MODELING THE ENERGY EFFICIENCY OF MECHANICAL HANDLING MACHINES AND SYSTEMS

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Abstract: The aim of this study is to justify a generalized basis model for investigating, evaluating and comparing the energy efficiency of the individual and the grouped mechanical handling machines and systems. Based on a conducted analysis and developed model technological schemes of the systems for continuous transport, dependencies are drawn for determining the basis power and minimizing the potential energy losses in loads passages, the losses of height and potential energy in the systems' auxiliary elements as well as the total energy losses. Additional indices for basis evaluation of the energy efficiency of the continuous-transport-systems technological schemes, regardless of the systems' type and scope, are developed and systematized.

Keywords: energy efficiency, mechanical handling machines and systems, methods, models

1. INTRODUCTION

The study of literature shows as a whole targeting the latest international research on mechanical handling equipment to the belt conveyors and systems.

A model for determining the motor shaft power through the belt speed and the actual output is worked out [1]. The model captures the kinetic energy of the transported load. The four coefficients in the model (θ_1 ... θ_4) can be determined on the basis of the parameters of the conveyor construction and individual elements. Based on [1], a comprehensive simulation model taking into account the motor and inverter efficiency is worked out for quantitative determination of the consumed electric power of belt conveyors with frequency control [2]. Using the model, it is proposed the optimization of the conveyors systems to be conducted with a constant load feeding in two directions – limiting the idle condition of the machines in the system without changing the speed of rotation, and reducing the electricity costs in accordance with the tariffs with variable motor speed. An optimization of a particular coal-feeding system in a thermal power plant is conducted. The problem with the lack of definitions of the inevitably existing restrictive optimization conditions is solved in [3], where the technological constraints are taken into account. The constraints taken are due to insufficient load feeding, the consumption in tariff zones with high electricity prices, high conveyor angle and the insufficient feeders control.

For screw conveyors, it appears that the use of "methods of discrete elements" allows prediction of the energy dissipation in load and the power consumption when changing the screw speed and the angle of inclination [4].

In [5] under steady-state condition of conveyors, the energy consumption is divided into the components energy to drive in idle condition P_{ec}, energy to move the load horizontally a certain distance P_h and energy to raise the load to a height P_l. Possibilities for improving energy efficiency of a particular system of belt conveyors are

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investigated, including change the speed of conveyors, increasing the available power of the converter devices, increase the supply from vibrating conveyors, change in the width and other belt characteristics [6]. Vector-controlled frequency converters with integrated technological controllers with a specific application to belt conveyor are described in [7]. For them, the advantage is the control not only of the individual machines, but of the overall system. Thus, mainly the reliability, but also the energy efficiency is improved by reducing the idle time for starting and stopping the system.

The generalized analysis of the above study shows that there are some disadvantages of the reviewed researches and developments which can be grouped into the following directions:

- Along with the quantitative assessment, models and indices for qualitative energy-consumption evaluation in transport machines and systems, including modeling the basis (useful) power, should be proposed;
- The approaches to optimize the electricity do not consider the efficiency of the transport-systems technological scheme in terms of the geometric characteristics of the route. Relevant indicators are missing;
- The load type and the amount of the occurred losses of height, respectively energy, due to the systems' cascading and availability of ancillary equipment are not accounted.

In Bulgaria, due to the need for methodological ensuring of the current legislation on energy efficiency [8, 9], a number of researches and developments have been published which tangs with the modeling, studying, evaluating and comparing the mechanical-handling-equipment efficiency.

An aggregate model and a based computer system are proposed which provide an automated investigation and evaluation of the induction-motor-drives energy efficiency through a set of systematic quantitative and qualitative indices [10, 11]. The workability and the relevance of the developments are ensured by a column-analytical model for determining the optimal drives loading and are proved by several investigations of industrial sites including belt conveyors and a coal-feeding system [12-15]. The levels of electrical consumption that characterize the electrical-consumers energy efficiency are defined. They have lied at the basis of synthesized case theoretical models for determination of the basis and non-useful power of the systems for transportation and grinding of coal in steam power stations [12, 16]. The models take into account the specifics of these systems and they are synthesized by starting from the total leveling of the two subsystems, the mass of coal (coal powder) and the electrical loads of induction-motor drives. A science-based procedure for training on energy efficiency of mechanical handling machines is proposed in [17].

