ГОРНАЯ МЕХАНИКА. ГОРНЫЕ МАШИНЫ И ТРАНСПОРТ

DOI: 10.21440/0536-1028-2021-4-57-63

Physical modeling of a skip pneumatic winder

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Abstract
Introduction. *The analytical phase of research on mine skip pneumatic winders has been passed, so the theoretical provisions have to be tested by the methods of physical modeling which is aimed at confirming the mathematical model adequacy and assessing the effectiveness of different types of sealing devices.*
Research methods. *Physical modeling phases have been formulated, including modeling by geometric and aerodynamic similarity criteria, constructing aerodynamic characteristics of the installation, carrying out experiments with non-contacting and combined seals, and calculating the values of the installation volumetric efficiency based on the experimental data obtained.*
Research results. *The lifting time of the skip model with different masses of material and seal types has been determined. The installation working points in the "flow rate–pressure" coordinate system have been identified, and the values of the volumetric efficiency have been calculated for each working point.*
Analysis of the results. *A satisfactory convergence of calculated and experimental parameters of the physical model has been established. The model's volumetric efficiency has reached a technically acceptable level. The expected value of the experimental model's volumetric efficiency has been calculated according to the similarity constants.*
Conclusions. *The model's study revealed the convergence of the experimentally obtained volumetric efficiency of the model with its calculated values and proved the applicability of the mathematical model to experimental sample parameters calculation. The volumetric efficiency of the installation with both non-contacting and combined seals is quite high allowing to recommend the studied sealing devices for mine pneumatic winders.*

Keywords: *mine pneumatic lift; skip; experimental model; physical model; seal; leakage; volumetric efficiency.*

Introduction. Possible designs of skip pneumatic winders have been theoretically studied since 2016. Over the past period, the prospects of their application have been substantiated, the features of the vessel kinematics and dynamics have been analyzed, thermodynamic processes in the winding pipeline have been considered. It has been shown that the skip pneumatic winder (SPW) has significant advantages compared to the cable one [1–3]. Work on SPW has currently reached the phase of physical modeling. The mathematical model is almost completely described by the obtained theoretical dependencies. However, to confirm its adequacy, it is important to carry out experiments with the physical model since they make it possible to check the effectiveness of design solutions accepted at the design stage.

An SPW designer is to face a serious issue of choosing a method of eliminating or limiting the air leakage through the gap between the skip and the pipeline wall. Under otherwise equal conditions, the power consumption of the power unit (pumping station) depends on the performance of the seal. There are various types of seals [4], each of which has advantages and disadvantages compared to the others. Physical modeling makes it possible to test the effectiveness of a particular sealing agent in practice. In the class of non-contacting seals, the simplest and most durable labyrinth [4, 5] is of great interest. The applicability of the labyrinth is due to the strict limitation of the medium leakage through the guaranteed gap. Of the contact seals, the circlip (piston ring) is preferable because its manufacture and replacement are rather simple [6–8].

The tasks of SPW physical modeling in this phase of development are as follows:

– to confirm the applicability of the mathematical model to SPW experimental model (hereinafter referred to as the model) parameters calculation;

– to establish the usefulness of the labyrinth and circlips in the sample.

Research methods. Physical modeling includes a number of sequential steps:

– formulating the conditions of a physical model similarity to the sample;

– producing a physical model in accordance with the similarity conditions;

– identifying the control parameters obtained from the physical model tests;

– evaluating test results.

The physical model (FM) is adequate to the sample in case of geometric similarity and equality of aerodynamic and thermodynamic criteria between them [9]. The steady motion of the skip model is considered, therefore, time similarity is ensured.

Similarity conditions for aerodynamic criteria are the same as for fan units [10]. Similar to fans, at low Mach numbers ($M \leq 0.6$), the influence of the Reynolds number is neglected, and the flow rate is taken as the main and only determining criterion for similarity.

The differences between the physical processes in the model and the fan unit are:

– a higher difference (drop) of static pressure under and above the skip and the associated change in air density;

– complex physics of processes in the lift line significantly affecting air physical properties [11–13].

