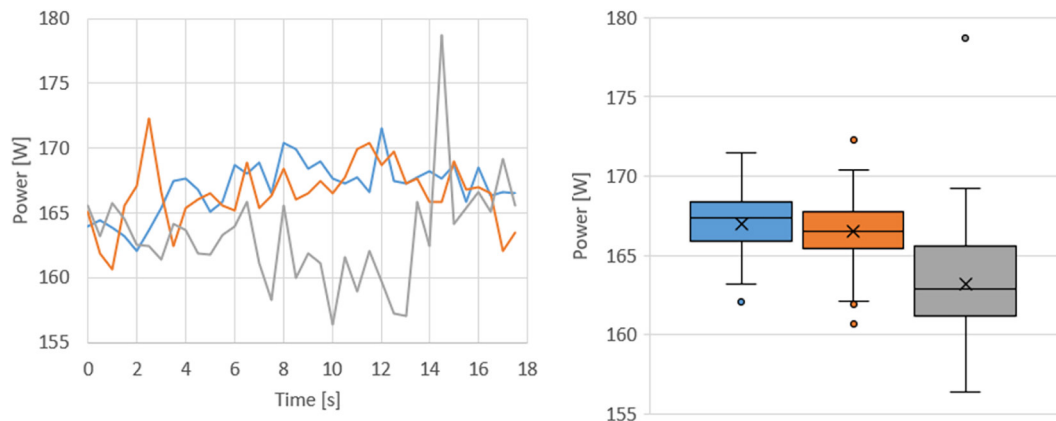


Figure 7. Records of the active power $P(t)$ waveform 5–10 mm fraction (left) and box plots (right)

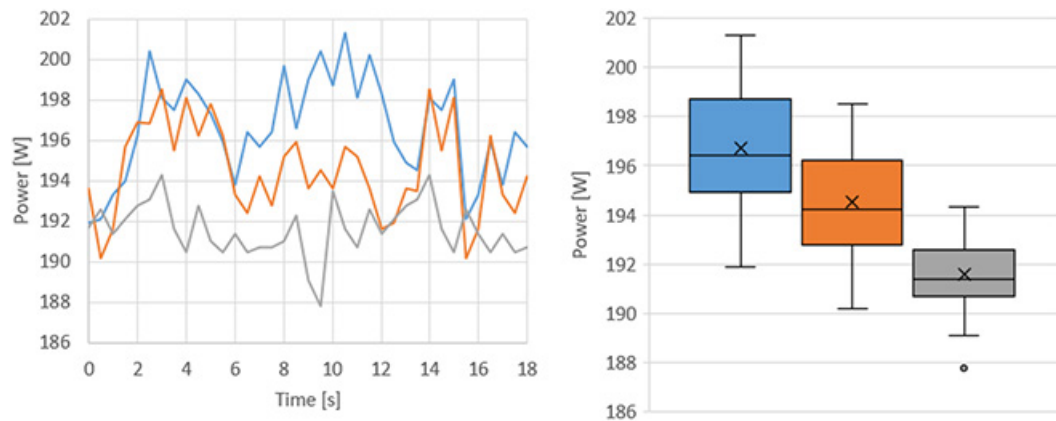


Figure 8. Records of the active power $P(t)$ waveform 2–5 mm fraction (left) and box plots (right)

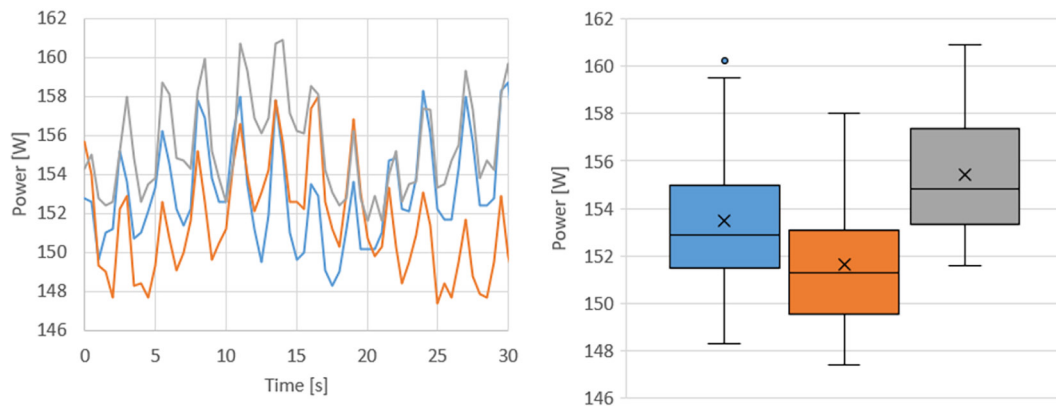


Figure 9. Records of the active power $P(t)$ waveform 0–2 mm fraction (left) and box plots (right)

