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Integrated energy model for energy requirement estimation in bulk material handling mechanical systems

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Abstract. An integrated energy model to estimate the energy requirement, in stationary operation, of different bulk material handling mechanical systems was presented. The integrated model was developed identifying similarities in the conveyance phenomena between systems, matching them up in four mathematical expressions based on existing models. The total power required by the drive system is estimated as the sum of those expressions. The integrated model was use to determinate the specific energy requirements to convey the material in horizontal and lifting applications. It allows to compare the energy consumption in bucket elevators, screw and belt conveyors, determining the most efficiency system for each application and explaining the differences between energy requirement of each system.

1 Introduction

Bulk material handling systems are widely used in different industries, they allow the reduction in wastage of time, in process cycle time and improve the process efficiency. Energy models for material handling systems are needed to design the drive system and to analyze their performance. There is a huge variety of energy models for each type of conveyors systems.

Energy models for bulk material handling systems could be used to estimate the power requirements in permanent operation or transitory operation. Standards, specifications or manufacture's codes present stationary models, which are used to the drive system selection and they are mainly based on experimental research and hardly on theoretical research [1]. In the other hand, recent models are useful for performance analysis, systems modification and operational optimization. They include the dynamic analysis of the system.

There are two categories of stationary models. One category based on resistance calculation, and the other one based on energy conservation [2]. The resistance based models consider almost all the issues contributing to the energy consumption, thus they are believed more accurate but more complicated [3].

Standards and manufacture's codes for belt conveyors as ISO 5048 [4], DIN 22101 [5], BS 5934 [6] and CEMA [7] belong to the category based on resistance calculation. BS 6318 [8] and ISO 7190 [9] propose resistance calculation models for bucket elevators. Energy conservation is most popular in systems like screw conveyor. ISO 7119 [10], BS 4409 [11] and CEMA N° 350 [12] propose an energy conservation model for screw conveyors.

The need of models useful for accurate design and performance optimization motivate the development of new models that include dynamic analysis. Since 1955 researchers work in the development of dynamic models for conveyor systems. Relevant studies of belt conveyors analyzed the axial (longitudinal) stress waves in the belt and their effect on the belt tension and the drive force [13], [14]. In 1984, Nordell and Ciozda [15] developed a one-dimension model to determinate a time dependent drive force in belt conveyors using Finite Element Method (FEM). Since 1975 twodimension dynamic models for belt conveyors have been developed using finite element method to analyze the belt sag and the axial stress waves propagation [16], [17]. In screw conveyor, Discrete Element Method (DEM) has been used to analyze the torque and power requirements. Guoming Hu [18] used DEM to analyze the performance of screw conveyor including visualization of the motion of particles, angular and axial velocity of particles, overall torque and total force, kinetic energy and total energy dissipation.

The phenomena that cause the energy consumption in each system could be modeled in a similar way and the existing empirical models share similarities between systems. However, the state of the art of bulk material handling equipment do not include a unique model that lump different conveyor systems.

Taking in account the wide application of those systems and the importance of model their energy requirement, it is needed an integrated energy model useful for different equipment, in order to make comparison among them and facilitate the estimation of energy consumption process.

In regard to this need, this paper aims to build an integrated model to estimate the power requirement of belt conveyors, bucket elevators and screw conveyors in stationary operation.

2. Methodology

Aiming to build an integrated energy model to estimate, in all studied system, the power requirement, we begin with the analysis of existing stationary models of mechanical conveyors systems, resistance based and energy conservation based.

Analyzing the physical phenomena occurring in each system, we match up all the similar phenomena that could be lumped in a mathematical expression. We use the same expression for each type of conveyor system. The total power required by the drive system is estimated as the sum of the energy consumed due to each component.

The components of power consumption expressions are constituted by two parts, the first part relates to the operational parameters and the second part of the expression related to the experimental values unique for each conveyor system. In that way the second part of each expression take in account the differences between systems. Those expressions and experimental values are based on existing models.

The integrated energy model is used to compare the energy requirement on belt, screw conveyors and buckets elevators.

