Acta Montanistica Slovaca Volume **22** (2017), number **2**, 206-214

Experimental determination of belt conveyors artificial friction coefficient

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The primary parameter determining the value of the resistance to motion of belt conveyor is the main resistance coefficient f also referred to as the artificial or fictive friction coefficient. This coefficient is primarily used for calculating belt conveyor resistance to motion accordingly to DIN 22101, PN-93/M-46552 and ISO 5048 standards. The f coefficient also allows to pre-estimate the quality of the belt conveyor in terms of energy consumption of the belt conveyor drive. Motion resistance coefficients are determined by measuring conveyor coasting time and used as a reference for the analysis. Such measurements allow only for a general idea of the energy-consumption of conveyor drive mechanisms used in open cast lignite mine. Further, the resistance to motion values of a single idler set were used to determine main resistance coefficients for two different belt conveyors. The first conveyor served to examine the influence of idler type, belt condition and upper idler set skewing on the main resistance coefficient. The second conveyor served to examine the performance of an innovative solution that comprises idler sets that automatically adjust the trough angle in the top run. The main resistance coefficient has been shown to depend on belt loading degree.

Key words: *resistance to motion, main resistance coefficient, measurement, belt conveyor, design solutions.*

Introduction

The energy consumption level observed for main drive mechanisms of belt conveyors operated in Polish open cast lignite mines may provide information on the technological advancement level in belt conveyor transportation. Various methods of calculating the main resistance and its individual components (Wheeler, 2016; Munzenberger, 2016; Robinson, 2016; Molnár, 2014) are known. One method for estimating a belt conveyor's energy consumption level may be to measure its main resistance coefficient *f*. At PGE KWB "Bełchatów" lignite mine, nine belt conveyors were tested with the goal of establishing this coefficient. Objects selected for tests included coal and overburden conveyors, as well as stationary and mobile types. The *f* coefficient was established on the basis of the conveyor's coasting time (Sołtysik, 1999). After the drive mechanism was disconnected, the belt conveyor – subjected to the resistance to motion and optionally aided by brakes – slowed down with constant negative acceleration (deceleration). At that time, calculations were performed on the basis of a relation:

$$f = \frac{\frac{m_{zr} \cdot v_t}{t_{SW}} - H_p \cdot m_u \cdot g - W_H}{C \cdot g \cdot L \cdot \left(2 \cdot m_T + m_u + m_K + m_D\right) \cdot \cos\delta}$$

where:

g – acceleration of gravity, in *m/s*^{2}
m_{zr} – mass (reduced to translational motion) of the conveyor's all moving parts, in *kg*
v_t – belt velocity, in *m/s*
t_{SW} – measured coasting time (slowing to standstill) of the conveyor, in *s*
H_p – lift (the difference between the elevation of head station and tail station), in *m*
C – non-dimensional concentrated resistance coefficient according to standards
L – conveyor length, in *m*
m_T – unit belt mass (converted to 1 running meter), in *kg*
m_u – unit transported material mass (converted to 1 running meter), in *kg*
m_K – unit mass (converted to 1 running meter) of rotational parts in upper idlers, in *kg*
m_D – unit mass (converted to 1 running meter) of rotational parts in lower idlers, in *kg*
δ – average slope angle for the conveyor's route, in *rad* or *deg*

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W_H – force exerted by activated brakes (reduced to translational movement)

Such method for calculating the coefficient is not precise, yet it allows to compare belt conveyors having various design features. The analysis of the results presented in Table 1 shows that belt conveyors designed and constructed according to scientific and technical knowledge available in the 1970s have relatively high energy consumption levels, much higher than modern long-distance conveyors, which offer resistance to motion coefficients below 0.018. Importantly, the values of main resistance coefficient shown in Table 1 apply to the complete conveyor, both the top and bottom runs.

Tab. 1. The results of main resistance coefficient f measurements performed in PGE KWB „Bełchatów" mine.

