ENERGY SAVING AT BELT CONVEYORS BY SPEED CONTROL

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ABSTRACT

Conventional troughed belt conveyors often receive material flows that are less than their potential conveying capacity. In addition, the capacity of these received material flows may be fluctuating. DIN 22101 indicates that reducing the belt speed, and thereby maximising belt load always results in a reduction of the required mechanical and electrical drive power. Predictions of the speed control savings by DIN 22101 however, are inaccurate because the prescription of the DIN f factor is not very accurate. Therefore power consumption savings can only be truly validated by physical measurements. With information on speed control savings, an evaluation can be made as to whether the capital expenditures required for speed control conversion are economically feasible. This paper provides a methodology to predict these savings with the use of DIN 22101, taking into account the fluctuations of the material flows and the layout and design of a belt conveyor system.

1. INTRODUCTION

Today the focus of many research projects in the field of transport engineering and logistics is on the ambient pollution caused by transport equipment including belt conveyors. Ambient pollution includes not only spillage of dry bulk material during transhipment, transfer or caused by carry-back, but also the carbon dioxide (CO_2) emissions caused by the generation of the energy required for operating transport equipment [1]-[4].

If it is possible to reduce the amount of energy used by a belt conveyor to transport a certain amount of dry bulk material from one place to another, then that automatically leads to a reduction of the emissions. Energy savings can be principally achieved by either reducing the friction in the belt conveyor or by optimising the logistic control of the system. The friction in a belt conveyor can, for example, be decreased by applying low loss rubber compound in the belt, (see [5] or [6]), or by using special low loss idler rolls and skirt boards. Energy savings can further be achieved by optimising the logistic control of a belt conveyor. The logistic control of a belt conveyor includes controlling the belt feed and belt speed. The belt speed can be controlled in a discrete (on/off) or continuous manner. This paper focuses on energy savings achieved by optimising the logistic control of the system.

Normally, a belt conveyor runs more or less at the same speed whether it is fully loaded or empty. It is possible to monitor the load on the belt by using a weight frame or a volume measurement system and adjust the belt speed in such a way that the belt is always running 'full' in terms of volumetric capacity. For this, a certain threshold value for the loading degree is defined, for example 85%, and if the belt loading degree falls outside a certain bandwidth, for example 10%, then the belt speed is adjusted. Changes in belt feed or required discharge capacity are caused by the total system in which the conveyor operates. In the case of a power plant, the reason for a discharge capacity range can be the result of coal qualities, boiler unit load factor and demand side implications [7]. In the case of an import and export terminal for dry bulk solid materials, it can be due to the unload procedure of an import vessel or to the reclaimer characteristics.

This paper discusses the effect of power savings by speed control and the emissions generated by a belt conveyor. Besides energy savings, decreasing the belt speed also results in an increase in the lifetime of belt conveyor components such as the conveyor belt and idler rolls. This aspect it is referred to in [7].

2. ENERGY CONSUMPTION AND EMISSIONS

In general it can be said that the electrical power P_e required to drive a belt conveyor depends on the total motional resistance F, the belt speed v, the drive's mechanical efficiency η_{mech}, the electrical efficiencies of the frequency converter η_{freq}, and the motor efficiency η_{motor}, and is equal to:

$$P_e = \frac{F(m'_L)v}{\eta_{mech}\eta_{freq}\eta_{motor}} \tag{1}$$

The total motional resistance F depends on among others, the load on the belt m'_L, the belt conveyor design characteristics, and its length. Reducing the belt speed at a given material flow, Q_m increases the load on the belt, which increases the motional resistance. However, an overall reduction of the required electrical power is expected due to the lower belt speed. This is caused by the fact that the increase in friction caused by the increase of belt load m'_L is less than the decrease in velocity. Therefore P_e decreases with a decrease of the belt speed v, although not linearly [8]. The speed control savings ΔP_e by lowering the belt speed from $v_{nominal}$ to v_n at non nominal material flow Q_m is given as:

$$\Delta P_e(Q_m) = P_e(Q_m, v_{nominal}) - P_e(Q_m, v_n) \tag{2}$$

The emission of CO_2, nitrous oxide (NO_x) and particulate matter (pm), depend on the energy used by a belt conveyor. The mass of the emission output is related to the amount of energy consumption E_S. The relation between the mass of emission output $m_{substance}$ and the energy consumption is given by the specific emission factor (s.e.f.) [9]:

$$m_{substance} = s.e.f._{substance} E_S \tag{3}$$

where $m_{substance}$ is the emitted mass of a substance in mg, $s.e.f._{substance}$ the specific emissions factor of a certain substance in mg/J, and E_S the energy consumption in J. For the emission output of the substance CO_2 , for example, equation 3 becomes:

$$m_{CO2} = s.e.f._{CO2}\ E_S \tag{4}$$

The specific emission factors for CO_2, NO_x and pm in the Netherlands are 0.15, 0.00016, and 0.0000018 respectively. Although E_S is the energy used to power a belt conveyor, it should be realised that in order to make electricity, primary energy resources such as coal, oil and gas are used. The amount of primary energy E_p is calculated by [9]:

$$E_p = r_p E_S \tag{5}$$

where r_p is the ratio of the used energy form and the used primary energy. This ratio, for example, is 2.2 for electricity and 1.2 for diesel fuel. The energy consumption E_S can be calculated by multiplying the power required to drive transport equipment with the time t it is operating:

$$E_S = P_e t \tag{6}$$

For a normal belt conveyor P_e is a function of time. Sometimes a belt conveyor is fully loaded and is P_e high, sometimes it is running empty and is P_e low. Also, the ambient conditions like temperature have an impact on the required drive power. Therefore the total amount of energy used in a certain period of time depends on the operational and ambient conditions and equation 6 must be rewritten to:

$$E_S = \int P_e(t)dt \tag{7}$$

With the speed control savings ΔP_e and using the equations 4 and 6 the reduction in the emission of CO_2 can be determined:

$$\Delta m_{CO_2} = s.e.f._{CO_2} \Delta P_e \left(Q_m\right) \Delta t \tag{8}$$

where Δt is the period of time the speed is reduced.

As an example, if a power reduction of 250 kW can be achieved for half an hour per day (125 kWh) then this leads to a reduction in the emission of CO_2 of 24,638 kg per year. In the Netherlands, the average cost of a kWh is € 0.10. The emission rights of CO_2 cost about € 15.- per ton. The total cost saving in this example therefore is about € 4, 932.10.- per year.

3. BELT CONVEYOR POWER CALCULATION

In the standard DIN 22101 [10] the total motion resistance is defined as:

$$F = F_H + F_N + F_{St} + F_S \tag{9}$$

where F_H is the primary or main resistance, F_N the secondary or side resistances, F_{St} the gradient resistance and F_S the special resistances. The primary resistance F_H is the resistance force that occurs in the carry strand of the belt and the normally unloaded return strand of the belt. It is independent of the change of elevation H. The secondary resistance F_N is the resistance force that is due mainly to frictional and acceleration forces in the feeding area. The secondary resistance can be expressed with sufficient accuracy for belt conveyors in excess of 80 metres by:

$$F_N = (1-C)F_H \tag{10}$$

where 1-C is the ratio between the primary resistance and the secondary resistance. If the special resistances are not taken into account then equation 9 can be written out to the following equation, using equation 10:

$$F = CfLg\left[m'_R + \left(2m'_B + m'_L\right)\cos\delta\right] + m'_L\, gH \tag{11}$$

where f is the artificial or fictive coefficient of friction, L the total length of the conveyor, m'_R the reduced mass of the idler rolls in both the carry and the return side of the belt, m'_B the reduced mass of the belt, m'_L the reduced material load on the belt, and δ the inclination or declination angle of the conveyor. Assume that a belt conveyor has been designed so that it can carry the required capacity Q_m in accordance with the guidelines given in DIN 22101 or ISO 5048. In that case the reduced material load on the belt is equal to:

$$m'_L = \frac{Q_m}{3.6 v \varphi_1} \tag{12}$$

where φ_1 is the slope factor of the installation. If the belt speed is changed proportionally with a change in capacity then the reduced material load on the belt remains constant. If the belt speed however, is changed at a constant capacity, then the reduced material load on the belt changes inversely, proportionate to the belt speed. Therefore, as far as the total motion resistance is concerned, the only two parameters that can change with a change in belt speed are the belt speed itself and the reduced material load on the belt. All other parameters remain constant. Therefore the total motion resistance can be expressed as a function of the reduced material load on the belt as used in equation 6. If all terms with the reduced material load on the belt are collected then equation 11 becomes:

$$F = F\left(m'_L\right) = CfLg\left[m'_R + 2m'_B\cos\delta\right] + \left[CfLg\cos\delta + gH\right]m'_L = C_1 + C_2 m'_L \tag{13}$$