The analysis of the publications shows that there are opportunities the developments to be successfully related and developed further in modeling the energy efficiency of mechanical handling machines and systems.

The aim of this study is to justify a generalized model for investigating, evaluating and comparing the energy efficiency of mechanical handling machines and systems.

2. ANALYSING THE ENERGY EFFICIENCY OF THE SYSTEMS FOR CONTINUOUS TRANSPORT

The continuous transport of bulk and unit loads is carried out using different types of transport machines (TM), the main of which are the belt, chain, walking-beam and pneumatic conveyors, elevators, and some conveyors without tow actuator [18]. In general, these machines are combined in complex systems for transport and processing but, despite the variety of the technologies used, they can be modeled by three typical flow diagrams representing the three major cases - transportation (raising) of load from the initial to the final level with a greater absolute altitude (Figure1a), transportation of load between points of equal absolute altitudes (Figure 1b) and transportation of load to a level with less absolute altitude (Figure 1c).

It is established from the analysis of the schemes that losses of potential energy of the load are inevitably occurred at different points of the system, which are generally low but in some cases they may reach and even to exceed the total out-of-levelling ΔH.

These losses are due to the overall loss of height in the passages of the load between machines, and the total loss of height in the various auxiliary elements in the system (Fig.1a and Fig.1b). The loss ΔP_p (A_{act}, Δh_p) of power due to decreasing the potential energy of the load in passages will depend on the type of the machines involved as well as on the system' actual mass output:

$$\Delta P_p\left(A_{act}, \Delta h_p\right) = g.A_{act}\left(\sum_{i=1}^{i=a}\Delta h_{pL,i} + \sum_{i=1}^{i=b}\Delta h_{pV,i} + \sum_{i=1}^{i=c}\Delta h_{pE,i} + \sum_{i=1}^{i=d}\Delta h_{pS,i} + \sum_{i=1}^{i=e}\Delta h_{pP,i} + \sum_{i=1}^{i=f}\Delta h_{pR,i} + \sum_{i=1}^{i=g}\Delta h_{pW,i} + \sum_{i=1}^{i=h}\Delta h_{pT,i}\right) =$$
$$= g.A_{act}.\left(\Delta h_{pL,\Sigma} + \Delta h_{pV,\Sigma} + \Delta h_{pE,\Sigma} + \Delta h_{pS,\Sigma} + \Delta h_{pP,\Sigma} + \Delta h_{pR,\Sigma} + \Delta h_{pW,\Sigma} + \Delta h_{pT,\Sigma}\right) \quad (1)$$

where A_{act} is the actual mass output of the system, g is the gravitational acceleration, $\Delta h_{pL,i}$, $\Delta h_{pV,i}$, $\Delta h_{pE,i}$, $\Delta h_{pS,i}$, $\Delta h_{pP,i}$, $\Delta h_{pR,i}$, $\Delta h_{pW,i}$, $\Delta h_{pT,i}$ are the i-th losses of height due to the load passages, for belt and chain conveyors, elevators, walking-beam, pneumatic, roller, screw and shuttle conveyors respectively, and a, b, c, d, e, f, g, h are – the corresponding numbers of the conveyors in each group.