Mobile conveyors				**Stationary conveyors**			
coal		**overburden**		**coal**		**overburden**	
Loaded with mined material	**Not loaded with mined material**	**loaded with mined material**	**Not loaded with mined material**	**Loaded with mined material**	**Not loaded with mined material**	**Loaded with mined material**	**Not loaded with mined material**
0.021÷0.030	0.015÷0.043	0.021÷0.040	0.018÷0.028	0.021÷0.024	0.021÷0.025	0.029÷0.031	0.023÷0.028

Such significant decrease of the resistance to motion in modern belt conveyors is the result of much research into new energy-efficient solutions for belts and idlers. The analysis of the components of resistance to motion in conveyor belts allows to indicate several possibilities to improve the already existing conveyors (Geesmann, 2001; Gładysiewicz et al., 2012; Król, 2013; Antoniak, 2001; Antoniak, 2003; Golka, 2007; Grimmer and Kessler, 1997; Jonkers, 1980; Lodewijks, 1995; McGaha and Santos, 1997; Sickinger and Noel, 1996; Spaans, 1991). Such task requires identifying the influence that some significant factors have on the value of the main resistance coefficient. This was achieved by measuring the resistance to motion of industrial conveyors in open cast lignite mines.

A team of researchers from the Faculty of Geoengineering, Mining and Geology at Wrocław University of Science and Technology developed an idea of determination of main resistance coefficient f on the basis of measurement of forces acting on single idler set during normal operation. The idea required special measuring frame which was developed and designed at the Wrocław University of Science and Technology. The method of determination of main resistance coefficient f with the use of measurement idler set allows determining resistance to the motion of a single idler set which allows to determine the coefficient f with known vertical load. Therefore, this method is superior to a method using coasting time. Moreover, a method using the coasting time to determine coefficient f can be affected by additional flaws caused by inaccuracy in determination of equation's components or additional resistance caused by the unreleased brake.

Plant tests of the resistance to motion

Pilot tests of the resistance to motion of an upper idler set were performed in 2010 on conveyor Z12 (B2250) in PGE KWB Bełchatów mine (Gładysiewicz et al., 2010; Gładysiewicz et al., 2011; Gładysiewicz et al., 2011). After the first tests, the measurement system was adjusted to operational requirements. The measurement method consisted in suspending the measurement idler set on force sensors with hinges, in vertical and horizontal planes. Details of the method have been provided in (Bukowski et al., 2011; Bukowski et al., 2011; Gładysiewicz et al., 2012; Król, 2013; Król et al., 2016). Over several years, the tests were performed on a special measurement frame, which was installed on the route of an overburden conveyor having the following parameters:

- conveyor length L=1200 m,
- lift H=12 m, average inclination angle 0.65°,
- belt width B=2250 mm,
- belt speed v_t =5.98 m/s,
- trough angle in the top run λ=45°
- three-idler upper set composed of ϕ194×800 mm idlers,
- upper idler set l_k = 1.2 m,
- bulk density of the transported material $\breve{a}$ = 1700 kg/m^3

The program for the first series of tests performed on conveyor Z12 (B2250) included taking measurements on the upper idler set composed of three types of idlers. First, resistance to the motion was tested on typical (standard) upper idlers, which the mine operated for many years, controlling only some of their structural parameters (radial run-out, bearing and sealing design, unbalance, etc.) These idlers, accepted as a standard type, had never been tested for rotational resistance. The standard idlers were fitted with ball bearings type 6312 with two-level film and labyrinth sealing. Laboratory tests of a group of standard idlers revealed that their rotational resistance without load is about 6 N, which is in the upper range of requirements imposed by standards. Recent research indicates that idler rotational resistance depends on radial load, and therefore average rotational resistance for the whole range of radial loads that can occur in operating conditions is an important parameter (Król, 2013; Król et al., 2015). For standard idlers, this resistance was 22.7 N. After the tests had been performed, the idlers were qualified for modernization. The modernization included improving bearing fittings and sealings as well as adjusting grease type to operating requirements (operation in low temperatures) (Król, 2013; Król et al., 2015). The modernization allowed to obtain a radically lower rotational resistance for upper idlers in the whole range of loads (11.2 N). The discussed idlers had rotational resistance without load at an average of 2.5 N. The third type of idlers comprised upper idlers with polyurethane shell, manufactured with the improved bearing and sealing technology. The measurements were performed for five separate top run supports:

- 1.2 m spacing with standard idlers
- 1.2 m spacing with modernised idlers
- 1.2 m spacing with modernised polyurethane-covered idlers
- 1.45 m spacing with modernised idlers
- 1.45 m spacing with modernised idlers and a skewed set.