Here it is implicitly assumed that the fictive coefficient of friction f is also independent of the reduced material load of the belt, and thus the capacity of the conveyor. This assumption will be discussed later. With equation 6 and equation 13, the power required for a belt conveyor to overcome the motion resistances using DIN 22101 can be expressed as follows:

$$P_e = \left[\frac{C_1}{\eta_{mech}\eta_{freq}\eta_{motor}} \right] v + \left[\frac{C_2}{\eta_{mech}\eta_{freq}\eta_{motor}} \right] m'_L\, v = C_1^* v + C_2^* m'_L\, v \tag{14}$$

Equation 14 can also be expressed in terms of capacity. Using equation 12, equation 14 becomes:

$$P_e = C_1^* v + C_2^* m'_L\, v = C_1^* v + \frac{C_2^* Q_m}{3.6\varphi_1} = C_1^* v + C_2^{**} Q_m \tag{15}$$

Alternatively from equation 13 an expression can be derived for the fictive friction coefficient f:

$$f = \frac{\dfrac{P_e \eta_{mech}\eta_{freq}\eta_{motor}}{v} - m'_L\, gH}{CLg\left(m'_R + \left(2m'_B + m'_L\right)\cos\delta\right)} \tag{16}$$

This equation is used later to derive the fictive friction coefficient from experimental results.

4. FICTIVE COEFFICIENT OF FRICTION

Looking back at equation 11, it becomes clear that the prediction of the required drive force, when using the DIN standard, depends on the selection of the fictive coefficient of friction f. All the reduced masses are normally known, as well as the conveyor's geometry that determine the parameters L, H and δ. The ratio between the primary and secondary resistance C is prescribed by the DIN standard. Values for f are recommended by the DIN standard and are generally between 0.016 for a well laid out, clean belt conveyor and 0.027 for unfavourable operating conditions. Well designed, long overland conveyors show f factors between 0.008 and 0.012. In practice, a fictive coefficient of friction in the range of 0.023 to 0.025 is generally considered a safe design value.

Belt conveyors are generally driven by squirrel cage induction motors. In order to allow for speed variation it must be possible to vary the frequency of the supply current which requires a frequency converter. Nowadays, frequency converters are priced comparably to other conventional belt conveyor drive configurations like fluid couplings. If a conveyor is originally not equipped with frequency converters then a conversion of the drive system is required to allow for speed variation. This, however, incurs serious costs. In order to be able to evaluate whether or not an investment in frequency convertors pays off within a certain period of time, an accurate calculation of the benefits of speed variation is required. Just using a general DIN f factor to calculate the power savings does not suffice. It is therefore necessary to calibrate the power calculation of the DIN standard by measuring the actual fictive coefficient of friction. In addition, in the analysis in Section 3 it was assumed that the fictive coefficient of friction is also independent of the reduced material load of the belt, and thus the capacity of the conveyor. This assumption will be challenged in the next section.

5. PHYSICAL MEASUREMENTS

A 660 metre long belt conveyor is used to determine the actual DIN f factor of that conveyor and to investigate a possible change in that factor with a change in belt load [10]. The data of the belt conveyor are given in Table 1.

L [m]	H [m]	v [m/s]	Q_m [MTPH]	m'_B [kg/m]	m'_R [kg/m]	C (DIN)	η_{mech}	ηf_{req}	η_{motor}
660	16.1	4.5	6,000	48.6	55.8	1.17	0.960	0.961	0.984

Table 1. Belt conveyor data

The electrical power consumption of the belt conveyor was measured with a digital clam meter around the power supply lines of the belt conveyor's frequency converter. This frequency converter was used to control the belt speed. The load on the belt was controlled by a speed-controlled apron feeder underneath the hopper.