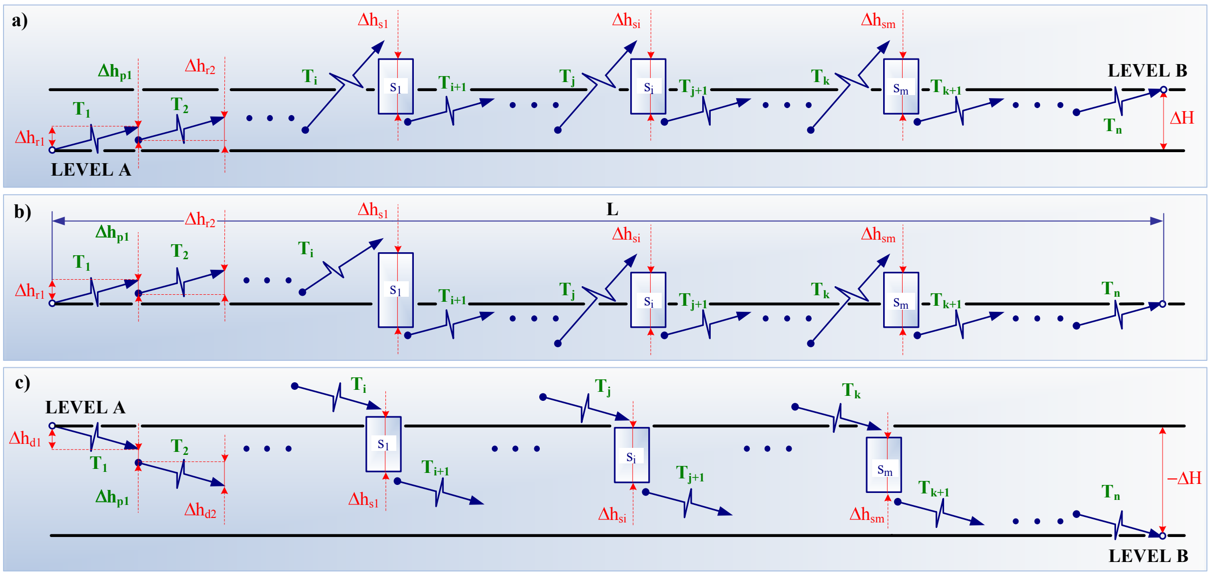

Fig. 1. Model flow diagrams of the systems for continuous transport:
T_1, T_2, ..., T_i, T_{i+1}, ..., T_j, T_{j+1}, ..., T_k, T_{k+1}, ..., T_n – transport machines; n – the machines number; Δh_{p1}, Δh_{p2}, ..., Δh_{pn} – the loss of height in the passages (pouring of load between the component transport machines; Δh_{r1}, Δh_{r2}, ..., Δh_{rn} – the difference between the absolute altitudes of the final and initial point of the transport machines (the out-of-leveling of the machines) in systems with a positive and a zero total out-of-leveling +ΔH; ΔH – the total out-of-leveling of the system; S_1, S_2, ..., S_i, ..., S_m – the auxiliary elements in the transport system; m - the number of these elements; Δh_{s1}, Δh_{s2}, ..., Δh_{si}, ..., Δh_{sm} – the loss of height in the auxiliary elements; Δh_{d1}, Δh_{d2}, ..., Δh_{dn} – the out-of-leveling of the transport machines in the systems with a negative total out-of-leveling -ΔH; L - the distance in a straight line between the transportation initial and final point in the systems with ΔH = 0.

Often along with transportation processes, additional operations such as storage, grinding, separation and more are required which are carried out by appropriate auxiliary elements. This leads to a proportional loss of height and potential energy in them, of power ΔP_s (A_{act}, Δh_s) respectively, that, for convenience and with a view to clear energy analysis, can be similarly differentiated according to the basic types of auxiliary elements:

$$\Delta P_s\left(A_{act}, \Delta h_s\right) = g.A_{act}.\left(\sum_{i=1}^{i=a'}\Delta h_{sS,i} + \sum_{i=1}^{i=b'}\Delta h_{sB,i} + \sum_{i=1}^{i=c'}\Delta h_{sP,i} + \sum_{i=1}^{i=d'}\Delta h_{sD,i} + \sum_{i=1}^{i=e'}\Delta h_{sT,i} + \sum_{i=1}^{i=f'}\Delta h_{sC,i} + \sum_{i=1}^{i=g'}\Delta h_{sM,i} + \sum_{i=1}^{i=h'}\Delta h_{sN,i}\right) =$$
$$= g.A_{act}.\left(\Delta h_{sS,\Sigma} + \Delta h_{sB,\Sigma} + \Delta h_{sP,\Sigma} + \Delta h_{sD,\Sigma} + \Delta h_{sT,\Sigma} + \Delta h_{sC,\Sigma} + \Delta h_{sM,\Sigma} + \Delta h_{sN,\Sigma}\right) \quad (2)$$

