Arch. Min. Sci. **64** (2019), 2, 251-259

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/ams.2019.128681

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INFLUENCE OF IDLER SET LOAD DISTRIBUTION ON BELT ROLLING RESISTANCE

WPŁYW ROZKŁADU OBCIĄŻEŃ ZESTAWU KRĄŻNIKOWEGO NA OPORY TOCZENIA TAŚMY

Theoretical and experimental research indicates that radial loads have a significant influence on the value of belt-on-idler rolling resistances. Computational models discussed in literature use the notion of unit rolling resistance, i.e. rolling resistance per unit length of the idler. The total value of the rolling resistance of belt on a single idler is determined by integrating unit rolling resistance with respect to the length of the contact zone between the belt and the idler. This procedure requires the knowledge of normal load distribution along the contact zone between the belt and the idler. Loads acting on the idler set have been the object of both theoretical analyses and laboratory tests. Literature mentions several models which describe the distribution of normal loads along the contact zone between the belt and the idler set (Krause & Hettler, 1974; Lodewijks, 1996; Gładysiewicz, 2003; Jennings, 2014). Numerous experimental tests (Gładysiewicz & Kisielewski, 2017; Król, 2017; Król & Zombroń, 2012) demonstrated that the resultant normal loads acting on idlers are approximate to the loads calculated in theoretical models. If the resultant normal load is known, it is possible to assume the distribution of loads acting along the contact zone between the belt and the idler. This paper analyzes various hypothetical load distributions calculated for both the center idler roll and for the side idler roll. It also presents the results of calculations of belt rolling resistances for the analyzed distributions. In addition, it presents the results of calculations with allowance for load distribution along the generating line of the idler.

Keywords: belt conveyor, belt, rolling resistance, idler set load

Z badań teoretycznych i eksperymentalnych wynika istotny wpływ obciążeń promieniowych na wielkość oporów toczenia taśmy po krążnikach. W znanych z literatury modelach obliczeniowych wykorzystywany jest jednostkowy opór toczenia taśmy tj. opór przypadający na jednostkę długości krążnika. Wielkość całkowitego oporu toczenia taśmy na pojedynczym krążniku wyznacza się całkując opór jednostkowy po długości strefy kontaktu taśmy z tym krążnikiem. Do tego potrzebna jest znajomość rozkładu obciążeń normalnych wzdłuż strefy kontaktu taśmy z krążnikiem. Obciążenia zestawu krążnikowego były przedmiotem zarówno analiz teoretycznych jak i badań laboratoryjnych. Z literatury znanych

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jest kilka modeli opisujących rozkład obciążeń normalnych wzdłuż strefy kontaktu taśmy z zestawem krążnikowym (Krause & Hettler, 1974; Lodewijks, 1996; Gładysiewicz, 2003; Jennings, 2014). Liczne badania eksperymentalne (Król, 2013; Gładysiewicz & Kisielewski, 2017) wykazały, że wypadkowe obciążenia normalne krążników są zbliżone do obciążeń wyznaczonych z modeli teoretycznych. Znając wypadkowe obciążenie normalne można założyć rozkład obciążeń wzdłuż długości strefy kontaktu taśmy z krążnikiem. W pracy przeanalizowano różne hipotetyczne rozkłady obciążeń dla krążnika środkowego i bocznego oraz określono opory toczenia taśmy dla tych rozkładów. Wyznaczono współczynniki obliczeniowe uwzględniające nierównomierność rozkładu obciążeń wzdłuż tworzącej krążnika.

Słowa kluczowe: przenośnik taśmowy, opory toczenia, taśma, obciążenia zastawu krążnikowego

1. Introduction

Tests performed on a belt conveyor operated in an open cast lignite mine showed that the calculated main resistances on a single idler set in the top run are smaller than the actual measured values, especially in the range of instantaneous capacities approximating nominal capacities (Król & Kisielewski, 2014). The analysis of the reasons behind these discrepancies points to the need to further develop the methods used for calculating the most significant component of the main resistance, i.e. the belt-on-idler rolling resistance. Numerous publications describe methods for calculating the rolling resistances of a belt moving on idlers (Jonkers, 1980; Spaans, 1991; Gładysiewicz & Konieczna, 2016). All of those methods are based on the notion of unit rolling resistance, which includes both the structural parameters of the conveyor and the damping parameters of the belt. Unit rolling resistance, i.e. the resistance per unit length of the idler roll, is expressed with the following theoretical relationship (Gładysiewicz & Konieczna, 2018):

$$w_e = 0.882 \cdot \psi_{lab} \cdot \sqrt[3]{\frac{{q_T}^4}{{D_K}^2 \cdot \lambda \cdot c_e}} \quad \left[\frac{\text{N}}{\text{m}}\right] \tag{1}$$

where:

- ψ_{lab} — damping factor determined in laboratory tests, -,
- q_T — unit load on the idler, N/m,
- D_K — idler diameter, m,
- λ — bending factor of belt on the idler, -,
- c_e — unit transverse stiffness of the belt, N/m.

