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ScienceDirect

Energy Procedia 142 (2017) 2754–2760

Energy Procedia

www.elsevier.com/locate/procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

A Comparative Study on the Cost-effective Belt Conveyors for Bulk Material Handling

Mukalu Sandro Masaki *, Lijun Zhang, Xiaohua Xia

Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

Abstract

Among the various types of belt conveyors, the multi-drive technology has gained worldwide popularity in recent years because of the cost saving opportunities as a result of the possible reduction of the belt weight. Until recently, however, limited knowledge on the cost-effective design of such conveyor systems was reported in the literature. Following the findings of a novel contribution on this matter, this paper presents a comparative numerical study for the identification of the most advantageous belt conveyor design for a specific bulk material handling application. Three types of belt conveyor are compared: the single drive belt conveyor, the single-tandem drive belt conveyor and the multi-drive belt conveyor. Subject to the assumption made and the manufacturers supplied information, the study shows that the implementation of the most cost-effective multi-drive conveyor will result in equivalent annual cost savings of about 63,120 \$(USD) and 29,475 \$(USD) over the cheapest single drive and single-tandem drive contenders, respectively. Other economic and environmental spin-off effects are also evaluated in the paper.

Keywords: Multi-drive belt conveyor; energy optimization; optimal design; component sizing; life cycle cost; environmental footprint.

1. Introduction

Nowadays, belt conveyors represent a substantial proportion in the bulk material handling industry because of their high efficiency of transportation over short and medium distances [1]. Despite this renowned, however, conveyor systems are regularly subject to low economic performance due to either oversizing or inadequate operation [1, 2].

* Corresponding author. *E-mail address:* sandro.masaki@up.ac.za

10.1016/j.egypro.2017.12.221

While the majority of previous contributions focused on improving operational performance of belt conveyors [1, 3, 4, 5, 6], the possibility to address the problem downstream from the design stage was also investigated in the literature [7, 8]. The latter, however, was limited to the cost-effective design of conveyor systems powered by a unique drive unit.

Over the past few decades, the multi-drive technology has gained worldwide popularity as an effective method of achieving high performance through the possible use of lighter belts [9]. The literature study showed that limited knowledge was, until recently, available on the economic design of multi-drive belt conveyors. As a contribution to bridge this gap, an optimization method for the cost-effective design of multi-drive conveyor systems was recently introduced by the authors [10, 11]. In order to further confirm the benefits induced by the proposed design approach, this paper reports a numerical study on the optimal belt conveyor solution for the cost-effective transport of a bulk material. The resulting optimal designs of three types of conveyor layouts, namely, the single drive belt conveyor, the single-tandem drive belt conveyor and the multi-drive belt conveyor, are compared in this study.

2. Cost-effective design of belt conveyors

2.1. Conveyor systems description

Fig. 1(a) displays a typical layout of an uphill single drive belt conveyor intended to transfer a bulk material of density ρ over a transport distance L with a lifting height H. In this system, the pulling force is applied to the belt by the drive unit situated at the head pulley, which consists of a unique drive pulley mounted on the output shaft of the motor-gearbox assembly. In order to withstand the pulling force entirely concentrated at a single point, belts with high rated breaking strength of the belt related to belt width, noted by k_N, are required for this layout, with the consequence of an increased motor load.

The typical uphill single-tandem drive belt conveyor is shown in Fig. 1(b). In this case, the unique drive unit positioned near the head pulley is composed of two drive pulleys mounted in tandem, each driven by a dedicated motor-gearbox assembly. By sharing the pulling force between two different points, belts with relatively low values of k_N can be considered.

The layout of the modern uphill multi-drive belt conveyor is shown in Fig. 2, where the introduction of one or more drive units along the carry side of the system gives the opportunity to reduce further the belt weight. While the illustration presents a multi-drive conveyor system composed of three intermediate drive units on the carry side and a fourth drive unit positioned on the return side, the more general design will comprise of $N+1$ drive units, N of which are distributed on the carry side as intermediate drive units.