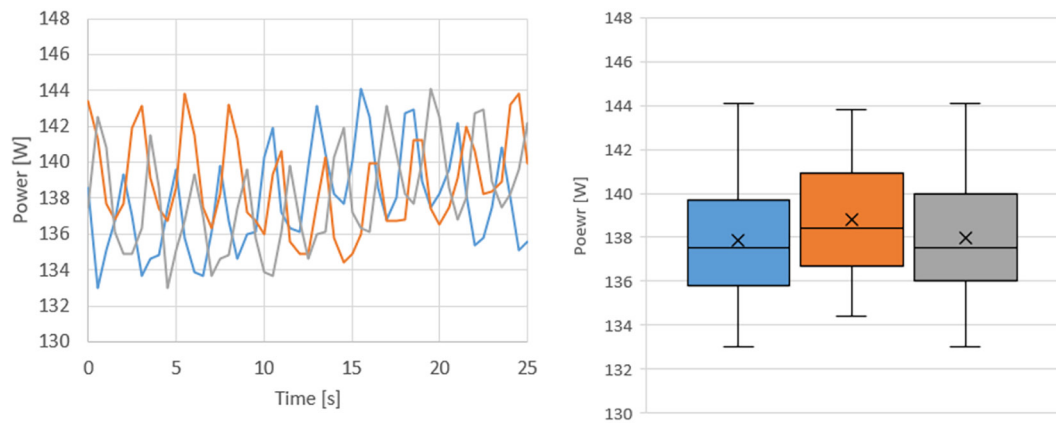


Figure 10. Records of the active power $P(t)$ waveform, empty conveyor (left) and box plots (right)

between the fractions and their clear separation are visible, allowing to consider the results as reliable, accurately illustrating the phenomenon being studied and allowing for further inferences.

Table 3 presents the complete test results. Results from three trials for each fraction are shown along with the Type A measurement uncertainty determined based on descriptive statistics. Type B measurement uncertainty results from the accuracy of the measuring device.

Homogeneity of variance was verified using Levene's test ($F = 0.976$, $p = 0.378$). Due to the large sample size in each group ($n = 79$ – 228), one-way ANOVA was considered robust to minor deviations from normality and was therefore applied.

To test whether grain size fraction affects power consumption, a one-way ANOVA was used - test statistic: $F = 4701.95$, significance level: $p = 6.36 \times 10^{-307}$. The obtained p-value is significantly lower than the assumed significance level of $\alpha = 0.05$; therefore, the null hypothesis of no difference between means was rejected. This means that the grain size fraction

has a statistically significant effect on the value of power consumption.

To determine which fractions differed, Tukey's post hoc test was performed. The results are presented in Table 4.

All analyzed pairs of fractions differed statistically significantly.

When analyzing the obtained results, clear differences can be observed in power consumption between the tested coal fines fractions. The lowest power consumption was recorded for the finest fraction of 0–2 mm. For the fraction 5–10 mm, the power consumption was higher than for the 0–2 mm fraction. The highest power consumption occurred for the 2–5 mm fraction. Based on the above results, it can be seen that the grain-size fraction significantly impacts the conveyor's energy consumption. It should be noted that this is the same material, differing only in grain composition, which novel approach in tubular conveyor research.

The above results allows assuming that the impact of the gap increases with rising conveyor

