

The Design of High Speed Belt Conveyors

G. Lodewijks, The Netherlands.

SUMMARY

This paper discusses aspects of high-speed belt conveyor design. The capacity of a belt conveyor is determined by the belt speed given a belt width and troughing angle. Belt speed selection however is limited by practical considerations, which are discussed in this paper. The belt speed also affects the performance of the conveyor belt, as for example its energy consumption and the stability of its running behavior. A method is discussed to evaluate the energy consumption of conveyor belts by using the loss factor of transport. With variation of the belt speed the safety factor requirements vary, which will affect the required belt strength. A new method to account for the effect of the belt speed on the safety factor is presented. Finally, the impact of the belt speed on component selection and on the design of transfer stations is discussed.

1 INTRODUCTION

Past research has shown the economical feasibility of using narrower, faster running conveyor belts versus wider, slower running belts for long overland belt conveyor systems. See for example [1]-[5]. Today, conveyor belts running at speeds around 8 m/s are no exceptions. However, velocities over 10 m/s up to 20 m/s are technically (dynamically) feasible and may also be economically feasible. In this paper belt speeds between the 10 and **20** m/s are classified as high. Belt speeds below the **10** m/s are classified as low.

Using high belt speeds should never be a goal in itself, if using high belt speeds is not economically beneficial or if a safe and reliable operation is not ensured at a high belt speed then a lower belt speed should be selected.

Selection of the belt speed is part of the total design process. The optimum belt conveyor design is determined by static or steady state design methods. In these methods the belt is assumed to be a rigid, inelastic body. This enables quantification of the steady-state operation of the belt conveyor and determination of the size of conveyor components. The specification of the steady-state operation includes a quantification of the steady-state running belt tensions and power consumption for all material loading and relevant ambient conditions. It should be realized that finding the optimum design is not a one-time effort but an iterative process [6].

Design fine-tuning, determination of the optimum starting and stopping procedures, including determination of the required control algorithms, and determination of the settings and sizes of conveyor components such as drives, brakes and flywheels, are determined by dynamic design methods. In these design methods, also referred to as dynamic analyses, the belt is assumed to be a three-dimensional (visco-) elastic body. A three dimensional wave theory should be used to study time dependent transmission of large local force and displacement disturbances along the belt [7]. In this theory the belt is divided into a series of finite elements. The finite elements incorporate (visco-) elastic springs and masses. The constitutive characteristics of the finite elements must represent the Theological characteristics of the belt. Dynamic analysis produces the belt tension and power consumption during non-stationary operation, like starting and stopping, of the belt conveyor.

This paper discusses the design of high belt-speed conveyors, in particular the impact of using high belt speeds on the performance of the conveyor belt in terms of energy consumption and safety factor requirements. Using high belt speeds also requires high reliability of conveyor components such as idlers to achieve an acceptable component life. Another important aspect of high-speed belt conveyor design is the design of efficient feeding and discharge arrangements. These aspects will be discussed briefly.

2 BELT SPEED

2.1 BELT SPEED SELECTION

The lowest overall belt conveyor cost occur In the range of belt widths of 0.6 to 1.0 m [2]. The required conveying capacity can be reached by selection of a belt width in this range and selecting whatever belt speed is required to achieve the required flow rate. Figure 1 shows an example of combinations of belt speed and belt width to achieve specific conveyor capacities, in this example it is assumed that the bulk density is 850 kg/m³ (coal) and that the trough angle and the surcharge angle are 35° and 20° respectively.