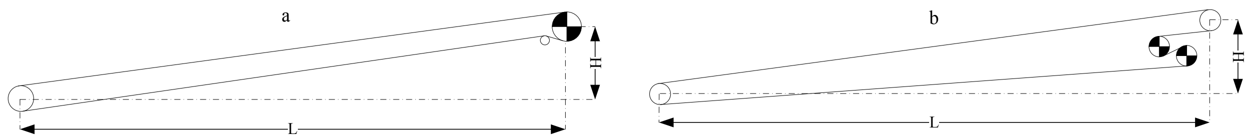

Fig. 1. (a) Single drive belt conveyor layout; (b) Single-tandem drive belt conveyor layout.

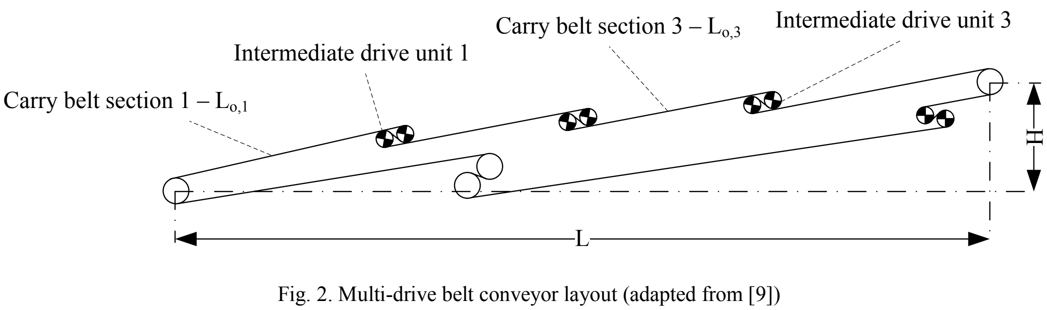

Fig. 2. Multi-drive belt conveyor layout (adapted from [9])

2.2. Cost optimization models

In practice, for a given bulk material transport specified by L, H, ρ, the angle of repose of the material β and the required material throughput Q, a large variety of designs can be envisaged for each type of conveyors previously described. Since each design solution will result into specific cost implications, the major plant owner's concern will be therefore to identify the conveyor system for which the lowest cumulative cost will be incurred over the lifespan of the transportation facility. In this perspective, a cost-optimizing design model was previously developed for each of the above conveyor layouts as reported earlier in [10]. Considering a specific type of belt conveyors, the associated optimization model intends to find the design with the minimum costs over the lifespan of the project.

In the optimization model, the common design variables common for belt conveyors were: the conveyor speed v, the belt width B, the rated breaking strength of the belt related to belt width k_N, the power rating of each motor P, the torque rating of each gearbox T, the diameter of each drive pulley D_{tr}, the wrap angle of the belt around each drive pulley α, the belt tension on both sides of the tensioning device F_{TU}, the shell diameter of the carry and return idler rolls D_o and D_u, respectively, the shaft diameter of the carry and return idler rolls d_o and d_u, respectively, and the spacing between the carry and idler rolls l_o and l_u , respectively. Besides, for a given number N of intermediate drive units, the set of design variables of the optimization model of multi-drive belt conveyors also includes the length $L_{o,j}$ of the carry belt section j ($j=1,\cdots,N+1$) exterior to the drive units (Fig. 2).

The equivalent annual cost (EAC) of a belt conveyor was adopted as a common performance indicator because of the popularity of this parameter in the assessment of engineering projects [7]. In general, the costs incurred for a conveyor system can be classified into operating and capital costs. Of the different operating cost items related to conveyor systems, only the energy cost was considered in the developed optimal design models. Because of the absence of previous investigations on the relation between the above design variables and the labor and maintenance costs, these two operating cost items were temporary excluded. Regarding the capital costs of belt conveyors, the formulated optimization models were limited to: the belt, motor, gearbox and carry and return idler rolls.