The rolling resistance of the idler set is the sum of resistances of individual idler rollers. In order to calculate the rolling resistance of an individual idler, relationship (1) is integrated with respect to the length of the contact zone between the belt and idler b. The parameter which changes its value along the contact zone is unit idler load q_T, and thus determining idler rolling resistance requires calculating the following integral:

$$W_e = \int_0^b w_e \cdot dx = 0{,}882 \cdot \frac{\psi_{lab}}{\sqrt[3]{{D_K}^2 \cdot \lambda \cdot c_e}} \int_0^b \left(q_T\right)^{\frac{4}{3}} \cdot dx \ \text{[N]} \tag{2}$$

where:

- x — coordinate with respect to idler length, -,
- b — length of the contact zone between belt and idler (Fig. 1), m.

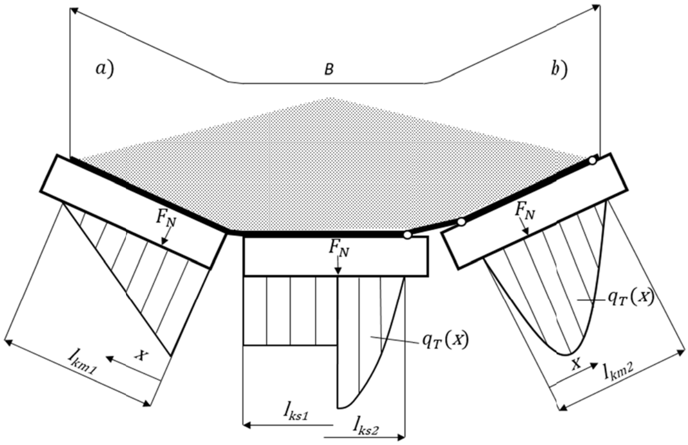


Fig. 1. Distribution of loads on the zone of contact between the idlers and the belt on a single three-idler set: a) according to a loose medium model without allowance for belt transverse stiffness, b) according to measurements (Kessler, 1986) with allowance for belt transverse stiffness

The analysis of relationship (2) shows that the key aspect is to define the length of contact zones between the belt and the side and center idler rollers, as well as to identify the load distributions along these contact zones. In the case of a three-idler set in the upper run, the length of the contact zone, as measured along the generating line of the idler, may be calculated from equations based on empirical tests (Gładysiewicz, 2003). For the center idler roll, this length is:

$$l_{km} = B \cdot (0{,}35 + 0.02 \cdot k_z^2)\ [\mathrm{m}] \tag{3}$$

and for the side idler roll:

$$l_{ks} = B \cdot (0{,}03 + 0.16 \cdot k_z^2)\ [\mathrm{m}] \tag{4}$$

where:

B — belt width, m
k_z — non-dimensional loading factor of belt with the transported material, -.

The length of the contact zone between the belt and the idler has no influence on the value of the rolling resistance. In the calculation models, it is most important to calculate the resultant normal force on idler F_N and the distribution of this force along the contact zone, i.e. to calculate function $q_T(x)$.

Normal loads on idlers (forces F_N) are caused by the interaction with transported material and with the belt. Calculations of normal loads on idlers due to the interaction with the transported material are performed with the use of a loose medium model (Krause & Hettler, 1974) which allow uniform load distribution for the center idler roll and linear load distribution for the side idler roll. Laboratory measurements proved that this method provides an accurate description of actual conditions. Belt interactions are the second factor influencing the value of normal load on idlers. The components of normal reactions due to belt interactions can be calculated on the basis of empirical relationships described by Kessler. Algorithms for calculating normal loads on idlers with allowance for the parameters of the transported material and transverse belt stiffness are provided in (Gładysiewicz, 2003). Recent tests of loads acting on a belt conveyor operated in an open cast lignite mine showed that the results of calculations are in good consistency with the results of actual measurements.