One of the goals for the first series of tests was to search for optimal spacing for upper idlers and to investigate the influence of idlers on the conveyor's resistance to motion. The skewing of the upper idler set was also considered in the tests, as an indication of imprecise construction of the conveyor route (Barfoot, 1995). Figure 1 shows a scheme of an idler set skewed in relation to the longitudinal axis of the belt.

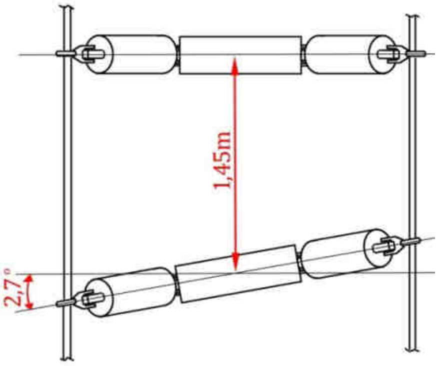

Fig. 1. A schematic representation of a skewed measurement set (Król, 2013).

Figure 2 shows the consolidated values of the main resistance coefficient as a function of belt loading for five belt support configurations. Here, the main resistance coefficient is calculated from the measurement results for the top run of the belt only.

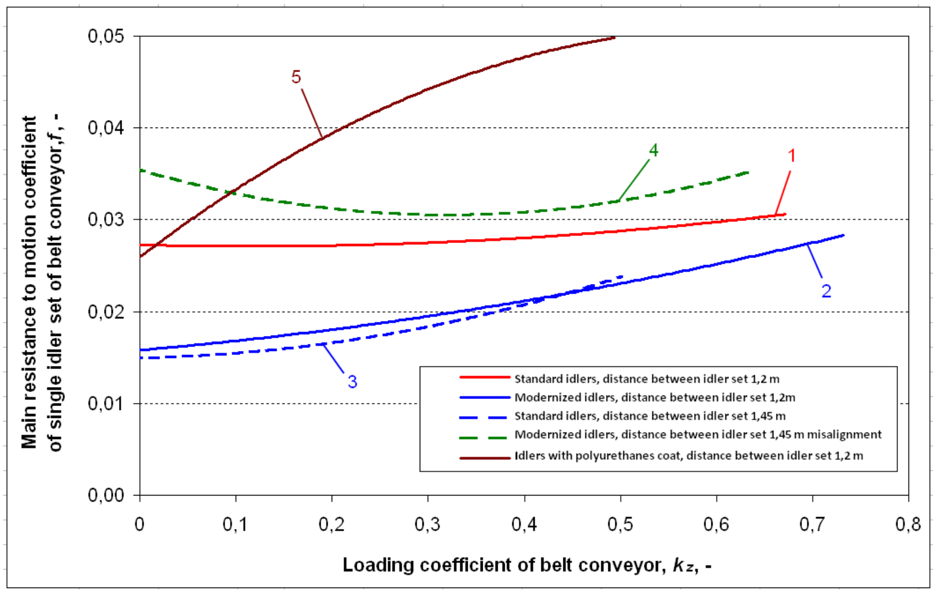

Fig. 2. Consolidated values of the idler set's main resistance coefficient as a function of belt loading for conveyor Z12 (B2250) (Kisielewski, 2016).