The formulation of the three optimization models is generalized as follows [10,11]:

$$\min \quad \textit{energy cost} + \textit{capital costs}, \tag{1}$$

$$\text{s.t.} \quad \textit{operational constraints} + \textit{design constraints}. \tag{2}$$

In the case of the single drive layout, the capital cost of the drive unit in (1) is composed of the costs of the unique motor, gearbox and drive pulley. The set of the operational constraints in (2) consists solely of the condition that guarantees the delivery of the specified material throughput. The set of the design constraints is composed of the conditions that ensure the local and global power balances, the effective transmission of the pulling force to the belt, the limitation of the belt sag and the mechanical endurance of the belt and the idler rolls. This set also includes the boundary limits that apply to the design variables.

In the case of the single-tandem drive layout, the capital cost of the drive unit in (1) is composed of the costs of the two motors, two gearboxes and two drive pulleys. While all the constraints in (2) are similar to those of the single drive layout, the design constraints on the power balance and the effective transmission of the pulling force are however adapted to take into account the presence of two identical drive pulley-gearbox-motor assemblies.

Lastly, in the case of the multi-drive layout comprising N intermediate drive units, the total capital cost of the driving system in (1) consists of the costs of the $N+1$ drive units, each with two motors, two gearboxes and two drive pulleys. In addition to the operational constraints on the material throughput, a condition that ensures the attainment of the transport distance and lifting height is necessary. Regarding the design constraints, the conditions on the power balance, the effective transmission of the pulling force to the belt and the limitation of the belt sag are revised to account for the presence of the intermediate drive units along the carry side of the system. Furthermore, in order to reduce the maximum belt tension, a design constraint intended to equalize the slight side tensions of all the drive units is introduced. In so doing, the lowest maximum belt tension is attained with a proportional reduction in the value of k_N, which is the determining factor of the belt weight [9].

Most of the above constraints were derived from the DIN 22101 guideline [12], while few were based on the SANS 1313 guideline [13]. Moreover, because of the limited number of equipment sizes considered in these guidelines, the following design parameters were treated as discrete variables: the belt width, the diameter of the drive pulleys, the shell diameter of the idler rolls and the shaft diameters of the idler rolls. The three formulated cost optimization models are therefore categorized as mixed integer nonlinear programmings (MINLPs). Since the modeling of cost-effective belt conveyors is beyond the scope of this paper, for a complete discussion on the formulation of the above optimization models the reader is referred to our previous works [10, 11].

3. Case study

In this numerical study, the transfer of a bulk material at a throughput of 3500 t/h over a transport distance of 2500 m with an incline of 1 in 100 is studied to compare the performance of three types of belt conveyors. The density and the angle of repose of the material are 1280 kg/m^3 and 20°, respectively. The basic design assumptions are:

- Troughing angle: 35°
- Belt type: steelcord conveyor belt
- Hypothetical friction coefficient: 0.03
- Gearbox: helical type
- Operation: 12 hours/day over 300 days per annum
- Project lifetime: 20 years

4. Simulation results and discussion

The MINLPs developed in [11] for the cost-effective designs of the three types of belt conveyors were solved by means of the MIDACO solver embedded into MATLAB. For analysis purposes, the MINLPs were solved for each size of belt width. Furthermore, in the case of the multi-drive layout, the MINLPs were simulated for N varying from 1 to 5.

Fig. 3(a) displays the EAC of conveyor as a function of the conveyor speed and the system configuration. On the conveyor system axis, SD refers to the single drive layout, SDT refers to the single-tandem drive layout, and MD-1 to MD-5 refer to the multi-drive layout with, respectively, 1 to 5 intermediate drive units. This figure shows that the single drive and single-tandem drive conveyor systems constitute the preferred options at high conveyor speed, while the gradual decrease of the conveyor speed tends to benefit the multi-drive technology.