3. Results

Analyzing the existing energy models belt conveyors, bucket elevator and screw conveyors, we have identified the principal similarity between system's models, the energy consumption phenomena could be match up in five components: energy consumption due to the resistance to move the empty system, P_E, energy consumption due to the resistance to move the load P_M, localized energy consumption, P_I and the energy to elevate the material, P_S.

$$P_T = P_E + P_M + P_I + P_S \quad (1)$$

This model does not consider the energy consumption due to the startup with load process because it is an occasionally energy consumption and most system have a soft start system, changing the operation conditions to avoid peak of energy consumption during the start up.

In belt conveyors, the energy consumption due to the resistance to move the empty belt considers the rotational resistance of the idlers and resistance of the belt itself due to flexing and sliding contact with various components, the energy consumption due to load considers the losses caused by the bulk material flexure resistance [20]. Localized energy consumption considers the frictional or inertial resistance which occur only at certain parts of the belt conveyor, owing to the inertial and frictional resistance at the feeder station [2]. Also, it considers the power consumes in pulleys by wrapping of the belt on the pulleys. And losses in bearings.

In bucket elevators, the energy consumption due to load considers the power to lift the material and localized energy consumption considers the digging force during the pickup of the material, the energy consumption owing to inertial resistance to accelerate the material and losses in pulleys or sprockets. Also, consider energy require due to losses caused by the loaded buckets swinging over the head pulley or sprocket [9], [21]. In bucket elevator, there are not energy consumption due to the empty system because the chain/belt and buckets cause the same weight distribution in the upward and downward side of the elevator.

Table 1. Classification of energy consumption phenomena by model's components.

Type of equipment	**Energy consumption due to the resistance to move the empty system**	**Energy consumption due to the resistance to move the load**	**Localized energy consumption.**	**Energy to elev the material**

Belt conveyor	-Rotational resistance of the idlers. -Flexing and sliding contact of the belt.	-Bulk material flexure resistance.	-Friction resistance at the feeder station. -Inertial resistance of the material. -wrapping of the belt on the pulleys. -Losses in bearings. -friction against chute flaps or skirt plates. -Friction between belt and pulley cleaners	-Lifting. the material
Bucket Elevator			-Inertial resistance of the material. -Digging force during pickup of the material. -Losses in pulley or sprocket.	-Lifting. the material
Screw Conveyor	-Frictional resistance between moving parts.	-Material frictional resistance.		-Lifting. the material

In screw conveyors, energy consumption due to the empty system considers power loses caused by the frictional resistance between moving parts. The energy consumption due to the load consider the power to move the material forward [11], [22].

Table 1 shows the energy consumption phenomena belonging to each component. It shows that some components do not occurs in some systems. Standard and manufacture's code do not consider localized energy consumption in screw conveyors. Although, there are localized energy requirements as losses in bearings, it is not taking in account because it is very low compared with other phenomena [22].

The integrated expression (1) for power estimation could be expressed as (2).

$$P = V*[C_E*M_E*L_E + C_M*M_M*L_M + C_L*M_L*L_L + M_I*H_I] \quad (2)$$

Table 3 and Table 4 contain the expressions belonging to each variable of (2).

Table 2. Symbols.

Description	Symbol	Unit	Description	Symbol	Unit
density of the conveyed material	ρ	kg/m^3	empirical belt friction coefficient	F_a	

gravity	g	m/s^2	empirical load friction coefficient	F_b	
angle of elevation	α	°	empirical localized losses coefficient	F_c	
mass per length of the idler on the carry side	m_c	kg/m	factor to estimate localized losses	H_o	m
mass per length of the idler on the return side	m_r	kg/m	moving parts friction coefficients	F_d	
mass of the belt per unit length	m_b	kg/m	empirical coefficient depending on the type of screw	F_f	
mass of conveyed material per unit length of the belt	m_g	kg/m	Empirical coefficient to account for the material	F_g	
mass per unit length of belt/chain	$\boldsymbol{m_l}$	kg/m	overall length of the conveyor center to center	L_b	m
mass of empty bucket	$\boldsymbol{b}$	kg	vertical height of the elevator	$\boldsymbol{H_e}$	m
buckets spacing	$\boldsymbol{S}$	m	overall length of the conveyor	L_s	m
capacity of individual bucket	$\boldsymbol{V}$	m^3	nominal velocity of the material in belt conveyor	$\boldsymbol{V_b}$	m/s
filling factor of the bucket	$\boldsymbol{f}$		nominal velocity of the bucket	$\boldsymbol{V_e}$	m/s
internal diameter of the casing	D_{sc}	m	Rotational speed of the screw	$\boldsymbol{N}$	rev/s
diameter of the shaft	D_{sh}	m	pitch of the screw	λ	m
trough filling factor	**k**				

Table 3. Mathematical expression for the model's components.