The analysis of the main resistance coefficient values measured for the upper idler set (Fig. 3) leads to the following conclusions:

- for standard idlers, the main resistance coefficient is in the upper range of requirements imposed by standards, above 0.026 (line 1),
- upon the installation of idlers characterised by significantly lower rotational resistance (modernised idlers), the main resistance coefficient decreases and reaches a lower range of requirements imposed by standards (lines 2 and 3),
- the skewing of the idler set causes the main resistance coefficient to rise in the whole range of belt loading, despite the usage of idlers with reduced rotational resistance (line 4),
- polyurethane-covered idlers – even though they have modernised bearing arrangements – generate the most significant resistance to motion (line 5),
- increased resistance to motion in case of the polyurethane idler set is caused by the increased rolling resistance of the belt, being the result of cyclical deformation processes of not only the pulley cover, but also idler coat (Knaul, 1997), which become more significant along with increasing idler load,
- for conveyor Z12 (B2250), the increase of the upper idler spacing from 1.2 m to 1.45 m results in a decrease in the value of the main resistance coefficient only within the range of minor loads (lines 2 and 3).

The measurements, the results of which are presented in Fig. 2, were performed in uniform operating conditions, in spring, at an ambient temperature between 15 and 19 °C. The conveyor was equipped with a standard St 3150 belt with the parameters shown in Table 1.

The next series of tests for conveyor Z12 (B2250) was performed on a special loop composed of 11 sections with different belt types (Table 2). The tested belts included three sections with the same type of energy-efficient belt: C1, C2 and C3. As the three belt sections varied only in thickness and as the range of variation was limited (between 28.2 and 29.1 mm), for the sake of further analysis they were considered as one type, labelled with symbol C (Fig. 3). All belt sections used in the conveyor loop had similar design parameters and varied mostly in respect of the rubber compound used in the covers. The comparison was performed with a standard St 3150 belt as a reference sample. The belts moving on the test set were identified using magnetic splice recognition system (Bukowski et al., 2011; Gładysiewicz and Kisielewski, 2014; Gładysiewicz et al., 2013).

Tab. 2. Parameters of the tested belt types (Gładysiewicz et al., 2012)

	Standard belt A			**Energy saving belt B**					**Energy saving belt C**
	Regenerated					**Regenerated**			
Belt designation	**A**	**AR**	**AR2W**	**B1**	**B2**	**BR**	**BR2W**	**B2W**	**C**
Length of belt sections [m]	240.3	239.6	247.6	125.1	126.6	241.3	240.6	235.7	748.3
Belt width [mm]	2235	2250	2250	2241	2245	2250	2250	225	2253
Belt thickness [mm]	27.7	29.6	29.6	28.7	28.4	29.6	29.6	27.8	28.2
Thickness of carrying side cover [mm]	13.3	14.0	14	14.0	13.8	14.0	14.0	13.1	14.0
Thickness of pulley side cover [mm]	6.8	7.0	8.0	7.0	7.0	8.0	8.0	7.1	7.0
Cable diameter [mm]	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.5
Cable number	146	146	146	146	146	146	146	146	144
Cable pitch	-	-	-	14.9	15.2	-	-	14.9	15
Abrasion [mm^3]	100	131	138	78/84	72/86	145/85	121/83	73	89/56
Shore hardness [^{0}ShA]	70	72	65	63/60	64/58	74/70	69/69	65	61/61

Fig. 3 shows a comparison of main resistance coefficient *f* measured for various belt types in an ambient temperature of 10 °C. Symbol A designates the standard belt type St 3150, commonly used in Polish open cast lignite mines. Symbols C, B1 and B2 designate belts of the same strength class, but with covers made of a special rubber compound characterised by low damping, used to decrease the rolling resistance of the belt moving on the idlers (energy-saving belts). Symbol W is used to designate the usage of special covers with reinforcements that increase the belt's rip resistance, while symbol R designates regenerated belts (Tab. 2).