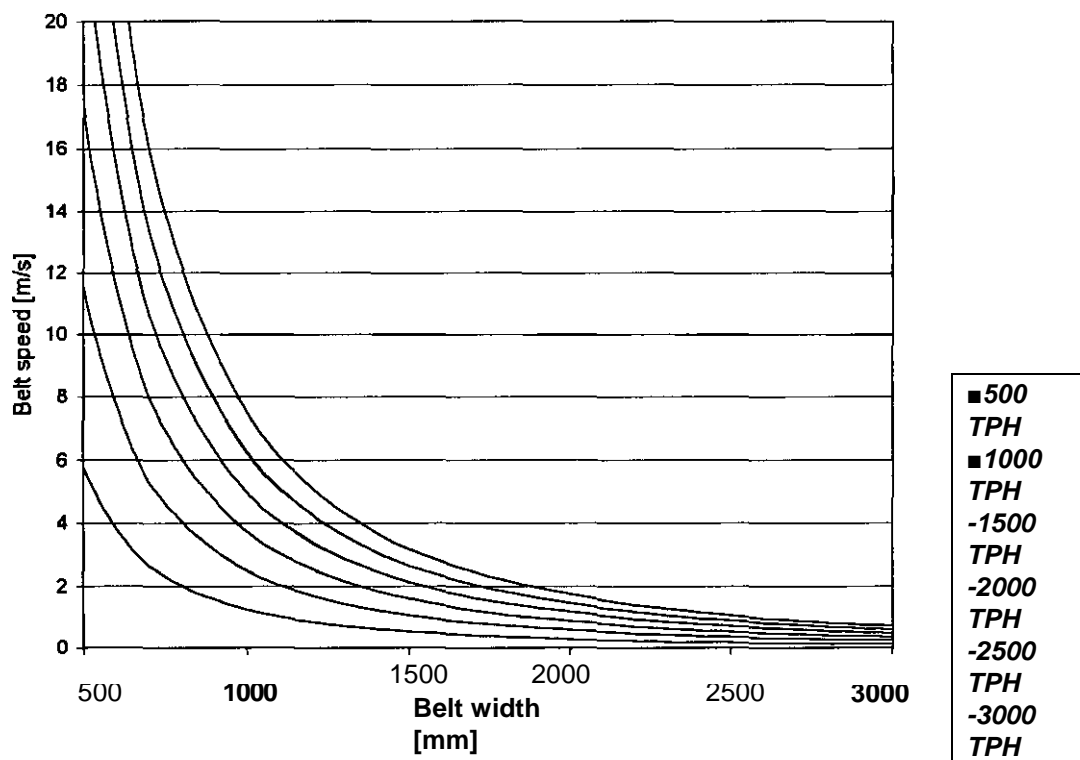


Figure 1: Belt width versus belt speed for different capacities.

Belt speed selection is however limited by practical considerations. A first aspect is the troughability of the belt. In Figure 1 there is no relation with the required belt strength (rating), which partly depends on the conveyor length and elevation. The combination of belt width and strength must be chosen such that good troughability of the belt is ensured. If the troughability is not sufficient then the belt will not track properly. This will result in unstable running behavior of the belt, in particular at high belt speeds, which is not acceptable. Normally, belt manufacturers expect a sufficiently straight run if approximately 40% of the belt width when running empty, makes contact with the carrying idlers. Approximately 10% should make tangential contact with the center idler roll.

A second aspect is the speed of the air relative to the speed of the bulk solid material on the belt (relative airspeed). If the relative airspeed exceeds certain limits then dust will develop. This is in particular a potential problem in mine shafts where a downward airflow is maintained for ventilation purposes. The limit in relative airspeed depends on ambient conditions and bulk material characteristics.

A third aspect is the noise generated by the belt conveyor system. Noise levels generally increase with increasing belt speed. In residential areas noise levels are restricted to for example 65dB. Although noise levels are greatly affected by the design of the conveyor support structures and conveyor covers, this may be a limited factor in selecting the belt speed.

2.2 BELT SPEED VARIATION

The energy consumption of belt conveyor systems varies with variation of the belt speed, as will be shown in Section 3. The belt velocity can be adjusted with bulk material flow supplied at the loading point to save energy. If the belt is operating at full tonnage then it should run at the high (design) belt speed. The belt speed can be adjusted (decreased) to the actual material (volume) flow supplied at the loading point. This will maintain a constant filling of the belt trough and a constant bulk material load on the belt. A constant filling of the belt trough yields an optimum loading-ratio, and lower energy consumption per unit of conveyed material may be expected. The reduction in energy consumption will be at least 10% for systems where the belt speed is varied compared to systems where the belt speed is kept constant [8].

Varying the belt speed with supplied bulk material flow has the following advantages:

- Less belt wear at the loading areas
- Lower noise emission
- Improved operating behavior as a result of better belt alignment and the avoidance of belt lifting in concave curve by reducing belt tensions

Drawbacks include:

- Investment cost for controllability of the drive and brake systems
- Variation of discharge parabola with belt speed variation
- Control system required for controlling individual conveyors in a conveyor system
- Constant high belt pre-tension
- Constant high bulk material load on the idler rolls

An analysis should be made of the expected energy savings to determine whether it is worth the effort of installing a more expensive, more complex conveyor system.

3 ENERGY CONSUMPTION

Clients may request a specification of the energy consumption of a conveyor system, for example quantified in terms of maximum kW-hr/ton/km, to transport the bulk solid material at the design specifications over the projected route. For long overland systems, the energy consumption is mainly determined by the work done to overcome the indentation rolling resistance [9]. This is the resistance that the belt experiences due to the visco-elastic (time delayed) response of the rubber belt cover to the indentation of the idler roll. For in-plant belt conveyors, work done to overcome side resistances that occur mainly in the loading area also affects the energy consumption. Side resistances include the resistance due to friction on the side walls of the chute and resistance that occurs due to acceleration of the material at the loading point.

The required drive power of a belt conveyor is determined by the sum of the total frictional resistances and the total material lift. The frictional resistances include hysteresis losses, which can be considered as viscous (velocity dependent) friction components. It does not suffice to look just at the maximum required drive power to evaluate whether or not the energy consumption of a conveyor system is reasonable. The best method to compare the energy consumption of different transport systems is to compare their transport efficiencies.