System	Energy consumption due to the resistance to move the empty system			Energy consumption due to the resistance to move the load		
	C_E	M_E	L_E	C_M	M_M	L_M
Belt Conveyor	F_a	$g*[m_c+m_r+2m_b*cos(\alpha)]$	L_b	F_b	$m_{g}*cos\alpha*g$	L_b
Bucket Elevator						
Screw Conveyor	F_d	$D_{sc}^{1.7}/\lambda$	L_s	F_f*F_g	$k*\rho*g*\frac{\pi}{4}*(D_{sc}^2-D_{sh}^2)$	L_s

Table 4. Mathematical expression for the model's components.

System	Localized energy consumption			Energy consumption to elevate the material		Lineal Velocity
	C_L	M_L	L_L	M_I	H_I	V
Belt Conveyor	F_c	$g*[m_c+m_r+(2m_b+m_g)*cos\alpha]$	L_b	m_g*g	H_I	V_b
Bucket Elevator	H_o	$\left(\frac{Vf\rho}{S}\right)gH_o$	1	$\left(\frac{Vf\rho}{S}\right)g$	H_e	V_e
Screw Conveyor				m_g*g	H_I	$N*\lambda$

All variables denote as M refers to the mass of mechanical components or load that influence in the energy consumption phenomena. All variables denote as L refer to the length in which the energy consumption occurs. All variables denote as C refer to empirical factor. H refers to the lifting height in an incline conveyor. V refers to the lineal velocity of the system.

Analyzing the expression of each variable it is possible to identify differences between system's models.

In belt conveyor and screw conveyor, the energy consumptions throughout the length of the system depend on complex physical phenomena and it is estimate using empirical factors. In bucket elevators, this energy consumption only depends on the energy to lift the material and the mechanical components of the system.

Localized energy consumption is modeled in a similar way in belt conveyors and bucket elevators. In both systems an empirical factor is used to take in account the resistances that cause the power requirement.

The integrated model was used to estimate the specific energy consumption of each studied system in vertical and horizontal conveying operation. For energy consumptions through the length of the system and energy consumption due to load and energy to lift the material, the comparison is made on energy (W.h) per meter lift (m) per conveyed ton of material (ton) base, and for localized energy consumption the comparison is made on energy (W.h) per conveyed tons of material base (ton). Energy consumptions was estimate taking in account different materials and capacities. For belt conveyor, energy consumption was estimate for capacities from 100 to 1000 tph, for screw conveyors and buckets elevators, it was estimated from 15 to 400 tph and 50 to 500 tph, respectively. The specific energy consumption was estimate as a function of the conveyed material. The conveyed material determinate operational parameters and system's characteristics that affect the energy consumption.

The following figures compare the specific energy consumption between inclined belt, inclined screw conveyors and bucket elevators using box plot to show the variation in the consumption due to the difference analyzed materials. It that way, the figures show the average and deviation of the energy consumption in each system.

Fig. 1 compares the energy consumption due to the empty system between inclined belt, inclined screw conveyors and bucket elevators. It shows that bucket elevators do not present energy consumption to move the empty systems, this was explained above. The energy consumption to move the empty system is in inclined screw conveyors, in average, 7.87 times higher than the consume in inclined belt conveyors.