2. Distributions of normal loads for a three-idler set

The calculations of the rolling resistance of belt on idlers should include assumptions on load distribution. Comparative analysis was used to investigate the influence of the assumed load distribution on the accuracy of the calculated rolling resistance for a single idler roll. Considerations covered three models of loads, as shown in Fig. 2. The distribution of Fig. 2a is a typical pattern for the transported material treated as a loose medium without allowance for belt interaction (transverse belt stiffness). This type of distribution is most frequently adopted in the calculations of belt-on-idler rolling resistances (Jonkers, 1980; Spaans, 1991; Lodewijks, 1996). Some publications (Jennings, 2014; Wheeler, 2006; Nordell, 1996) present load distributions in which maximum values are observed on the edges of the contact zones, but the character of the changes remains typical for a loose medium. Fig. 2b shows this type of a model distribution, which may occur in the case of a pliable belt (having limited transverse stiffness). The influence of belt interaction manifests itself in the changing load distribution as compared to the theoretical relationships shown in Fig. 2a). Due to a certain transverse belt stiffness, linear loads have a zero value on the edges of contact zones for both the center idler and the side idlers. In such case, the model distribution takes a form shown in Fig. 2c.

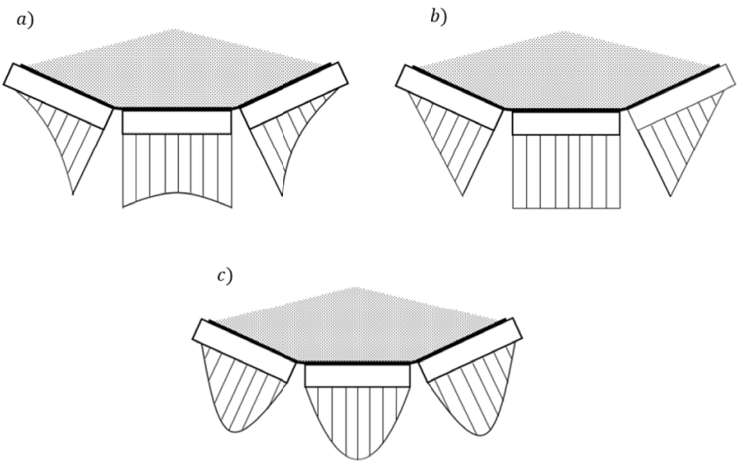


Fig. 2. Load distribution along the contact zones between the belt and the idler for a three-idler set: a) according to a theoretical model for a loose medium, b) according to models in which maximum values occur on the edges of the contact zone (Jennings, 2014), c) adjusted with laboratory measurement results (Kessler, 1986)

Each model (both for the center and the side idlers) was matched with relationships which describe load distribution along the $q_T(x)$ contact zone, so that the resultant load was always equal to the normal force acting on the idler. In the next step, relationship (2) was used to calculate the following integral:

$$F_N = \int_0^{l_k} q_T(x)^{\frac{4}{3}}\, dx \ \ [\mathrm{m}] \tag{5}$$

where:

F_N — resultant normal force on idler,
l_k — length of the contact zone between belt and idler, m.

In the case of a conveyor with correctly adjusted belt pretensioning force and with the tensioning device working properly – so that belt sag between idler sets do not exceed maximum allowable sag – belt bending geometry factor λ tends to 1 and in such case the rolling resistance equation can be simplified in the following manner:

$$W_e = C \cdot 0{,}882 \cdot \psi_{lab} \cdot \sqrt[3]{\frac{F_N{}^4}{D_K{}^2 \cdot b \cdot c_e}} \ \ [\mathrm{N}] \tag{6}$$

where:

C — constant resulting from integral (5) for the assumed load distribution $q_T(x)$, -.

Table 1 shows the influence of integration constant C on the results of the calculations of rolling resistance for a single idler, for various model normal load distributions.

TABLE 1

Selected load models and the integrations results in accordance with relationship (2)