Three different bulk solid materials were transported with the belt conveyor at different speeds and capacities. Figure 1 shows the results of the measurements in terms of derived DIN f factors using equation 16.

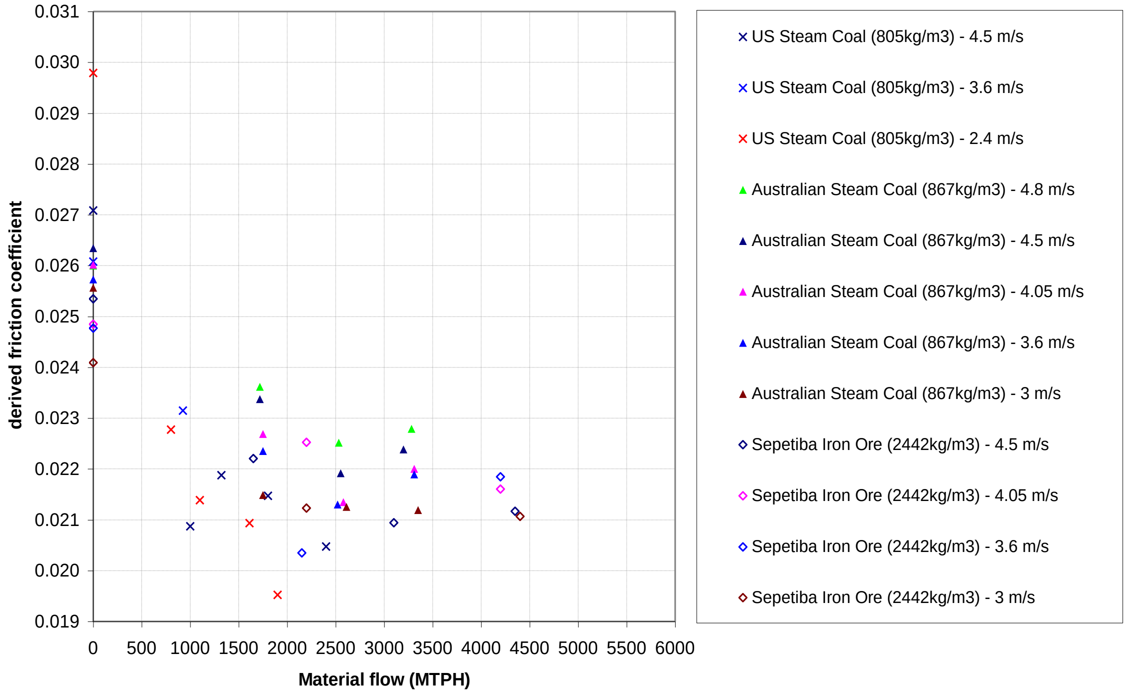

Figure 1. Derived friction coefficient

From Figure 1 it can be seen that the average value for f is about 0,022. Deriving a trend of the friction coefficient instead of a fixed value does not have any added value at the moment. The variance which arises due to measurements with different dry bulk materials and operating conditions is larger than the variation of f itself (see Figure 1). Therefore the assumption that the DIN f factor is independent of the reduced material load of the belt, and thus the capacity of the conveyor is justified.

At a capacity of 0 MTPH, Figure 1 shows different values for the fictive coefficient of friction f. In essence, one would expect that for an unloaded conveyor the value for f under this condition would be a constant. However, due to the fact that the power required to drive the belt conveyor was determined electronically and not mechanically, and that the different tests were done at different belt speeds, the change in electrical efficiency at different belt speeds affects the value of f.

6. CASE STUDY I

In practice, many belt conveyors are not utilised to the capacity for which they are designed. This may have various reasons. One reason can be that the belt conveyors are designed to accommodate future capacities that may be reached after expansion of a mine or bulk handling facility. In that case the volumetric capacity is underutilised and a reduction of the belt speed is possible during normal operation without jeopardising the functionality of the system.