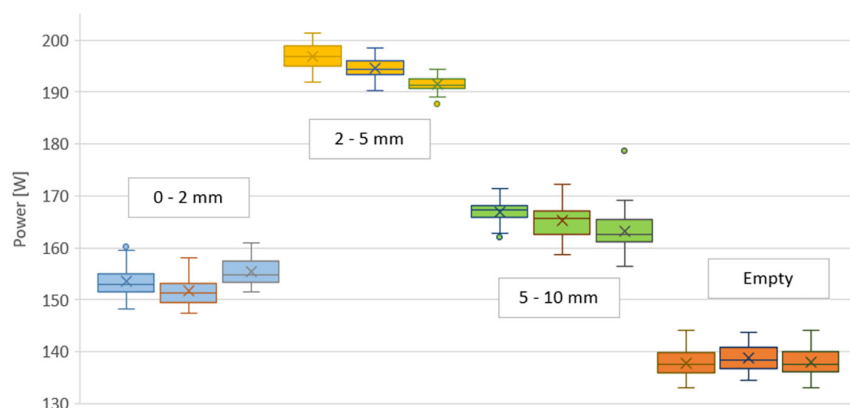


Figure 11. Summary box plots

Table 3. The complete results

Size grade	Exp.	Power [W]				Mean of three experiments
		Mean power	Uncertainty			
			Type A	Type B	Combined	
0–2 mm	1	153.5	±2.76	±2.3	±3.59	153.5±1.90
	2	151.6	±2.69	±2.27	±3.52	
	3	155.4	±2.48	±2.33	±3.41	
2–5 mm	1	196.9	±2.54	±2.95	±3.89	194.3±2.75
	2	194.5	±2.11	±2.92	±3.61	
	3	191.4	±1.43	±2.87	±3.21	
5–10 mm	1	166.9	±2.05	±2.51	±3.24	165.3±2.05
	2	166.5	±2.41	±2.49	±3.46	
	3	163.2	±3.94	±2.44	±4.63	
Idle run	1	137.8	±2.72	±2.06	±3.41	138.2±0.55
	2	138.8	±2.58	±2.08	±3.31	
	3	137.9	±2.83	±2.07	±3.51	

Table 4. Tukey’s post hoc test results

Comparison	Mean difference	Significance
0–2 mm vs 2–5 mm	40.98	p < 0.001
0–2 mm vs 5–10 mm	11.54	p < 0.001
2–5 mm vs 5–10 mm	29.44	p < 0.001

energy consumption. This, in turn, depends on the grain size to gap size ratio. The gap size in the test conveyor was 4 mm, and the highest energy consumption was for the 2–5 mm fraction. Therefore, grains of sizes close to the gap size determine the gap’s effect.

DISCUSSION

The preliminary analysis of the test results showed a significant influence of coal fines granulation on the energy consumption. The gap effect strongly depends on the size grade of transported coal fines, and the key issue is the particle size to gap size ratio.

Based on the results obtained, it is possible to determine the power required to move the bulk material itself. It was estimated by subtracting the measured idle power of the conveyor from the power when transporting each grain fraction. Recorded idle power was $P_i = 138.2$ [W]. By dividing the power ΔP by the length of the test route $L = 2.8$ [m], the unit power P_{um} [W/m] is obtained. Results shown in Table 5.

When analyzing the data in Table 5, significant differences in power demand depending on the coal fines size grade can be seen. The highest value was observed for the 2–5 mm fraction, whereas the lowest value was observed for the 0–2 mm fraction. Assessing quantitative differences shows that for the grade 2–5 mm unit power is approximately 4 times as for grade 0–2 mm and approximately twice that for the 5–10 grade. These are significant differences, and that is why further analysis will involve comparing experimental results with the theoretical model.

In the [1,5] thesis, a theoretical model and calculation method of a tubular drag conveyor were developed and experimentally verified. For the purposes of this article, the basic relationships related to the test conveyor are presented below. The unit drag force of the rope with scrapers and the transported material on a straight route is described by the equation:

$$w_u = \phi \cdot \frac{\pi(D^2 - d_r^2)}{4} \cdot \gamma_m \cdot (\mu \cos \alpha + \sin \alpha) \cdot \left(e^{\frac{4 \cdot \mu \cdot k \cdot D \cdot h}{D^2 - d_r^2}} + q(f \cos \alpha + \sin \alpha) \left[\frac{N}{m} \right] \right) \quad (2)$$

where: D – tube inner diameter [m], d_r – rope diameter [m], ϕ – fill factor [-], γ_m – bulk density [N/m³], μ – bulk external friction coefficient, α – tube inclination angle [°], k – Rankine’s coefficient of active lateral pressure [-], h – disc pitch [m], q – rope and disc unit weight [N/m], f – rope and disc friction coefficient.

The drag force of the rope with scrapers on tube bend is described by equation [5]:

$$w_b = \frac{f \cdot S_0}{\cot \xi - f} + \left(f \cdot \frac{S_0}{\cos \xi - f \sin \xi} \cdot \left(1 + \frac{1+f \cdot \tan \xi}{1-f \cdot \tan \xi} \right) \cdot \sin \xi \right) \cdot \frac{q_b^n - 1}{q_b - 1} \text{ [N]} \quad (3)$$

where: S_0 – force in the rope at entering tube bend [N], $\xi = h/2R$ – angle of deflection of the rope on the tube bend [rad], R – bend radius [m], $n = ((\beta R \pi / 180 h) - 1)$ – number of discs on tube bend, β – bend angle [°], q_b – the quotient of the increase in drag on subsequent discs in the tube bend.