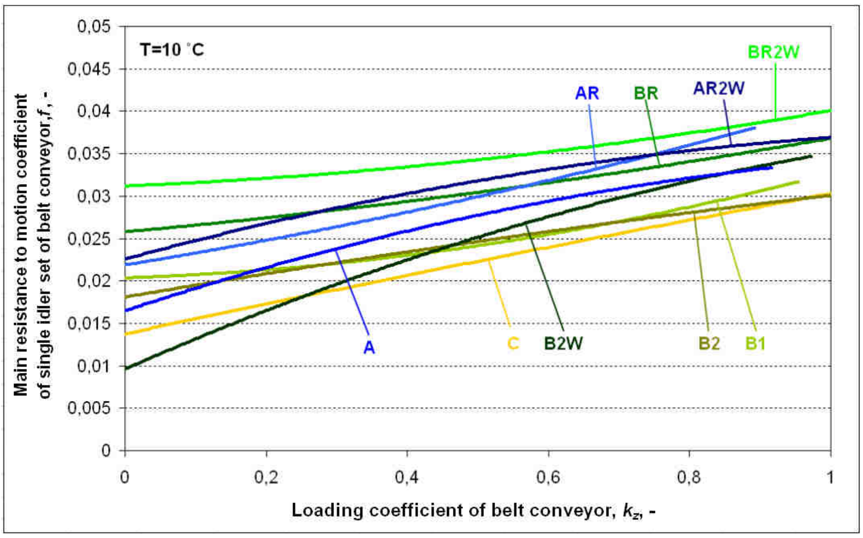

Fig. 3. Comparison of the idler set's main resistance coefficient for various belt types as a function of belt loading, with an ambient temperature of 10 °C and for conveyor no. Z12 (B2250) (Kisielewski, 2016).

The comparison of the results of the experiment performed for conveyor Z12 (B2250) in PGE KWB Bełchatów allows for the following observations:

Within the range of belt loading k_z= 0.2÷0.4, the main resistance coefficient for the tested belts has minimal values, the lowest resistance to motion is observed for energy-saving belts C, B1 and B2. Within the whole range of the investigated efficiencies and regardless of the ambient temperature, the highest resistance to motion is observed for regenerated belts.

Further motion resistance tests were performed on belt conveyor Gbf 50 (B2000) used for overburden transportation at Mibrag, a German open cast lignite mine. Below are the conveyor's parameters:

- conveyor length L=625 m,
- conveyor width B=2000 mm,
- max. capacity Q_m=16 000 t/h,
- drive power N_o=2×900 kW,
- belt speed v_t=6.53 m/s,
- trough angle in the top run λ_g=33° (in standard version)
- trough angle in the bottom run λ_d=12°,
- belt type St 2500/14:8,
- upper three-idler set composed of ϕ159 ×840 mm side rolls and of a shorter (ϕ159 ×420 mm) centre roll
- upper set spacing l_k=2.5 m,
- lower set spacing l_d=5 m,
- bulk density of the transported material γ = 1800÷2000 kg/m^3.

The conveyor was tested using the same methodology for the resistance to motion tests of a single upper idler set as in the case of Z12 (B2250) conveyor in PGE KWB Bełchatów. For this purpose, a special measurement frame was designed and built (Fig. 4). Simultaneous recording of momentary vertical and horizontal loads on the measurement set allowed, among other things, to analyse the measurement results in a coordinate system: main resistance coefficient f as a function of belt loading coefficient k_z.

Fig. 4. View of the measurement frame mounted on conveyor Gbf 50 (B2000).

Conveyor Gbf 50 (B2000) was different from conveyor Z12 (B2250) not only because of different belt width and type, but most importantly because of a different top run support system. While Z12 (B2250) had top three-idler sets of uniform shell length, Gbf 50 (B2000) had idler sets with shorter centre roll (Fig. 5) and 2.5 m spacing. Moreover, conveyor Gbf 50 (B2000) was tested for two various upper run support systems. The first system was a typical support with hinged sets. The other system involved spring suspension of upper idler sets, which allowed for automatic trough angle modification under the load of the transported material. The sets were called “intelligent sets” and were used to lower the motion resistance of both an empty belt and of a belt minimally loaded with run-of-mine material. The idea of the so-called “intelligent sets” was discussed in more detail in (Schwandtke and Gładysiewicz, 2008).