To illustrate the effect of the speed reduction on the power consumption and emissions of belt conveyors, three actual operating belt conveyors are considered with different lengths and change of elevation (see Table 2). In Table 2, Belt Conveyor (BC) 1 is the same conveyor that was used for the measurements described in Section 5.

	BC 1	**BC 2**	**BC 3**
Length [m]	660	1,410	95
Material lifting height [m]	16.1	5.8	9.0
Width [mm]	1,800	1,800	1,800
Trough angle [°]	40	40	40
Nominal speed [m/s]	4.5	4.5	4.5
Nominal capacity [t/hr]	6,000	6,000	6,000

Table 2. Belt conveyor characteristics

All three belt conveyors have a nominal capacity of 6,000 MTPH at the nominal belt speed of 4.5 m/s. If in practice it turns out that the real required capacity is about 3,250 MTPH then the belt speed can be reduced to 2.75 m/s. At that belt speed the conveyors still have 10% overcapacity that can cater for fluctuations in the material flow. It is assumed that the belt conveyors are occupied for 35% of the available time (360 days at 24 hours per day). In that case reducing the belt speed from 4.5 m/s to 2.75 m/s leads to energy savings as presented in Table 3.

	BC 1	**BC 2**	**BC 3**
P_e (6,000t/hr) [kW]	722	946	259
P_e (3,250t/hr, 4.5m/s) [kW]	449	625	153
P_e (3,250t/hr, 2.75m/s) [kW]	400	529	142
$P_{e,savings}$ [kW]	49	96	11
CO_2 reduction [Tons]	80	157	18
Speed control savings [€/yr]	14,818	29,030	3,326
CO_2 emission costs reduction [€/yr]	1,200	2,352	269
Total savings [€/yr]	16,018	31,382	3,595

Table 3. Speed control savings of a frequency controlled belt conveyor.

The belt conveyors 1, 2 and 3 that were described in Table 2 in reality do have frequency converters to regulate the belt speed. If however, they were equipped with fluid couplings then the total savings given in the last row of Table 3 can be used to assess whether or not a conversion to frequency converters is feasible or not. In that analysis also the cost of the control system as well as the belt load monitoring device should be considered.

7. CASE STUDY 2

Besides underutilisation of the capacity of a belt conveyor, as illustrated in Section 6, a significant fluctuation of the material flow can also be a reason to apply speed control in order to maximise the volumetric capacity. Assume that belt conveyor BC-2 of the previous case study is fed by a reclaimer and experiences a fluctuating material flow due to the nature of the reclaiming process. Assume that the capacity of the material flow fluctuates as follows:

$$Q_m = Q(t) = Q_1 + Q_2 \sin\frac{2\pi t}{p} \qquad (17)$$

where p is the cycle time. Here it is assumed that a four quadrant drive is used so that deceleration forces and acceleration forces cancel each other out and that the cycle time is in minutes, not seconds. If it is desired that the reduced material load on the belt is kept constant, then the belt speed has to vary with the capacity as described in equation 18. A combination of equation 12 and 18 yields:

$$v(t) = \frac{Q_1}{3.6m_l'} + \frac{Q_2}{3.6m_l'}\sin\frac{2\pi t}{p} = Q_1^* + Q_2^*\sin\frac{2\pi t}{p} \tag{18}$$

If the reduced mass of the material load on the belt is constant then the total motion resistance, as defined in equation 13, is constant as well. With a constant resistance force the required drive power, using equation 1, simplifies to:

$$P_1(t) = \frac{Fv(t)}{\eta_{mech}\eta_{freq}\eta_{motor}} = \frac{F}{\eta_{mech}\eta_{freq}\eta_{motor}}\left\{Q_1^* + Q_2^*\sin\frac{2\pi t}{p}\right\} = P_1 + P_2\sin\frac{2\pi t}{p} \tag{19}$$

Therefore, with equation 7, the total amount of energy used in the cycle time p is:

$$E_{S,1} = \int_0^p \left(P_1 + P_2\sin\frac{2\pi t}{p}\right)dt = P_1 p + \frac{P_2 p}{\pi} \tag{20}$$