3.1 TRANSPORT EFFICIENCY

There are a number of methods to compare transport efficiencies. The first and most widely applied method is to compare equivalent friction factors such as the DIN f factor. An advantage of using an equivalent friction factor is that it can also be determined for an empty belt. A drawback of using an equivalent friction factor is that it is not a "pure" efficiency number, it takes into account the mass of the belt, reduced mass of the rollers and the mass of the transported material. In a pure efficiency number, only the mass of the transported material is taken into account.

The second method is to compare transportation cost, either in kW-hr/ton/km or in \$/ton/km. The advantage of using the transportation cost is that this number is widely used for management purposes. The disadvantage of using the transportation cost is that it does not directly reflect the efficiency of a system.

The third and most "pure" method is to compare the loss factor of transport [10]. The loss factor of transport is the ratio between the drive power required to overcome frictional losses (neglecting drive efficiency and power loss/gain required to raise/lower the bulk material) and the transport work. The transport work is defined as the multiplication of the total transported quantity of bulk material and the average transport velocity. The advantage of using loss factors of transport is that they can be compared to loss factors of transport of other means of transport, like trucks and trains. The disadvantage is that the loss factor of transport depends on the transported quantity of material, which implies that it can not be determined for an empty belt conveyor.

The following are loss factors of transport for a number of transport systems to illustrate the concept:

Continuous transport:

- Slurry transport around 0.01
- Belt conveyors between 0.01 and 0.1
- Vibratory feeders between 0.1 and 1
- Pneumatic conveyors around 10

Discontinuous transport:

- Ship between 0.001 and 0.01
- Train around 0.01
- Truck between 0.05 and 0.1

3.2 INDENTATION ROLLING RESISTANCE

For long overland systems, the energy consumption is mainly determined by the work done to overcome the indentation rolling resistance. Idler rolls are made of a relatively hard material like steel or aluminum whereas conveyor belt covers are made of much softer materials like rubber or PVC. The rolls therefore indent the belt's bottom-cover when the belt moves over the idler rolls, due to the weight of the belt and bulk material on the belt. The recovery of the compressed parts of the belt's bottom cover will take some time due to its visco-elastic (time dependent) properties. The time delay in the recovery of the belt's bottom cover results in an asymmetrical stress distribution between the belt and the rolls, see Figure 2. This yields a resultant resistance force called the indentation rolling resistance force. The magnitude of this force depends on the visco-elastic properties of the cover material, the radius of the idler roll, the vertical force due to the weight of the belt and the bulk solid material, and the radius of curvature of the belt in curves in the vertical plane.

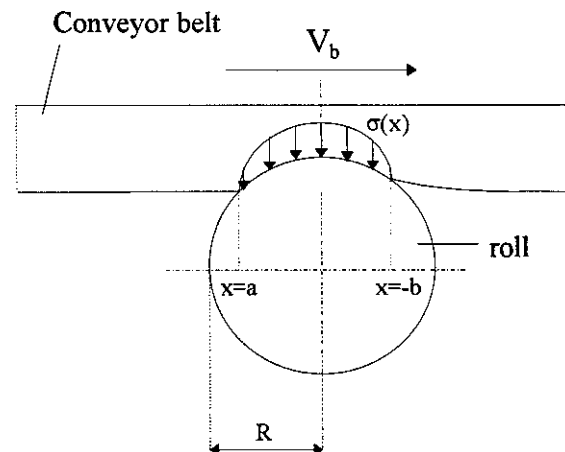


Figure 2: Asymmetric stress distribution between belt and roll [7].

It is important to know how the indentation rolling resistance depends on the belt velocity to enable selection of a proper belt velocity, [11].

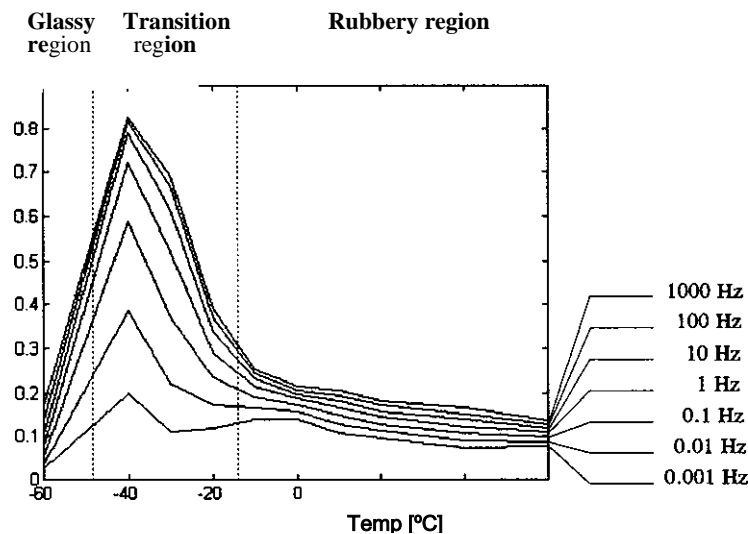


Figure 3: Loss factor of typical cover rubber [7].