The breakdown of the most cost-effective designs per conveyor configuration shown in Fig. 3(b) indicates that the lowest EAC is achieved by the multi-drive belt conveyor equipped with three intermediate drive units (MD-3), for an equivalent annual cost saving of about 63,120 $(USD) and 29,475 $(USD) over the cheapest single drive and single-tandem drive conveyor systems, respectively. It is also noticed that the significant reduction in the energy

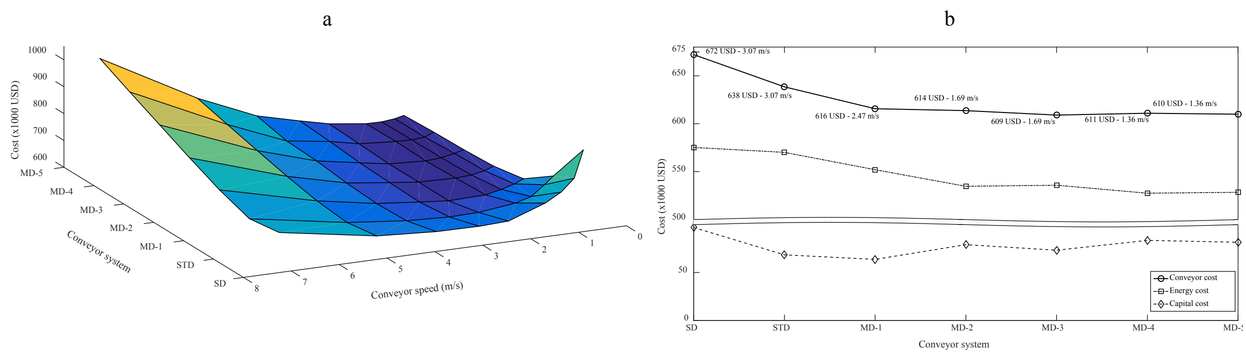

Fig. 3. (a) Optimal belt conveyor designs; (b) Most cost-effective design per conveyor configuration.

Table 1. Cheapest design per belt conveyor configuration.

	B (m)	v (m/s)	P (kW)	T (kNm)	α (°)	l_o (m)	l_u (m)	F_{TU} (kN)	k_N (N/mm)
SD	1.4	3.97	1297.6	152.0	240.0	2.0	4.3	129.5	1568.3
STD	1.4	2.47	643.0	59.3	208.6	1.9	4.5	62.1	1350.3
MD-1	1.5	2.47	311.3	28.4	227.5	1.9	4.5	80.8	853.4
MD-2	1.8	1.69	201.0	26.7	230.3	1.2	4.5	66.9	647.5
MD-3	1.8	1.69	151.1	16.1	217.7	1.4	3.9	87.0	571.3
MD-4	2.0	1.36	117.9	15.6	185.1	1.0	4.5	73.9	476.6
MD-5	2.0	1.36	99.3	13.1	213.7	1.5	4.5	114.5	510.3

Table 1. Cheapest design per belt conveyor configuration (continued).

	D_{tr} (mm)	D_o (mm)	D_u (mm)	d_o (mm)	d_u (mm)	$L_{o,1}$ (m)	$L_{o,k}$ (m)	$L_{o,N+1}$ (m)
SD	800	102	102	30	25	-	-	-
STD	630	63	63	30	25	-	-	-
MD-1	500	63	63	25	25	1212.0	-	1288.6
MD-2	500	63	63	30	30	788.6	866.5	846.0
MD-3	400	63	63	30	30	573.0	649.7	628.9
MD-4	400	63	63	35	30	452.4	517.2	497.8
MD-5	400	63	63	35	30	364.7	431.4	411.8

*For k=2,···,N

cost resulting from the use of a lighter belt, is the primary reason of the overall improvement observed. Subject to both the conveyor components considered and the manufacturers supplied information used, Fig. 3(b) shows that beyond the MD-1 belt conveyors, the equivalent annual capital cost of the multi-drive belt conveyor tends to gradually increase with the number of the drive units on the system.

In line with the previous observations on Fig. 3(a), the information on the optimal conveyor speed of the cheapest system in Fig. 3(b) confirms that the minimum EACs of the multi-drive conveyor will usually occur at lower speed compared to that of the single drive and single-tandem drive contenders.