where $\Delta h_{sS,i}$, $\Delta h_{sB,i}$, $\Delta h_{sP,i}$, $\Delta h_{sD,i}$, $\Delta h_{sT,i}$, $\Delta h_{sC,i}$, $\Delta h_{sM,i}$, $\Delta h_{sN,i}$ are the i-th losses of height due to the presence in the system of stores, bunkers and bunker gates, feeders, dispensers, weighters, separators, mills and screens, respectively, and a´, b´, c´, d´, e´, f´, g´, h´ are the corresponding numbers of the auxiliary elements in each group.

Regardless of their nature, the potential energy losses are covered by the electrical energy consumed by the transport systems and, taking into consideration the models (1) and (2), the aggregate dependence for determination of the total losses ΔP_Σ (A_{act}, Δh_p, Δh_s) of active power as a result of load passages and the auxiliary processes can be summarized:

$$\Delta P_\Sigma\left(A_{act},\Delta h_p,\Delta h_s\right)= g.A_{act}.\left(\Delta h_{pL,\Sigma}+\Delta h_{pV,\Sigma}+\Delta h_{pE,\Sigma}+\Delta h_{pS,\Sigma}+\Delta h_{pP,\Sigma}+\Delta h_{pR,\Sigma}+\Delta h_{pW,\Sigma}+\Delta h_{pT,\Sigma}+\right.$$
$$\left.+\Delta h_{sS,\Sigma}+\Delta h_{sB,\Sigma}+\Delta h_{sP,\Sigma}+\Delta h_{sD,\Sigma}+\Delta h_{sT,\Sigma}+\Delta h_{sC,\Sigma}+\Delta h_{sM,\Sigma}+\Delta h_{sN,\Sigma}\right)=\Delta P_p\left(A_{act},\Delta h_p\right)+\Delta P_s\left(A_{act},\Delta h_s\right) \quad (3)$$

It can be seen that the considered losses depend on the size of the particular load passages which are different for the different types of TM. On the other hand, the factor, which should be necessarily taken into account when analyzing the technological-scheme efficiency, is the presence or absence of auxiliary elements in the scheme due to the significant loss of height in them. It follows from the analysis of the resulting model (3) that the optimization should be achieved only by minimizing the loss of height without reducing the output, since this leads to under-loading of objects and increases the relative power consumption.

The case is different when the out-of-leveling ΔH between the initial and the final level is negative (Fig.1c). In this case, the main factor for improving the technological-scheme efficiency is the maximum gravity utilization with a minimum use of electric drives.

3. DETERMINATION OF THE BASIS POWER

According to the generalized model [16], the level of the physically-needed power consumed completely for counteracting the gravity forces that acts on transported loads is considered as a basis level of the energy efficiency of TM. On the other hand, due to its wide application in practice, it is convenient to make the definitions using the mass output of the particular mechanical handling machine or system [18]. Thus, the dependences for determination of the basis power of the mechanical handling machines and systems are defined in accordance with Table 1. According to the classification made, the machines that work independently without their work to depend on the work of other TM are considered as individual. Depending on their specific application, the continuous transport machines (belt, chain and walking-beam conveyors, elevators, etc.) the transport machines with a cyclic operation (lifts, winches, electric trucks, hoists, cranes, etc.) can be assigned to this group of machines [18].

Table 1. Dependencies for determination of the basis power of the mechanical handling machines and systems.