Required power can be calculated according to equation:

$$P = \frac{W_t \cdot v}{\eta_d} \text{ [W]} \quad (4)$$

where: W_t – total drag force [N], v – rope linear speed [m/s], η_d – total drive performance.

Drive unit of test conveyor consists of a Nord SK 4382 motoreducer with AC motor Nord 0.37 kW SK 71 L/4 and sprocket as shown in Figure 12.

Total performance of drive is given by equation:

$$\eta_d = \eta_r \cdot \eta_m \cdot \eta_s \quad (5)$$

For calculations performance η_d was assumed from 0.51 for empty conveyor and 0.53 for loaded, based on estimation of drive load according to motor efficiency characteristic (Figure 12a). Assumed performance of tensioning sprocket 0.98 and direction wheel 0.99. The calculation diagram of the conveyor with the marking of the route sections is shown in Figure 13. Geometric parameters are also given. The initial tension force of the rope was set to 500 N.

The discs of the test conveyor are made of PA6 polyamide. The coefficient of friction between the discs and the pipe was determined empirically based on tests of the unloaded conveyor. The determined value of the coefficient $f = 0.58$. It should be noted that friction between the discs and the steel pipe occurs under the conditions of residual contamination from the conveyed material, in this case, coal fines. The f coefficient was determined for such conditions.

Table 5. Measured unit power demand for each size grade

Size grade	P [W]	$\Delta P = P - P_i$ [W]	Unit power P_{um} [W/m]
0–2 mm	153.5	15.3	5.46
2–5 mm	194.3	56.1	20.03
5–10 mm	165.3	27.1	9.67

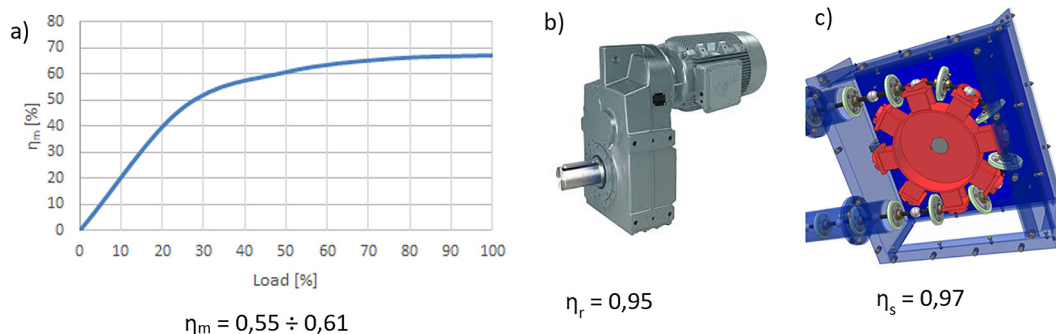


Figure 12. Drive components and their efficiency: a) – motor efficiency characteristics, b) – three-stage reducer, c) – drive sprocket

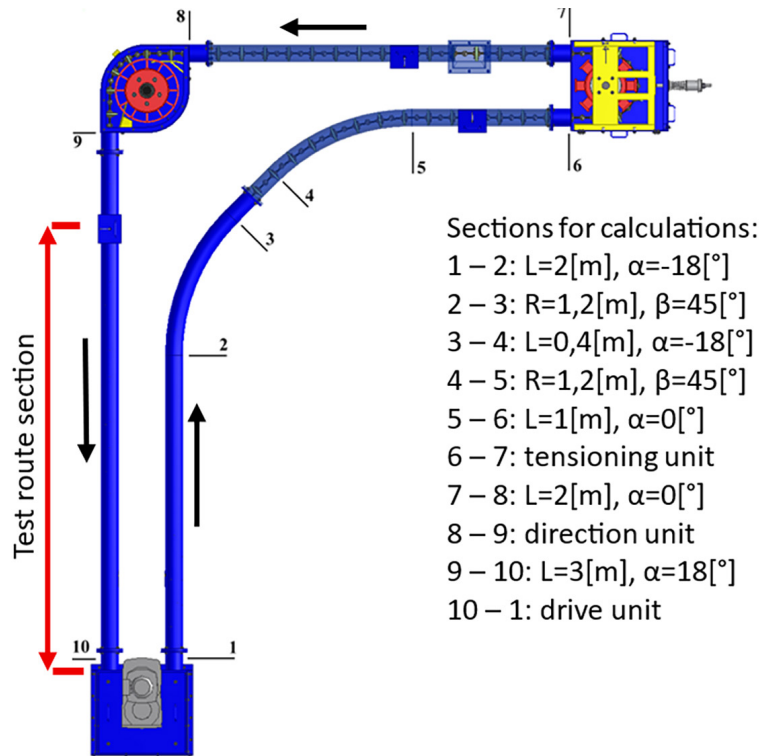


Figure 13. Conveyor calculation diagram

Theoretical calculations of the power requirements of the test conveyor were performed for the assumed data as in the text above. The calculation results were compared with the experimental data. Results shown in Table 6.