Firstly, the indentation rolling resistance depends on the vertical load on the belt, which is the sum of the belt and the bulk material weight. If the vertical load on the belt decreases with a factor 2 then the indentation rolling resistance decreases with a factor 2.52 ($2^{4/3}$). The bulk load decreases with increasing belt speed assuming a constant capacity. Therefore, the indentation rolling resistance decreases more than proportionally with increasing belt speed.

Secondly, the indentation rolling resistance depends on the size of the idler rolls. If the roll diameter increases with a factor 2 then the indentation rolling resistance decreases with a factor 1.58 ($2^{\frac{1}{2}}$). In general the idler roll diameter increases with increasing belt speed to limit the bearing rpm's to maintain acceptable idler life. In that case the indentation rolling resistance decreases with increasing belt speed.

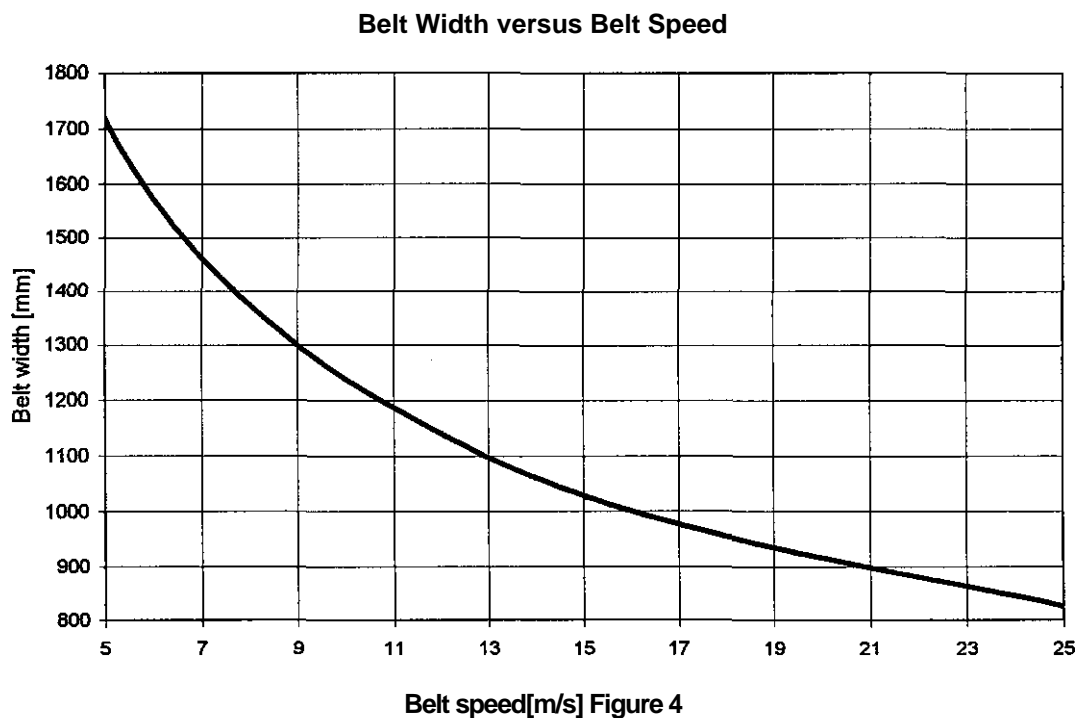
Thirdly, the indentation rolling resistance depends on the visco-elastic properties of the belt's cover material. These properties depend on the deformation rate, see Figure 3. The deformation rate in its turn depends on the size of the deformation area in the belt's bottom cover (depending on belt and bulk load) and on the belt speed. In general the indentation rolling resistance increases with increasing deformation rate (and thus belt speed), but only to a relatively small account.

Fourthly, the indentation rolling resistance depends on the belt's bottom cover thickness. If the bottom cover thickness increases with a factor 2 then the indentation rolling resistance increases with a factor 1.26 ($2^{1/3}$). If a bottom cover is increased to account for an increase in belt wear with increasing belt speed, then the indentation rolling resistance increases as well.

It should be realized that the indentation rolling resistance, although important, is not the only velocity dependent resistance. The rolling resistance of the idler rolls for example depends on the vertical load as well as on their rotational speed. The effect of the vertical load, which directly depends on the belt speed, is large. The effect of the rotational speed is much smaller. Another resistance occurs due to acceleration of the bulk solid material at the loading point. This resistance increases quadratically with an increase in belt speed assuming that the bulk material falls straight onto the belt. This will affect smaller, in plant belt conveyors in particular.

EXAMPLE

To illustrate the concept discussed above let's consider a 6 km long conveyor belt with a capacity of 5000 TPH. The trough angle, the surcharge angle and the bulk density are again taken 35° , 20° and 850 kg/m^3 respectively. Figure 4 shows the required belt speed as a function of the belt width to achieve the required capacity of 5000 TPH. This figure is somewhat similar to Figure 1.