Taking into account the fact that in this phase of development it is impossible to simulate thermodynamic processes, it was decided to limit ourselves to tests under the conditions of the SPW discharge pipeline, where the temperature drops are minor, and their effect on aerodynamics can be neglected. According to preliminary calculations, the static pressure drop here does not exceed 0.1 bar (10 kPa), which makes it possible to roughly consider air as an incompressible medium with a constant density.

Research results. Geometric similarity and previously accepted assumptions make it possible to obtain a set of dimensionless constants:

$$\begin{cases} k_L = \dfrac{D_{\text{sample}}}{D_{\text{model}}}; \\ k_Q = \dfrac{Q_{\text{sample}}}{Q_{\text{model}}} = k_L^3; \\ k_m = \dfrac{m_{\text{sample}}}{m_{\text{model}}} = k_L^3; \\ k_p = \dfrac{p_{s\ \text{sample}}}{p_{s\ \text{model}}} = k_L, \end{cases} \tag{1}$$

where k_L is the geometric similarity constant; k_Q is the cost similarity constant; k_m is the skip masses similarity constant; k_p is the static pressure drop similarity constant; D is the internal diameter of the pipeline; Q the flow rate under the skip; m is the skip mass; p_s is the static pressure drop; “sample” index is the sample parameter; and “model” index is the model parameter.

Special attention is paid to the issue of the labyrinth local resistance coefficient ζ impact on the value of SPW volumetric efficiency η_{vol}.

The volumetric efficiency similarity constant k_η is determined from the formula

$$k_\eta = \frac{\eta_{\text{vol.sample}}}{\eta_{\text{vol.model}}} = \frac{\left(Q_{\text{sample}} - \Delta Q_{\text{sample}}\right) Q_{\text{model}}}{\left(Q_{\text{model}} - \Delta Q_{\text{model}}\right) Q_{\text{sample}}}, \tag{2}$$

where ΔQ is the leakage through the gap in the labyrinth.

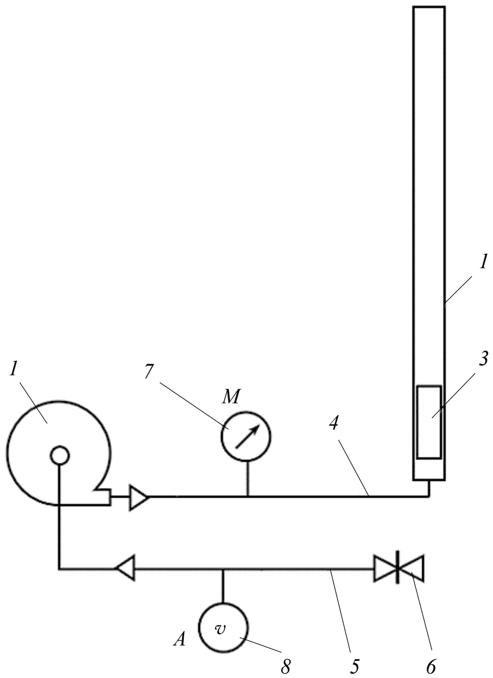

Fig. 1. Circuit diagram of the physical model of the installation
Рис. 1. Схема физической модели установки

There are two ways of finding k_η. The first is based on the acceptance of the equality of the model's and sample's efficiency, i.e. $\eta_{\text{vol.sample}} = \eta_{\text{vol.model}}$. In this case, $k_\eta = 1$; and with the help of the provisions of the mechanics of liquid and gas [14], formula (2) is transformed into the equation:

$$\sqrt{\frac{p_{s\ \text{sample}}}{\zeta_{\text{sample}}}} D_{\text{sample}} \delta_{\text{sample}} = \sqrt{\frac{p_{s\ \text{model}}}{\zeta_{\text{model}}}} D_{\text{model}} \delta_{\text{model}} k_Q, \tag{3}$$

where δ is the gap in the labyrinth.