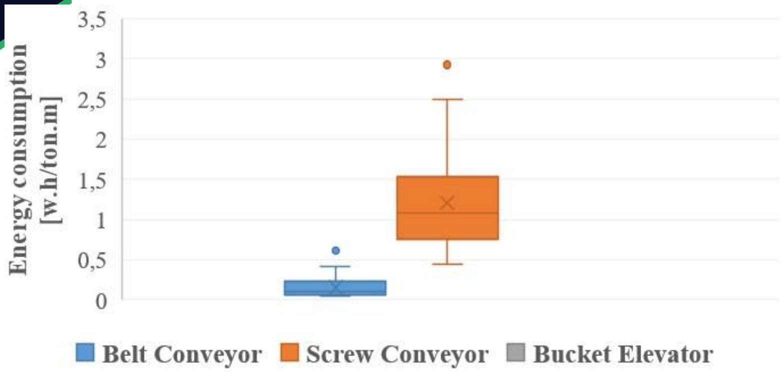

Fig. 1. Energy consumption due the resistance to move the empty system in bucket elevators, inclined belt and inclined screw conveyors [W.h/ton.m].

The comparison of the energy consumption due to the load, which occurs in belt and screw conveyor is shown in Fig. 2. The energy consumption is considerably higher in screw conveyors as a result of the significant resistance to move the bulk material forward through the conveyor. This energy consume is, in average, 148 times higher in screw conveyor compare to the belt conveyor consume.

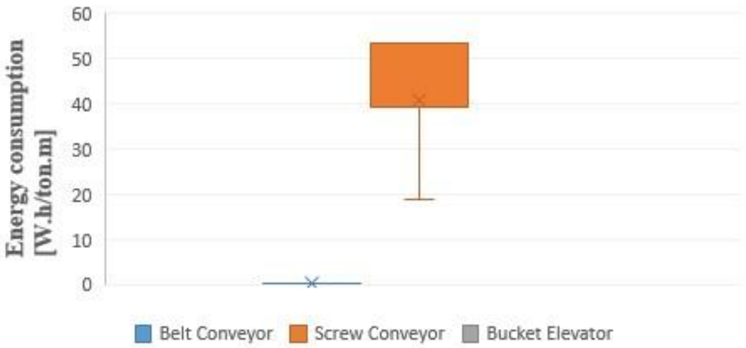

Fig. 2. Energy consumption due the resistance to move the load in inclined belt and inclined screw conveyors [W.h/ton.m].

The comparison of the localized energy consumption, which occurs in belt conveyors and bucket elevators is shown in Fig. 3. In average, the localized energy consumption is slightly higher in belt conveyor.

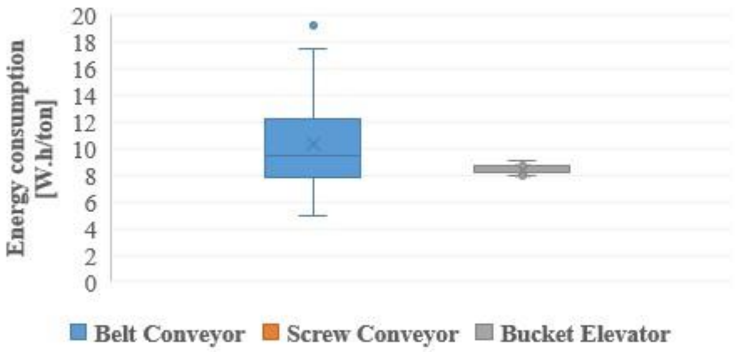

Fig. 3. Localized energy consumption in bucket elevators, inclined belt and inclined screw conveyors [W.h/ton].

Aiming to compare the total energy consumption of the studied system, Fig. 4 shows the specific energy consumption [W.h/ton] as function of the lifting distance for bucket elevators, inclined belt and inclined screw conveyors.