The figures 5 and 6 show the required belt strength and the required drive power as a function of the belt speed. The required belt strength decreases and the required drive power slowly increases with increasing belt speed as can be seen in those figures. Figure 7 shows the loss factor of transport and the DIN f factor versus belt speed. The loss factor of transport is always higher than the DIN f factor because the DIN f factor takes the mass of the belt into account (in the denominator) whereas the loss factor of transport only accounts for the mass of the bulk solid material. Intuitively, it may be expected that there will be an economically optimum belt speed in the high belt speed range. The determination of the optimum belt speed however, requires more information and is beyond the scope of this paper.

3.3 RUBBER COMPOUNDS

The indentation rolling resistance depends on the visco-elastic properties of the belt's bottom cover as discussed in the preceding section. This implies that the rolling resistance can be decreased by selecting a special low indentation rolling resistance (rubber) compound that is available on the market today. A small premium has to be paid for this special compound, but costs can be limited by applying it for the bottom cover only and using a normal wear-resistant compound for the carrying top cover. In that case turnovers are required to fully use the energy saving function of the bottom compound.

A quantitative indication of the level of indentation rolling resistance is the indentation rolling resistance indicator $\tan(\delta)/E'^{1/3}$, where δ is the loss angle and E' the storage modulus of the compound. Compounds with a reasonable indentation rolling resistance performance have indicators below 0.1. Figure 8 shows these indicators for typical medium to good performing rubbers. As can be seen in that figure, the choice for a specific rubber compound affects the energy consumption of the belt conveyor, in particular as a function of the ambient temperature.

One comment (warning) must be made. A special belt with low indentation rolling resistance compound should never be selected if only one conveyor belt manufacturer offers it. In that case the conveyor system can only perform in accordance with its design specifications when that specific belt is used. It is much better, also cost wise, to specify the upper limit of the resistance indicator as given above that can be met by more than one conveyor belt manufacturer.

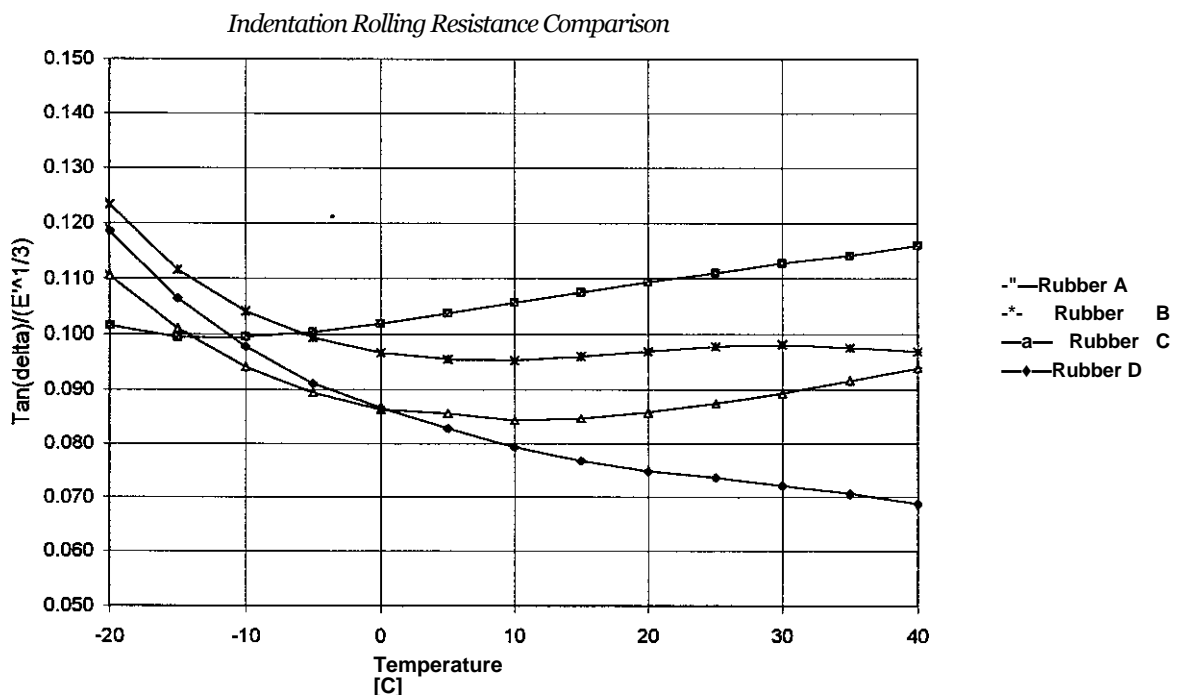


Figure 8: Indentation rolling resistance indicators for four different rubbers as a function of temperature.

4 SAFETY FACTOR REQUIREMENTS

For design purposes, standards like DIN 22101, ISO 5048 and CEMA provide safety factors (SF) that limit the permissible belt loads. Two types of safety factors can be distinguished: safety factors on the steady-state running tensions and safety factors on the non-stationary tensions. In general the safety factor on the steady-state running tension is based on:

- Stationary (full and empty, summer and winter) and non-stationary belt tensions
- Belt tensions from extra resistances and deformations in horizontal and vertical curves, troughing transitions, belt turnovers, on pulleys etc.
- Belt conveyor system maintenance
- Belt conveyor system operational data including hours per day, days per year and years of service
- Belt splice design and fatigue characteristics including those of the belt tensile carrying member (steel cords or fabric) and the rubber
- Splice kit storage and handling.