From equation (3), in turn, the similarity constant of the local resistance coefficient is obtained:

$$k_\zeta = \frac{\zeta_{\text{sample}}}{\zeta_{\text{model}}} = \frac{p_{s\ \text{sample}} D^2_{\text{sample}} \delta^2_{\text{sample}}}{p_{s\ \text{model}} D^2_{\text{model}} \delta^2_{\text{model}} k_Q^2} = \frac{k_p k_L^4}{k_Q^2} = \frac{1}{k_L}. \tag{4}$$

According to the second variant, the local resistance coefficients of the sample and FM are equal: $\zeta_{\text{sample}} = \zeta_{\text{model}} = \zeta$. Then expression (2) takes the following form:

$$k_\eta = \frac{Q_{\text{sample}} - \sqrt{\dfrac{2p_{\text{sample}}}{\rho\zeta}}\pi D_{\text{sample}}\delta_{\text{sample}}}{Q_{\text{sample}} - \sqrt{\dfrac{2p_{\text{sample}}}{\rho k_p \zeta}}\pi \dfrac{D_{\text{sample}}\delta_{\text{sample}}}{k_L^2}k_Q}. \qquad (5)$$

Since in this version, $k_\eta = f(Q_{\text{sample}}, p_{\text{sample}}) \neq \text{const}$, then k_η cannot serve as a similarity constant.

A sufficiently high $\eta_{\text{vol.sample}}$ determines the value of the coefficient $\zeta_{\text{sample}} \approx 10$. The geometric similarity constant adopted for physical modeling is $k_L = 10$. According to the first variant, the equality $k_\eta = 1$ can be obtained under $\zeta_{\text{model}} \approx 100$ (4), which is technologically very difficult. Therefore, in FM, the second option is realized, as a result of which $\eta_{\text{vol.model}} < \eta_{\text{vol.sample}}$ (5).

Similarity constants are implemented in the FM design (1).

The FM circuit diagram is shown in fig. 1. Designations: *1* – blower; *2* – lift line (hereinafter – pipeline); *3* – skip; *4* – delivery pipe; *5* – inlet (measuring) air duct; *6* – gate valve; *7* – manometer (*M*), *8* – anemometer (*A*).

Vortex blower MT 03-M1C-230 *Erstevak* provides flow rate up to 80 m^3/h and pressure up to 110 mbar. Excess static pressure is measured with a *b.Well* manometer, the flow rate is recorded with a *Testo 416* vane anemometer, and skip lifting time is recorded by an electronic stopwatch "Integral S-01". The lift line is made up of sections of polypropylene pipes with a diameter of 110 x 2.4 mm and a length of 1 m each. The number of sections varies from one to six.

Blower *1*, delivery pipe *4*, inlet air duct *5*, the lower section of the pipeline *2*, and the measuring instruments form the pumping station.

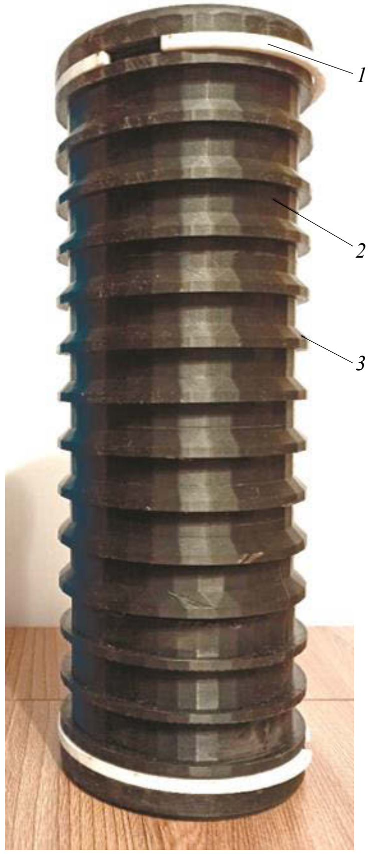

Fig. 2. Skip model
Рис. 2. Модель скипа

A sketch of the skip model is shown in fig. 2. Skip body *2* is a 3D printed capsule made of *ABS* thermoplastic (fig. 2). In the end sections of the body, grooves *1* with a width of 5±0.2 mm are made for installing circlips *1*. Edges *3*, together with the inner faces of the end sections, form 13 labyrinth chambers. The calculated coefficient ζ_c of local resistance created by the labyrinth is 11 [5].