The design specifications of the most cost-effective conveyor system are presented in Table 1. Based on their respective total number of gearbox-motor assemblies, the total rated power of the motors of these conveyor systems are such that the implementation of the cheapest MD-3 belt conveyor will result into 93.60 kW and 81.43 kW power demand reduction in comparison with the cheapest single drive and single-tandem drive belt conveyors, respectively. This can further benefit the plant owner in case the tariff structure applied by the power utility company involves demand charges, which was not considered in the above energy cost model. The table also shows that the cost-effective design of multi-drive belt conveyors will generally lead to relatively small driving equipment but a large belt. These physical characteristics develop in opposite directions when moving backward towards the single drive layout. Therefore, the aspects relating to the costs and technology for handling these conveyor components could also be considered in the decision making process of certain projects. Finally, Table 1 shows the net decline of the value of k_N as a consequence of the insertion of intermediate drive units.

The breakdown of the power consumption between the different load components of the belt conveyors is shown in Fig. 4(a). It is observed that with the increase in number of the drive pulleys, the proportion of power consumption due to the payload tends to further dominate the other components. This growing trend of transportation efficiency will always give an economic advantage to the multi-drive technology in case of material

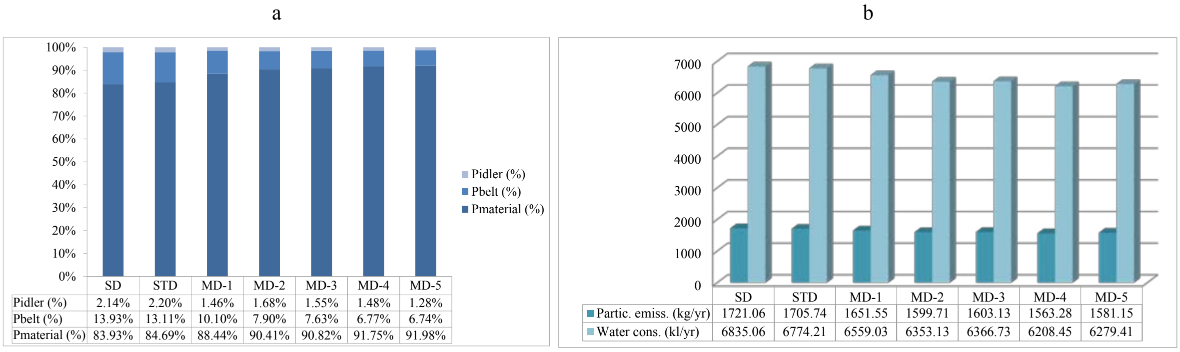

Fig.4. (a) Percentage of power consumption per conveyor load (b) Particulate emissions and water consumption.

handled over relatively long distances.

In the national grid of South Africa, the relative particulate emissions and the specific water consumption due to electricity generation are evaluated at 0.35 kg/MWh and 1.39 l/MWh, respectively [14]. Fig. 4(b) shows the corresponding annual environmental footprint of the cheapest conveyor designs with respect to the annual operating time of the facility given in Section 3, the rated power of the motors given in Table 1 and their efficiency estimated at 0.95. It is observed that the implementation of the MD-3 belt conveyor will reduce the total particulate emissions per year by 117.92 kg (6.85%) and 102.60 kg (6.02%) with respect to the single drive and single-tandem drive belt conveyors. Annual savings on water consumption of 468.33 kl (6.85%) and 407.48 kl (6.02%) will be also achieved.

5. Conclusion

A numerical study on the economic design of a belt conveyor for a specified bulk material handling application is presented in this paper. Based on previously developed cost optimization models for the cost-effective design of single drive, single-tandem drive and multi-drive belt conveyors, the study compared their performances and established the significant cost savings potential of the optimal multi-drive belt conveyor systems for a specific application. The environmental benefit of using the multi-drive technology was also demonstrated.

Acknowledgements

The authors acknowledge the support for this work provided by the National Hub for Energy Efficiency and Demand Side Management and the National Research Foundation of South Africa under grant unique number 105047.

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