All these six items should be taken into account when determining the safety factor.

Standards like the DIN standard base the recommended safety factor on reduction factors. DIN 22101 uses three reduction factors. The first (r_0) generally accounts for the reduction of the strength of the belt (splices) due to fatigue. The second (r_1) accounts for the extra forces that act on the belt in transition zones and on pulleys etc. The third (r_2) accounts for the extra dynamic stresses in the belt during starting and stopping. The required minimum safety factor can be calculated as follows:

$$SF = 1 / (1 - (r_0 + r_1 + r_2)) \quad (1)$$

The DIN standard also gives values for the three reduction factors. For example, for a steel cord conveyor belt under "normal" operational conditions the values are as follows: $r_0 > 0.665$, $r_1 > 0.15$, $r_2 > 0.06$, which yields a safety factor $SF > 8$.

Although much can be said about the applicability of the safety factor determined with the DIN standard for the design of long belt conveyor systems, the major drawback, keeping the belt speed selection in mind, is that the conveyor system's operational data and the real fatigue properties of the belt are not taken into account.

It is possible to account for these factors and to achieve a tailor-made safety factor by taking the belt's operational data into account. The reduction factors r_1 and r_2 are independent of the fatigue properties of the belt and thus constant with increasing number of load cycles. Let's assume that the reduction factor r_0 varies linearly with the \log_{10} of the number of load cycles (revolution of the belt through the total belt conveyor) from 0 to 0.665 at 10,000 load cycles (approximation of DIN standard):

$$r_0 = 0.166 \log_{10}(N) \quad (N < 10,000) \quad (2)$$

where N is the number of load cycles. After 10,000 load cycles r_0 hardly increases. Now let's assume that the conveyor under design has a length of 10,000 m, a life expectation of 5 years at 5000 operational hours per year. The total number of load cycles can be calculated with the following equation:

$$N = [(3600 V) / (2 L)] H Y \quad (3)$$

where V is the belt speed, L the conveyor length, H the number of operational hours per year and Y the number of expected years of operation. Equation (3) is visualized in Figure 9.

Number of Load Cycles versus Belt Speed

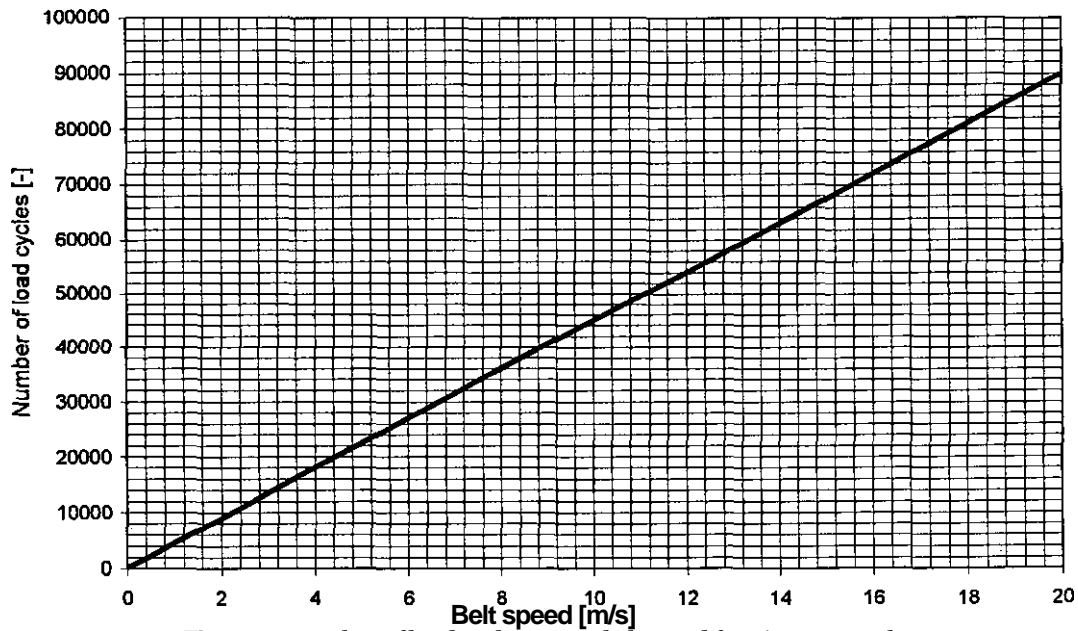


Figure 9: Number of load cycles versus belt speed for given example.

The value of the reduction factor r_0 can be determined with equation (2) and the number of load cycles as given in Figure 9. The result is shown in Figure 10.