If the belt speed is not varied in accordance with the variation of the material flow but kept constant, then the reduced material load on the belt will vary in accordance with:

$$m_l' = \frac{Q(t)}{3.6v} = \frac{Q_1 + Q_2\sin\frac{2\pi t}{p}}{3.6v} \tag{21}$$

If equation 22 is combined with equation 14 then the following expression is obtained for the required drive power:

$$P_2(t) = C_1^* v + C_2^* v\left(\frac{Q_1 + Q_2\sin\frac{2\pi t}{p}}{3.6v}\right) = P_1^* + P_2^*\sin\frac{2\pi t}{p} \tag{22}$$

Again, with equation 7, the total amount of energy used in the cycle time p can be calculated:

$$E_{S,2} = P_1^* p + \frac{P_2^* p}{\pi} \tag{23}$$

Presume that the average capacity Q_1 is equal to 4,625 MTPH, the amplitude of the capacity fluctuation Q_2 is 1,375 MTPH and the cycle time is 15 minutes. In that case the capacity fluctuates between the design capacity of 6,000 MTPH and the reduced capacity used in Case Study I of 3,250 MTPH. The base case (Case 1) is the situation described in Case Study I where the conveyor runs with a belt speed of 4.5 m/s carrying 6,000 MTPH. Two more cases came from Case Study I: the conveyor carrying 3,250 MTPH at a belt speed of 4.5 m/s (Case 2) and the conveyor carrying 3,250 MTPH at a belt speed of 3.27 m/s (Case 3). Here, two more cases are added using the data of belt conveyor 2 (BC-2) as described in Section 6. Case 4 is the situation where the belt speed fluctuates to accommodate the fluctuating material feed. Finally, Case 5 is the situation where the belt speed is kept constant at 4.5 m/s and the reduced load of the bulk material on the belt fluctuates with varying material feed. Table 4 summarises the results and illustrates the possible power savings.

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Capacity [MTPH]	6,000	3,250	3,250	Fluctuating between 6,000 and 3,250	Fluctuating between 6,000 and 3,250
Belt speed [m/s]	4.5	4.5	2.75	Fluctuating between 4.5 and 2.44	4.5 m/s
Reduced material load [kg/m]	370.37	200.62	328.28	370.37	Fluctuating between 370.37 and 200.62
Required power [kW]	946	625	529	783	834

Table 4. Power requirements for the different operational cases

From Table 4 it can be learned that with a fluctuating material feed, it is beneficial to control the belt speed so that the volumetric capacity is kept constant at the design capacity. In the given example, the average power per cycle time reduces by 36.5 kW from 834 kW to 783 kW. With this, the cost saving per year in terms of electricity is € 11,038.-. The reduction in CO_2 emission is 59.6 ton, which reduces the CO_2 compensation by € 894.- per year. In total the cost savings of varying the belt speed with a varying material feed in this specific case is € 11,932.-

8. CONCLUSION

In this paper two case studies were presented illustrating the effects of varying the belt speed with a variation of bulk solid material load on the belt. The effects mentioned are a reduction in power consumption and the corresponding reduction of emissions, in particular CO_2. The first case study illustrated the effect of continuously reducing the belt speed in situations where the belt conveyor is structurally underutilised in terms of volumetric capacity. If the belt carries less bulk solid material than it is designed for, then the belt speed can be reduced.

The second case study illustrated the effect of varying the belt speed with a varying load, in this case caused by a not constant feed capacity from a reclaimer that feeds the belt conveyor. In both cases it was shown that the reduction in terms of power consumption and emissions is significant and that it justifies a change in the logistic control of the belt conveyor in such a way that speed control is possible. In the second case study the effects of accelerating and decelerating the conveyor belt are not taken into account. Where that may be valid for slowly varying belt speeds with low acceleration and deceleration levels, it may not be valid for quickly changing belt speeds. This however, is a topic for further research.

A potential disadvantage of continuous belt speed variation can be a challenging chute design. With a change in belt speed the trajectory of the bulk solid material at the discharge point will also change. This requires a chute that can handle a variation in trajectory of the bulk solid material stream, for example, a dead or rock box. Besides a reduction in power consumption and emissions, speed control leads to additional benefits such as a reduction in maintenance costs. These benefits have not been included in the analyses described in this paper.

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