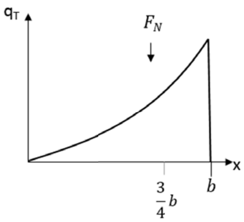
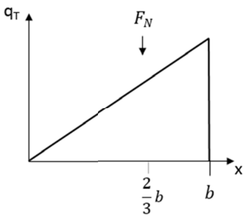
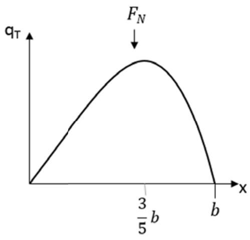
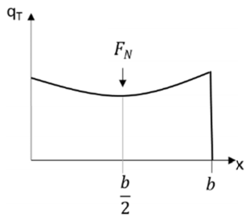
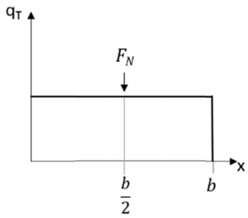
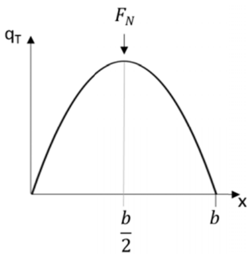
A model of interaction between belt and idler			**Predicted load distribution location**	**Integration result along the contact zone**
Graphical	**Physical**	**Mathematical**		
	Exponentially increasing distribution from 0 along length b	$q_T(x) = x^2 \cdot \frac{3F_N}{l_k^3}$	Side idler (pliable belt)	$1{,}18 \cdot \sqrt[3]{\frac{F_N{}^4}{l_k}}$
	Linearly increasing distribution from 0 along length b	$q_T(x) = x \cdot \frac{2F_N}{l_k^2}$	Side idler	$1{,}08 \cdot \sqrt[3]{\frac{F_N{}^4}{l_k}}$

TABLE 1. CONTINUED

	Parabolically increasing distribution along length *b* with zero values on the edges	$q_T(x)=\left(x^2-\frac{x^3}{b}\right)\cdot\frac{12F_N}{l_k^3}$	Side idler (stiff belt)	$1,09\cdot\sqrt[3]{\frac{F_N^4}{l_k}}$
	Distribution with maximum values on the edges	$q_T(x)=\left(3\frac{x^2}{b^2}-3\frac{x}{b}+1\right)\cdot\frac{2F_N}{l_k}$	Center idler (pliable belt)	$1,04\cdot\sqrt[3]{\frac{F_N^4}{l_k}}$
	Uniform distribution along length *b*	$q_T(x)=\frac{F_N}{l_k}$	Center idler	$1,00\cdot\sqrt[3]{\frac{F_N^4}{l_k}}$
	Parabolic distribution along length *b* with zero values on the edges	$q_T(x)=\left(\frac{x}{b}-\frac{x^2}{b^2}\right)\cdot\frac{6F_N}{b}$	Center idler (stiff belt)	$1,05\cdot\sqrt[3]{\frac{F_N^4}{b}}$

Except the model for a center idler roll with uniform load distribution, each of the analyzed models, after integrating, produced a rolling resistance equation with the constant value greater than 1. This fact implies that rolling resistance increases due to non-uniform distribution of normal loads along the contact zone of belt and idler. In the case of the side roller, where the non-uniformity of load distribution is greater than on the center idler, the rolling resistance increases by 8%-18% in relation to normal distribution (depending on the model). The increase of the rolling resistance due to non-uniform distribution of loads on the center idler is between 4% and 5%. If assumed that abrupt changes of linear loads do not occur in actual conditions and that transverse belt stiffness has an influence on the results, it seems appropriate to base the calculations of rolling resistances on constant C = 1.09 for the side roller and on C = 1.05 for the center roller. The above values have been computed for a model of load with zero values on

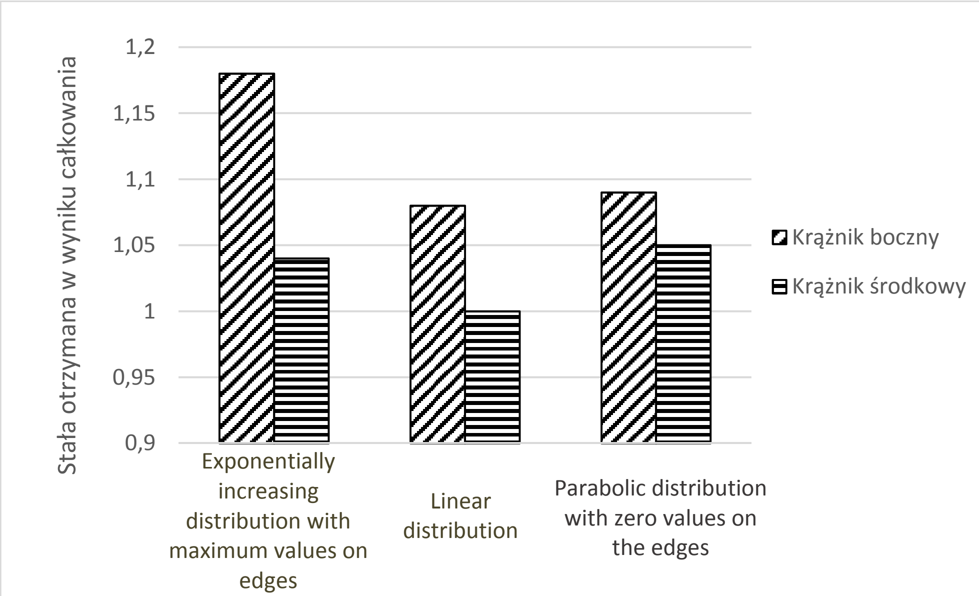


Fig. 3. Comparison of integration constants C for various load models along the contact zone between belt and side and center idler (for a three-idler set)