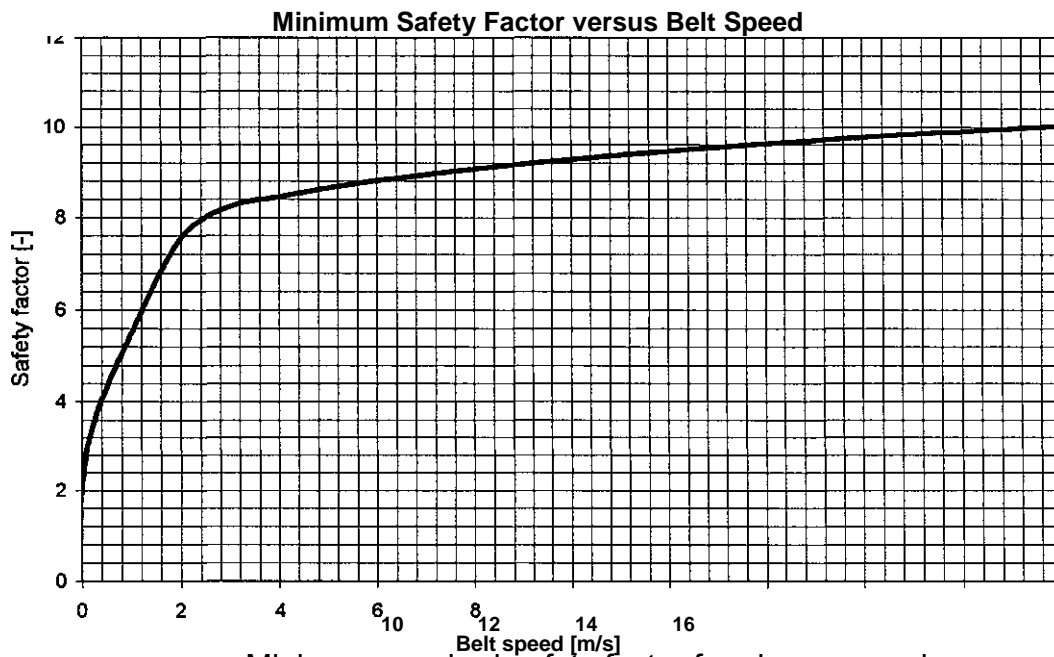


Figure 11: Minimum required safety factor for given example.

From Figure 11 it can be learned that for the belt under design the required minimum safety factor on the steady-state running tensions is about 7.5 if the belt is running at 2 m/s, and about 10 in case the belt is running at 20 m/s. Taking the belt speed into account during safety factor determination thus prevents overrating of the belt at low speeds and underrating at high speeds (also depends on the length of the conveyor system).

The above given figures and numbers are to illustrate the procedure only. This procedure can be fine tuned by taking measured fatigue properties of the belt tensile-carrying member (steel cords or fabric) and the rubber into account, as well as the actual load cycle of the belt (empty, fully loaded, steady state running, starting and stopping, summer, and winter conditions etc.).

5 BELT CONVEYOR DYNAMICS

In essence the dynamics of a belt conveyor does not change with the belt speed. However, with increasing belt speed the rate of changes increases, which will result in a decreasing running stability of the belt. This paper is not intended to fully discuss belt conveyor dynamics. It is referred to [7] where this topic is extensively discussed. However, a number of notes on the dynamics of high belt speed conveyors can be made.

When a belt between two idlers is exited by an idler roll in or near a natural frequency of transverse vibration of the belt span, resonance phenomena occur. The amplitude of transverse vibration increases considerably when resonance occurs yielding increased roll/bearing wear and an increased power consumption of the belt. This increase in vibration amplitude, also referred to as belt flap, must be avoided. In high-speed belt systems the effect of resonance on the structure is very destructive, as observed with lower speed belts that resonate and destroy idler bearings. Care should therefore be taken to design a belt conveyor so that the possibility of resonance in the belt is avoided and at the same time best use is made of current static design methods so that the economics of the design are saved.

Belt tracking must be excellent at high speeds. If the belt does not track properly then run off may be expected since, with increasing belt speed, side displacements and the rate of side displacement increase. The combination of belt width and strength must be chosen such that good troughability is ensured, see Section 2.1. Also maximum effort must be made by the belt manufacturer to make straight belts and to construct true belt splices. In addition, longer manufactured belt lengths reduce the number of splices and thus increase the chance of straightness.

A similar comment can be made for the design of horizontal belt curves. The position of the belt on the idlers changes with a change in belt tension mainly due to a change in loading degree. The belt will move sideward in particular during large tension variations as occur during (aborted) starting and (emergency) stopping. The change in belt tension during starting and stopping will increase with increasing belt speed. For low belt speed conveyors static design methods may be sufficient to determine the maximum side displacement. For high belt speed conveyors however, dynamic design methods are required to predict the side displacement to a sufficient level of accuracy.