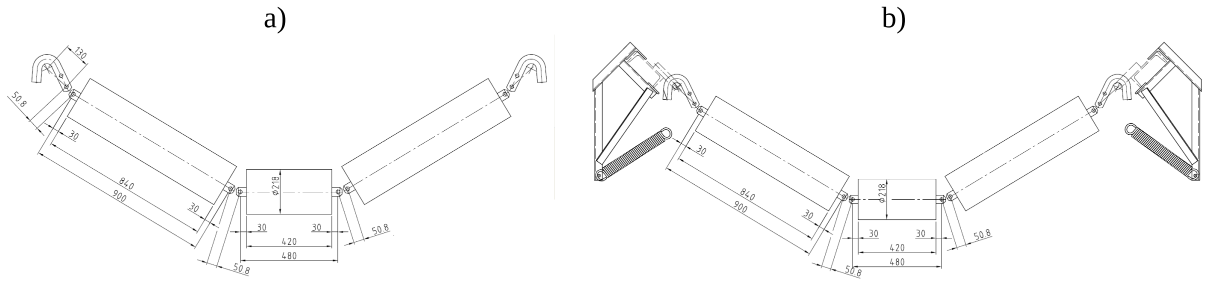

Fig. 5. Idler set in conveyor Gbf 50 (B2000) [technical documentation of the belt conveyor]:

a) typical version

b) with springs that adjust the trough angle depending on belt load degree “intelligent” set (Schwandtke and Gładysiewicz, 2008).

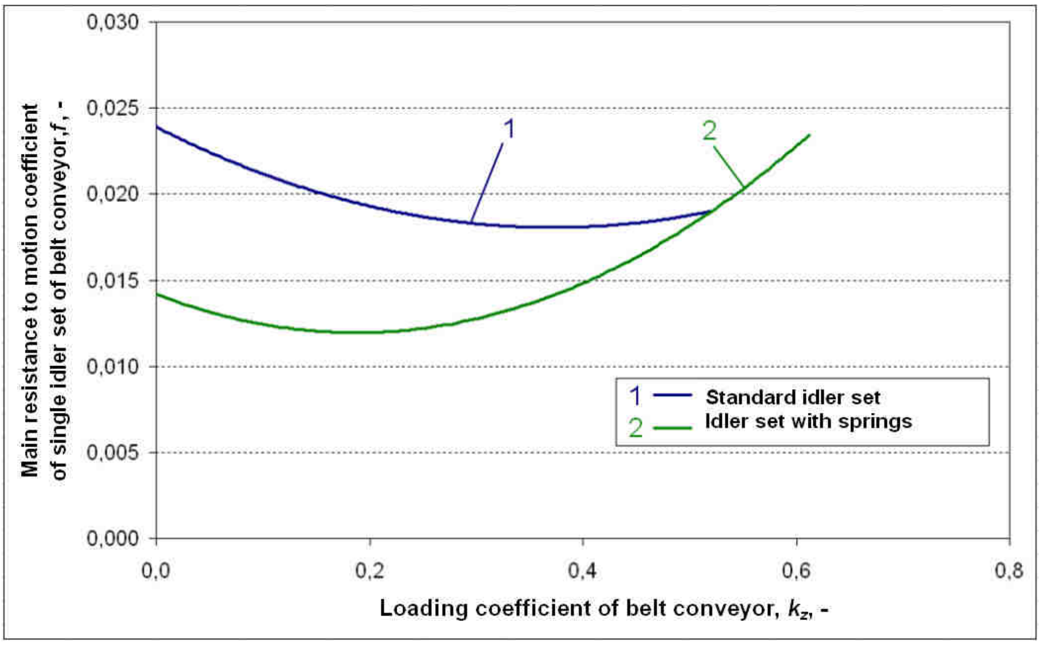

Fig. 6. Consolidated values of the idler set’s main resistance coefficient as a function of belt loading for the conventionally suspended set and the set suspended on springs, conveyor Gbf 50 (B2000) (Kisielewski, 2016).