	General purpose loads	Solid fuels
Individual mechanical handling machines	$P_b\left(A_{act},\Delta h_T\right)= g.A_{act}.\Delta h_T$ (4)	$P_b\left(k_{ball},A_{act},\Delta h_T\right)= g.k_{ball}.A_{act}.\Delta h_T$ (6)
Systems for continuous transport	$P_b\left(A_{act},\Delta H\right)= g.A_{act}.\Delta H$ (5)	$P_b\left(k_{ball},A_{act},\Delta H\right)= g.k_{ball}.A_{act}.\Delta H$ (7)
Nomenclature: A_{act} – the actual mass output of the given machine or system; g – the gravitational acceleration; Δh_r and ΔH – the differences between the absolute altitudes of the final and initial point of load transportation for the given individual machine or system for continuous transport, respectively.		

According to their type, very often a large part of the individual machines are combined in systems for continuous transport. Given the technological connection between machines, the basic power required of a system for load carrying from the route beginning (T_1) to the route end (T_n) is dictated by the total out-of-leveling ΔH (Figure 1).

Besides general purpose loads, the discussed objects often transport solid fuels. It is known [19] that both useful and unwanted (non-useful) ingredients are included into their composition so transportation is inevitably associated with carrying of a ballast (non-useful) mass. Therefore, the actual output A_{act} involved in the dependencies in Table 1 should be reduced by introducing a correction coefficient of ballast k_{ball} (m^*_u, m^*) determined through the amount of the useful mass:

$$k_{ball}\left(m_u^*, m^*\right) = \frac{m_u^*}{m^*} \tag{8}$$

where m^*_u and m^* are the useful and the total mass contained in a given volume of fuel.

This coefficient can be calculated using the quality indicators of a given fuel. For instance, the "ash-free dry mass" [19] is considered as a useful for coal, which in turn can be determined if the values of ash and moisture content in coal in percentages are known [19].

4. SELECTING AND SYNTHESIZING INDICES FOR ENERGY-EFFICIENCY EVALUATION

4.1. Individual machines

The generalized indices for electric drives [10, 11] can be used for assessment of the energy efficiency in individual electrical driven material handling machines. In general, the more objective index C_2 (instead of C_1) is used to assess the losses level due to the existing of a convenient practicable possibility to determine the basis power by the drawn models (Table 1). This index considers the energy-loss variable component and is determined as a difference between the active power P_a and the basis power P_b consumed by a given machine:

$$C_2\left(P_a, P_b\right) = P_a - P_b \tag{9}$$

When an individual machine does not have out-of-levelling ($\Delta h_T = 0$), its basis power in a random operation is zero and the evaluation by the above set of indices is insufficiently informative. In this case, the classical criterion "specific energy consumption k_e, kWh/tm" [20] should be used. The same criterion can be similarly used and for the systems for continuous transport.

4.2. Systems for continuous transport

The indexes in section 4.1 are used for primary evaluation of the energy efficiency of the TM involved in these systems and of the systems themselves. Along with these indexes and with a view to take into account the objects specificity, additional basis indices of assessment should be developed and proposed that should consider the technological-scheme characteristics and allow investigation and comparison regardless of the type and scope of the given system. For this purpose, using relative units towards basic variables and reflecting only the geometric characteristics of the route (the cascade), without taking into consideration the load nature, is appropriate.

Based on the above analysis and commentary, and according to the three presented model schemes (Figure 1), four new indices H_1, H_2, H_3 and H_4 for evaluating the energy efficiency of the technological schemes of the continuous transport systems are synthesized (Table 2). The indices are divided into separate classification group H according to the approved systematization [10-12].

When optimizing processes, the goal is the indices relative load lift H_1 and relative load descent H_3 to be equal to one relative unit, and the coefficients of loss of height H_2 and of utilization of the gravity forces H_4 to be equal to zero. The initial and final levels (level A and level B in Figure 1) for each particular case are different and can be selected according to the concrete systems characteristics and to the manufacturing-processes technology. The complex systems can be divided into subsystems under the terms of the model flow diagrams in Figure 1 as the scheme energy efficiency is to be estimated separately for each subsystem.