Comparing the results in Table 6, clear differences between the theoretical and experimental results can be seen. For the idle run conveyor and the one loaded with a 0–2 mm fraction, the differences are within the measurement error and demonstrate good correlation. For fractions 2–5 mm and 5–10 mm, differences are significant, 30.5% and 15% respectively. This means that the theoretical model's assumptions do not account for the effect of the gap depending on grain size and bulk material type, and they are valid for materials with grain sizes much smaller than the gap size only. The difference in theoretical power demand between grain fractions results from the density of the bulk material and the angle of internal friction. However, differences in measured power result from the interaction between the disk and the tube and the material particles. Of course, it is impossible to assess this phenomenon based solely on energy consumption measurements. This requires a much broader research program that also takes into account random factors.

If the theoretical assumptions are correct for materials with a grain size significantly smaller than the gap size, it is necessary to correct these assumptions for a grain size corresponding to the gap size "c" to some extent. The basic characterisation of the transport processes in all mechanical conveyors is done by the addition of positive or negative motion resistance components [4]. These may be correction factors in additive or multiplicative form.

Using the results of experimental studies (Table 5) and the theoretical model, the correction factors were estimated. Using Equation 2, the unit power of conveying bulk material at speed v is expressed by the formula:

$$P_{ut} = v \cdot \phi \cdot \frac{\pi(D^2 - d^2)}{4} \cdot \gamma_m \cdot (\mu \cos \alpha + \sin \alpha) \cdot e^{\frac{4 \cdot \mu \cdot k \cdot D \cdot h}{D^2 - d^2}} \left[\frac{W}{m} \right] \quad (6)$$

The correction factor is expressed as the ratio:

$$c_f = \frac{P_{um}}{P_{ut}} \quad (7)$$

The correction factor is only taken into account when calculating the motion resistance

Table 6. Comparison of theoretical and experimental results

Size grade	Theoretical power P_t [W]	Measured power P_m [W]	Difference P_t vs P_m [%]
Idle run	135.2	138.2	2.2
0–2 mm	156.1	153.5	-1.7
2–5 mm	148.8	194.3	30.5
5–10 mm	143.7	165.3	15

Table 7. Correction factors and power demand comparison

Size grade	P_{um} [W/m]	P_{ut} [W/m]	c_f	P_{tc} [W]	P_m [W]
0–2 mm	5.46	5.33	~1	156.1	153.4
2–5 mm	20.03	3.96	5	220.5	194.5
5–10 mm	9.67	2.96	3.4	173.5	167.8

in the sections where the bulk material and the rope with discs move. The multiplicative form was used. Thus, the corrected unit resistance on a straight section is expressed by the equation:

$$w_{uc} = c_f \cdot w_u \left[\frac{N}{m} \right] \quad (8)$$

Correction factors were determined for each grain size class. Theoretical power requirements P_{tc} were calculated, taking into account the correction factors, and compared with the measured power P_m . The results are presented in Table 7.

The correction factors determined to account for the gap effect are simplified; however, the power P_{tc} calculated based on the c_f factor is slightly higher, but shows good correlation with the measured power P_m . It should be noted that the correction factors are valid for the conditions of the above experiment, and their application to other materials should be considered carefully.

Developing more general guidelines and expanding the theoretical model requires a much broader program of research on the grain size effect.

CONCLUSIONS

The experimental studies conducted in this article demonstrated a significant impact of bulk material granulation on the energy consumption of a tubular drag conveyor. The particle-size distribution of the bulk material and the conveyor gap size are closely related, determining the operation of a tubular conveyor like resistances to motion and energy consumption. Tested material was coal fines 0–20 mm. Specimen was divided into three

size grades: 0–2mm, 2–5 mm, and 5–10 mm. The highest energy consumption was observed for the 2–5 mm fraction, which coincides with the clearance value, which is $c = 4$ mm. The effect of the 0–2 mm fraction was minimal. The 5–10 mm fraction can be estimated to be moderate. Based on a comparative analysis of experimental results and the theoretical model, correction factors were proposed. The factors were estimated for each of the tested grain fractions. These conclusions are valid for the coal fines investigated in this study. Bulk materials with parameters similar to the tested one (e.g., coefficient of friction, compressive strength, grain composition) may exhibit similar behavior in the conveyor, and the proposed approach may be applicable.

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