Sets that are able to automatically adjust the trough angle to the load from the carried material have a significantly lower main resistance coefficient than conventional hinged sets, albeit only for low belt loading value range (for k_z = 0÷ 0.5). A significant percentage of the operating time of conveyors used in open cast mines and fed with run-of-mine material from a bucket ladder excavator is observed to be within such low load range (Dworczyńska, 2012; Dworczyńska et al., 2012) and hence in such case “intelligent” sets considerably decrease the energy consumption level for conveyor drive mechanisms. For “intelligent” sets, the main resistance coefficient reaches its minimum value f=0.012 at about 20 % load while for conventional conveyors minimum value f=0.018 is reached at about 40 % load. The measurement results shown in Fig. 6 were obtained at an ambient temperature of about 20°C.

Conclusions

The tests allowed for the comparison of the idler set main resistance coefficient as a function of belt loading, for various conveyor designs. Fig. 7 shows the consolidated, experimentally determined relationships. The graph shows the different influence that belt load degree has on the value of the main resistance coefficient. The analysis should not cover the two lines that are positioned in the upper range of the motion resistance coefficient (lines 1 and 4). Line 4 was determined for an "artificially" devised skewing of the idler set in relation to the belt's longitudinal axis, and it should be only treated as an example illustrating the consequences of imprecise belt conveyor construction.

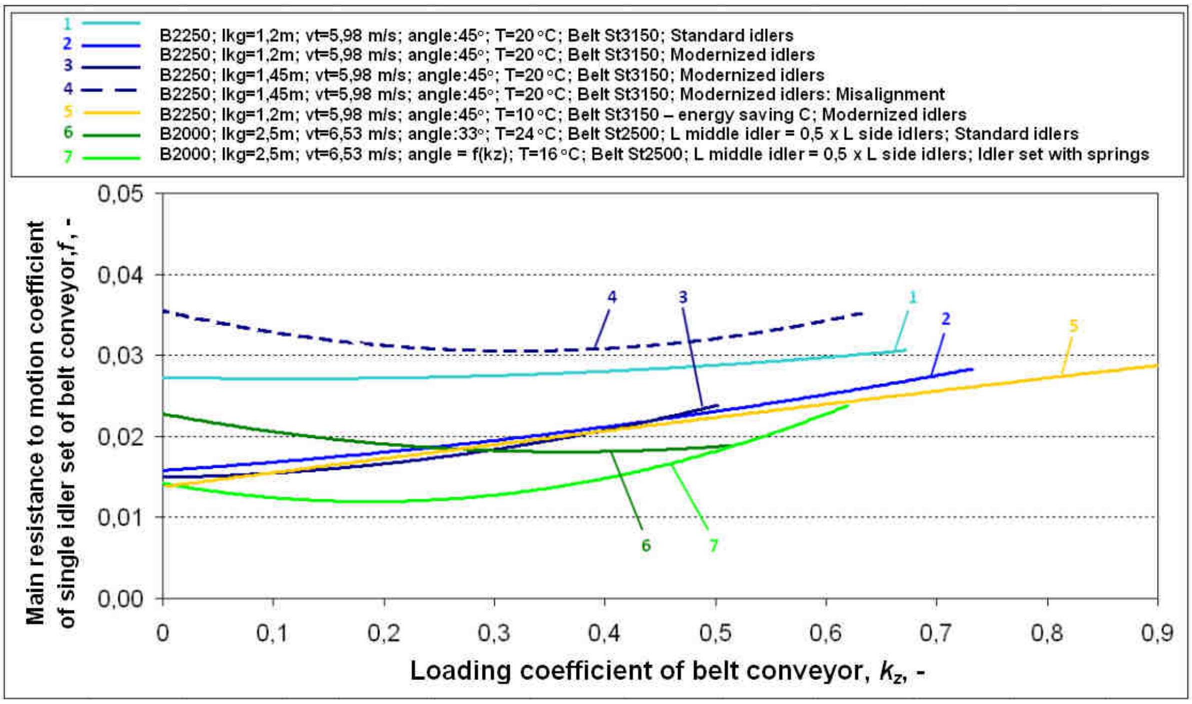

Fig. 7. Consolidated values of the idler set main resistance coefficients determined for a single idler set as a function of belt loading, for conveyors Z12 (B2250) and Gbf 50 (B2000) (Kisielewski, 2016).