5. CONCLUSIONS

Complete model technological schemes of the systems for continuous transport have been proposed on the basis on which the study of the systems' energy efficiency to be conducted in terms of their configuration and geometrical characteristics.

The model schemes are analyzed resulting in drawn dependencies for determining and minimizing the potential energy losses in loads passages, the losses of height and potential energy in the systems' auxiliary elements as well as the total energy losses.

Table 2. Indices for investigation and evaluation of the energy efficiency of the technological schemes of the systems for continuous transport.

Classification group	**Symbol**	**Description**	**Dependence for determination**	**Dimension**	**Application**
group H	H_1	Relative load lift	$\mathbf{H_1 = \frac{1}{\Delta H} \cdot \sum_{i=1}^{i=n} h_{r,i} \Rightarrow 1}$ (10)	relative units	Systems with a positive total out-of-leveling *(+ΔH)*
	H_2	Coefficient of loss of height	$\mathbf{H_2 = \frac{1}{L} \cdot \sum_{i=1}^{i=n} \Delta h_{r,i} = \frac{1}{L} \cdot \left(\sum_{i=1}^{i=n} \Delta h_{p,i} + \sum_{i=1}^{i=m} \Delta h_{s,i} + \sum_{i=1}^{i=u} \left| \Delta h'_{d,i} \right| \right) \Rightarrow 0}$ (11)	relative units	Systems with a zero total out-of-leveling *(ΔH = 0)*
	H_3	Relative load descent	$\mathbf{H_3} = \frac{1}{\left|\Delta H\right|} \cdot \left(\sum_{i=1}^{i=n} \left|\Delta h_{d,i}\right| + \sum_{i=1}^{i=n} \Delta h_{p,i} + \sum_{i=1}^{i=m} \Delta h_{s,i} + \sum_{i=1}^{i=v} \Delta h'_{r,i} \right) \Rightarrow 1$ (12)	relative units	Systems with a negative total out-of-leveling *(-ΔH)*
	H_4	Coefficient of gravity forces utilization	$\mathbf{H}_4 = \frac{\sum_{i=1}^{i=w} \left|\mathbf{\Delta h_{d\,ED,i}}\right|}{\sum_{i=1}^{i=n} \left|\mathbf{\Delta h_{d,i}}\right|} \Rightarrow 0$ (13)	relative units	

Nomenclature: $\Delta h'_{d,i}$ and u – the out-of-leveling of the i-th TM with a negative out-of-leveling and the number of the machines with a negative out-of-leveling in the given continuous transport system with a zero total out-of-leveling, respectively ($\Delta H = 0$); $\Delta h'_{r,i}$ and v – the out-of-leveling of the i-th TM with a positive out-of-leveling and the number of the machines with a positive out-of-leveling in the given continuous transport system with a negative total out-of-leveling, respectively ($- \Delta H$); $\Delta h_{dED,i}$ and w – the out-of-leveling of the i-th TM with an available electric drive and the number of the machines with available electric drives in the given continuous transport system with a negative total out-of-leveling, respectively ($- \Delta H$), m.

The other symbols in the table are according to Figure 1.

The dependencies for accurate determination of the average basis power of the mechanical handling machines and systems through their actual output are synthesized and summarized. The influence of ballast on the energy efficiency in solid fuels transportation is accounted and modeled.

The main indices for investigating and evaluating the energy efficiency both of the individual material handling machines and of the complex systems for continuous transport with available electric drives are selected and ranked.

Additional indices to assess the energy efficiency of the continuous transport systems technological schemes, including the systems with negative total out-of-leveling are developed and systematized. The definition of these indices towards basis variables such as total out-of-leveling and distance in a straight line from the initial to the final point of transportation allows they to be successfully applied for a uniform collation and comparison of the scheme effectiveness regardless of the transport-system type and scope.

An integral theoretical model for studying, evaluating and comparing the energy efficiency in the material handling machines and systems is developed.

The model functionality and the possibilities of its application in practice should be proved and justified for individual material handling machines and complex continuous transport systems of different type and with different specificity and functions.

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