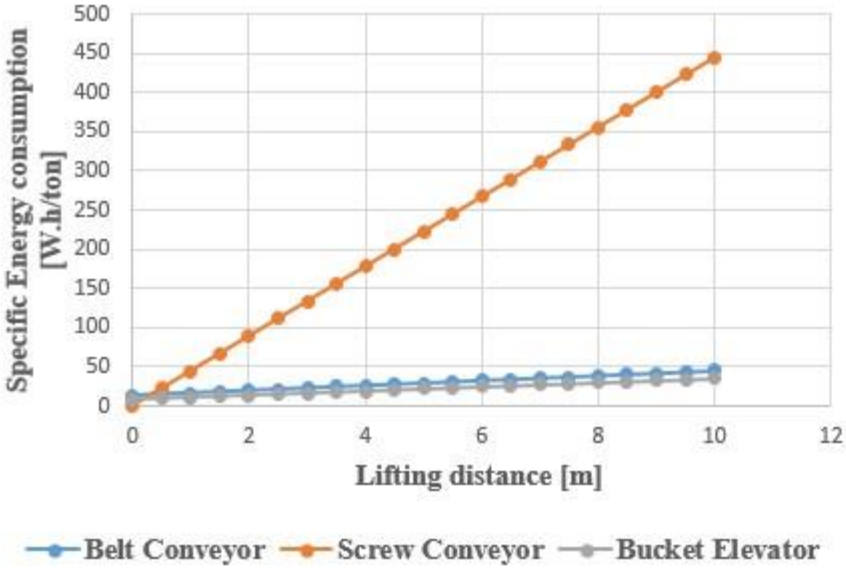

Fig. 4. Specific energy consumption [W.h/ton] as function of the lifting distance in bucket elevators, inclined belt and inclined screw conveyors.

Fig. 4 shows that the bucket elevators require less energy to lift the material compare to screw conveyor and belt conveyors. The screw conveyors present significant higher consumptions caused by the high energy requirement to move the material forward. The belt conveyor has a slightly higher consumption compare to elevators. In bucket elevators, there are not an energy requirement to move the empty system while in belt conveyor the rotational resistance of the idler, the flexing and sliding contact of the belt, produce it.

In a similar way, the comparison between horizontal belt and horizontal screw conveyor is made, Fig. 5. the efficiency is significant higher in belt conveyor caused by the high energy requirement to move the load in the screw conveyors.

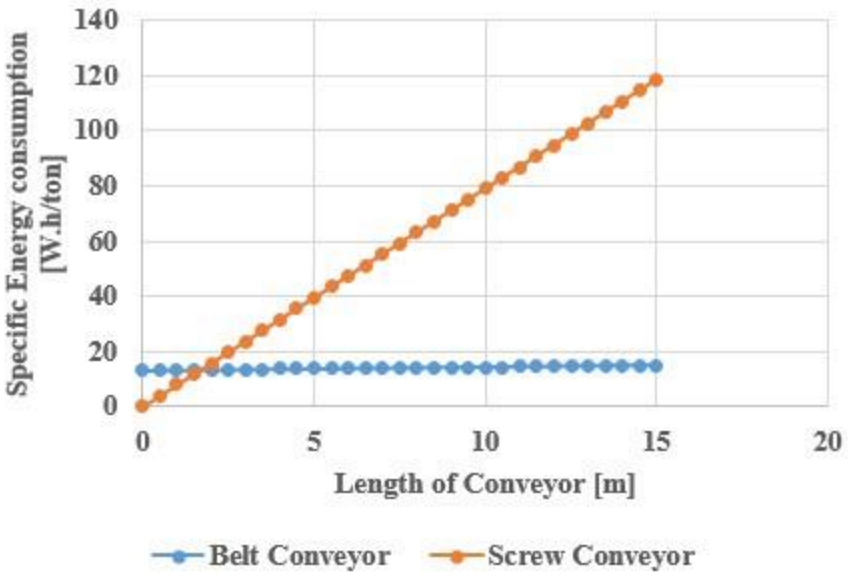

Fig. 5. Specific energy consumption [W.h/ton] as function of the conveyed horizontal distance in horizontal belt and horizontal screw conveyors.

4. Conclusions

Bulk material handling mechanical systems presents similarities in their energy consumption phenomena. However, there is not an energy model that lumps different mechanical systems. An integrated energy model to estimate the specific power consumption of bucket elevators, belt and screw conveyors was developed and it was used to compare their energy requirements and to explain the differences in the amount of energy consumed by each system.

Taking in account that material handling system are widely used in different industries, an integrated model represents a huge contribution owing to it eases the estimation of energy consumption process and it enables the comparisons between systems.

The results shown that the belt conveyor presents the lower energy requirement in horizontal material movement. It is cause by the low energy requirement to move the material forward, compare to screw conveyors consumption, where there is a high resistance to move the material forward through the conveyor.

Bucket elevator presents the lower energy requirement to lift the material, it is slightly lower that the consumption in belt conveyors as a result of bucket elevators do not require energy to move the empty system.

It is shown that screw conveyors are not efficient to long conveyance distance compare to belt conveyors and bucket elevators.

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