the edges of the contact zone. With the above assumptions, the equation describing the rolling resistance for the center idler is as follows:

$$W_e = 0{,}961 \cdot \psi_{lab} \cdot \sqrt[3]{\frac{F_N{}^4}{D_K{}^2 \cdot b \cdot c_e}} \ \text{[N]} \tag{7}$$

and for the side idler roll:

$$W_e = 0{,}926 \cdot \psi_{lab} \cdot \sqrt[3]{\frac{F_N{}^4}{D_K{}^2 \cdot b \cdot c_e}} \ \text{[N]} \tag{8}$$

3. Verification of the proposed theoretical model

Verification of the proposed calculation model was based on the measurements of rolling resistances obtained from a conveyor operated in an open cast lignite mine (Kisielewski, 2015). The measured total resistance of the idler set is mostly affected by the rolling resistance of the belt on the idlers and therefore an accurate estimation of this component is vital to achieve consistency between the calculation results and the actual measurement results. The calculations of belt-on-idler rolling resistances allowed for the laboratory-tested belt damping parameters (damping coefficient ψ_{lab}) and for different relationships in the case of the center and the side idler rollers, in accordance with the derived equations (7) and (8). As the actual measurement results included data on the total resistance on the idler set and the resultant vertical load on the idler set, it was possible to obtain a relationship between the resistance to motion of a single idler set and the mass capacity of the conveyor. Fig. 4 shows a comparison of measurement results and of calculation results.

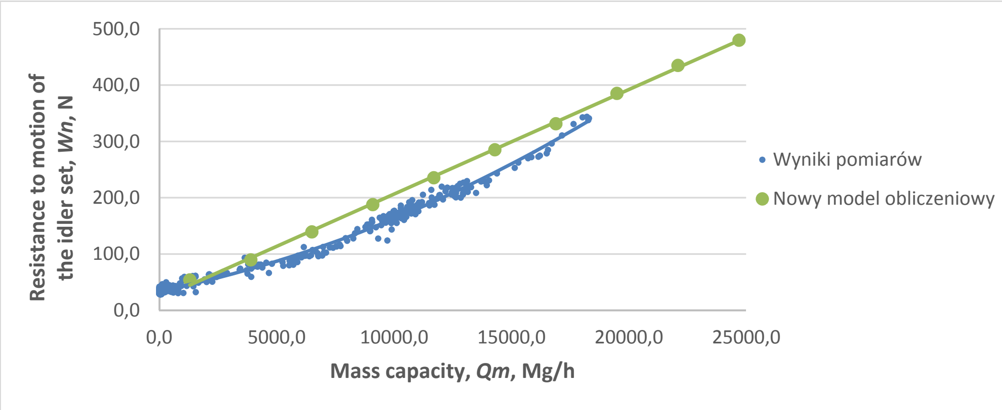


Fig. 4. Comparison of the measured and the calculated total resistance on the idler set as a function of conveyor mass capacity

4. Conclusion

1. The existing methods for calculating the rolling resistances of belt on idlers use an idler load model in which the transported material is viewed as a loose medium. Despite different load distributions along the contact zone between the belt and the center and side idlers, the analyses never covered how non-uniform normal load distribution on idlers influence the calculation accuracy for this most important component of motion resistance.

2. The analyses performed for various hypothetical load distributions along the contact zone between the belt and the idler showed that non-uniform loads effect a 9% to 18% increase in the rolling resistances on the side idler and a 4% to 5% increase on the center idler. Fragmentary laboratory tests indicate that load distribution along the idler may deviate from theoretical assumptions for loose medium model. Therefore it is important for the calculations to allow for the integration constant.

3. Due to transverse belt stiffness, the distribution of loads acting along the contact zone between the belt and the idler may be assumed to have zero boundary values and therefore calculations should be based on integration constant $C = 1.09$ for the side roller and on $C = 1.05$ for the center roller.

4. The adjusted equations describing the rolling resistances of belt on idlers allowed high consistency between calculation results and actual measurement results. The results of calculations and the results of measurements show 80% to 100% consistency.

Acknowledgements

Financial support by the project No. 0401/0048/18

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