Skewed sets might occur on the conveyor's route, but not commonly and with a smaller skewing angle. Line 1 describes a conveyor with idlers whose rotational resistance is above standard values. Such situation is another example of how increased resistance to motion is caused by a lack of information on the influence of idler condition on the energy-consumption of conveyor drive mechanism. The remaining lines in Fig. 7 show the changes of the main resistance coefficient as being within the variation range recognised and recommended by standards (DIN 22101, PN-93/M-46552, ISO 5048). The lowest motion resistance coefficients for belts loaded with the run-of-mine material were recorded for the conveyor operated in German open cast lignite mine Mibrag (Gbf 50 B2000 - lines 6 and 7). This conveyor is different from the Polish design so that its belt is supported in the top run by idler sets with the centre roll shorter than the side rolls. Such design increases the stiffness of the troughed belt, which allows for greater idler spacing in the top run – up to 2.5 m, and in consequence, lowers the resistance to motion. The implementation of idler sets that automatically adjust the trough angle (the so-called intelligent sets – line 7) additionally minimises the resistance to motion. No effects were observed for conveyor Z12 (B2250) that would significantly reduce resistance to motion at increased idler spacing, as increasing idler spacing from 1.2 to 1.45 m – with belt stiffness greater than in case of conveyor Gbf 50 (B2000) and with top idler rolls being each of the same length – results in increased belt sag and hence in increased flexure resistance of the belt and of the bulk solids transported on the conveyor. A comparatively low main resistance coefficient was recorded (line 5) for the energy-saving belt installed on conveyor Z12 (B2250), and that was despite performing the measurements in ambient temperature lower than for other belts installed on conveyor Z12. Additionally, the belt's loading degree does not cause its main resistance coefficient values to grow as significantly as in case of other configurations. The analyses and measurements show operational directions seeking energy saving solutions. Conducted research directions are consistent with other studies in the world (Lodewijks, 2011; Hanger and Hintz, 1993; Hintz, 1993).

Summary

1. The developed method of experimental investigation of the resistance to motion of a single idler set allows determining the main resistance coefficient *f* with by higher accuracy than the previous method which uses coasting time. Moreover, developed method has enabled to enhance the knowledge about the idlers' rotational resistance and the impact of operational loadings on the resistances to the motion of a belt conveyor.
2. The recorded main resistance coefficient values are within the broad range of variation limits recommended in DIN 22101, PN-93/M-46552 and ISO 5048 standards. The variation range *f* is between 0.012 and 0.035, but it applies only to atmospheric temperatures (ambient operating temperatures) that do not fall below 0 °C.
3. The resistance to motion coefficient is not a value constant for belt conveyors, but primarily depends on belt loading. For empty belts, the coefficient has values within the upper standard range. With average belt loading, the coefficient values are minimal and rise with maximum loading. The character of the changes has been already pointed to in literature.
4. A significant increase in the resistance to motion of a belt conveyor, and hence an increase of the main resistance coefficient *f* can be observed when the conveyor route is assembled with little precision (idler skewing in relation to belt axis) and when the idlers are in poor technical condition and show increased resistance to motion.
5. Idlers with polyurethane shell generate significantly greater resistance to motion that steel-coated idlers.
6. Analysis of the measurements of motion resistance coefficient suggests the following solutions to energy-saving belt transportation:
   - using belts with carrying cover that lowers rolling resistance (energy-saving belts),
   - using good quality idlers with low rotational resistance,
   - using upper idler sets with shorter centre idler roll and increased upper idler spacing,
   - using upper idler sets that automatically adjust the trough angle (intelligent sets).

***Acknowledgement**: This paper was financially supported partly by the Polish Ministry of Science and Higher Education as scientific project No 0401/0166/16.*

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