Normal operational starting and stopping procedures will not change for high belt speed conveyors, except that starting and stopping will take more time. The nature of emergency stop procedures however will change. In general emergency stop procedures are designed to stop the belt in a short period of time without the use of the drive system and so that the belt conveyor is not damaged. A typical emergency stop time for a long overland conveyor is 30 seconds, which may be short enough to prevent casualties. However at high belt speeds the amount of energy (which increases quadratically with increasing belt speed) that has to be transferred from the conveyor belt into a braking system is much higher, which will result in considerably longer emergency stopping times. Therefore the chance of casualties is much higher in case an emergency happens. For high belt speed conveyors it is therefore even more important to be equipped with appropriate safety guards.

6 IDLER SELECTION

The most important selection criterion of idlers for high-speed belt conveyors is the idler diameter. In general it can be said that the diameter of idlers will need to be increased for high speed belts compared to the diameter of idlers used in low-speed belts for a number of reasons including:

- with low rotational speed idler bearings can be used with L10 ratings that are currently available and used in low speed belt conveyors. This implies that currently used maintenance schedules can be followed. The diameter of an idler has a considerable effect on the idler performance. Together with the belt speed, it fixes the speed at which the idler, and thus the roller bearing, rotates. The permissible operating temperature limits the speed at which roller bearings can operate. Bearing types with low friction and correspondingly low heat generation in the bearing itself are therefore the most suitable for high-speed operation. The highest speed can be achieved with

- deep groove ball bearings when loads are purely radial, and with angular contact bearings for combined loads.
- if there is any slippage between the belt and the idler shell then the diameter governs the belt cover wear. Slippage may occur if the axis of the idler is not in line with the direction of the belt.
- the resistance to rolling friction offered by an idler and the break-away torque decrease with increasing idler diameter.

The only adverse factors of increasing idler diameters are the higher idler price and greater inertia.

The life of idler bearings decreases as rotational speed (and thus the belt speed) increases. The bearing life is inversely proportional to the belt speed, and is raised with idler load to the third power. The limiting factor of idler life however, is grease life rather than the idler's L10 life.

The permissible eccentricity of idler rolls has to be decreased quadratically with increasing belt speed. Thus reducing the risk of violent vibrations when the idlers rotational speed approaches the critical speed (belt flap). As a result the price of the idlers will increase.

7 TRANSFER STATIONS

An important aspect of conveyor design for the higher velocity ranges is the design of efficient feeding and discharge arrangements. The practical problem with the loading of high speed belts is to develop a material feeding system that can place the material on the belt with a similar velocity and direction to that of the belt. This minimizes the wear of the belt cover and quickly stabilizes the material flow on the belt.

One method to achieve this is to install acceleration belts. Low cost fabric or solid woven belting can be used as accelerator belts. Thus taking the wear caused by friction between the belt and the bulk material during acceleration of the belt. Another method for feeding high speed belts is the use of a gravity-fed curved chute system to force the bulk material flow onto the belt with minimum speed and direction difference to that of the belt.

Today, design methods such as methods based on the Discrete Element Method (DEM) are available to simulate the bulk material flow through the transfer station onto the belt [12]. Application of these methods enable the designer to determine velocity variations in the bulk material flow in size as well as direction, and to calculate the forces that the bulk material flow exerts on the chute and the belt. Herewith an optimum chute arrangement can be designed that minimizes wear of the chute and the belt, and which prevents degradation of the bulk material.

Similarly, the discharge of high speed belts also request attention. At high speed a deflection plate would cause substantial product degradation resulting in dust and fine material. A special collection bunker or bin should be designed that could incorporate a receiver chute arrangement.

8 CONCLUSION

This paper discussed aspects of high-speed belt conveyor design. Based on the above discussion the following conclusions can be drawn:

- Starting with a given belt width, the conveyor capacity can be reached by selecting whatever belt speed is required to achieve the required flow rate. Belt speed selection is however limited by practical considerations. Failure to recognize these considerations will lead to operational problems, including unstable running behavior, and unacceptable dust and high noise levels.
- It is not easy to determine the relationship between the belt speed and the belt's energy consumption. This is partly because the calculation of the indentation rolling, which forms the largest part of the rolling resistance, requests detailed knowledge of the visco-elastic properties of the used rubber compound. In addition the (unknown)

velocity dependent components of the coulomb friction and seal and viscous drag of the roller bearings play an important role. Also the resistances that occur at transfer stations, in particular due to the acceleration of the bulk solid, play a role especially at high belt speeds.

- Selecting a safety factor on the steady-state belt tension that is based on the belt speed and other operational data will prevent underestimation or overestimation of the fatigue life of the belt, depending on the total number of cycles that the belt will make during its operational life. Further fine-tuning of the safety factor requires accurate knowledge of the fatigue properties of the belt's tension carrying member and core rubber as well as a more accurate estimate of the operational circumstances.
- The belt speed has a large effect on the design of conveyor components like the idlers, and sections like horizontal curves and transfer stations. Accurate dynamic design methods are required to design these components and sections so that they will result in acceptable life and wear characteristics of components including idlers, the belt and chute liners.

In short: Designing high-speed belt conveyors request state of the art design methods!

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