Circlips with a cross section of 5 x 5 mm are also 3D printed from *ABS* thermoplastic.

The first stage of FM testing was installation aerodynamic characteristics measurement, the diagram of which is shown in fig. 1 in the form of a functional dependence $p_{\text{s model}}$ (Q_{model}). This task was performed in accordance with the standard methods (*GOST 10921 - 2017. Radial and axial fans. Methods of aerodynamic tests*).

The aerodynamic characteristics (hereinafter referred to as the characteristics) is curve *1* in fig. 3. For the convenience of analytical calculations, it is approximated with a high accuracy by a linear dependence (line *2* in fig. 3).

The second stage was to lift a skip with a variable load weight and record the lifting time.

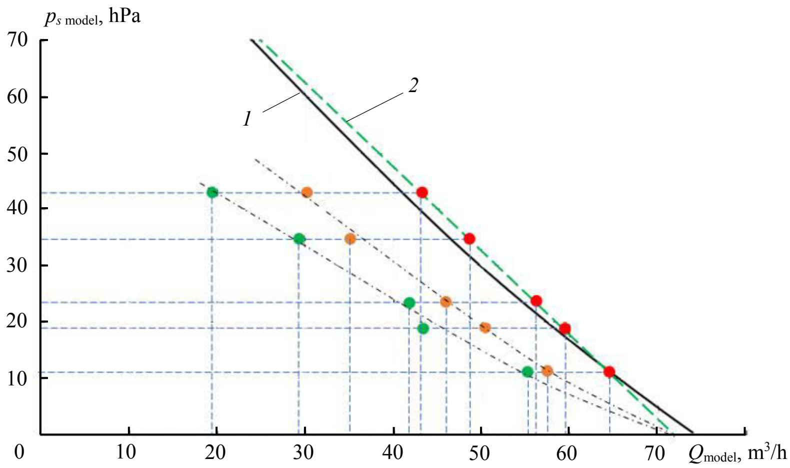

Fig. 3. The results of experimenting with the physical model:
1 – installation characteristics; *2* – characteristics approximation
Рис. 3. Результаты экспериментов с физической моделью:
1 – характеристика установки; *2* – аппроксимация характеристики

The masses m_{model}, kg, of the skip made up a series: 1.0; 1.7; 2.0; 3.0; 3.7. For each mass, a series of five lifts with a non-contacting seal in the form of a labyrinth and five lifts with a combined seal in the form of circlips and a labyrinth was performed. Aerodynamic and mechanical resistance to the skip movement was considered insignificant, which made it possible to find $p_{s\ model}$, N, analytically using the formula

$$p_{s\ model} = \frac{4m_{model}g}{\pi D^2_{c\ model}}, \quad (6)$$

where g is the gravitational acceleration, $g = 9.81$ m/s^2; $D_{c\ model}$ is the outer diameter of edges *3*, $D_{c\ model} = 0.104$ m.

The results of measurements and calculations of working points in experiments on the FM with a hoist height $H = 4$ m are presented in table 1, 2 and in fig. 3.

The $p_{s\ model}$ values calculated by formula (6) made it possible to find the corresponding values of the blower performance Q_{model} from the characteristics of the installation. Using the measured duration of the hoist $t_{h.model}$ under the steady motion, the values of the speed v_{model} of the skip were determined for the corresponding values of $p_{s\ model}$.

Then, using the expression

$$Q_{h.model} = \frac{3600\pi D^2_{c\ model} v_{model}}{4} \approx 2830 D^2_{c\ model} v_{model}$$

useful actual air flow rates, m³/h, were found corresponding to each mass of the skip from the series, and the values of the installation actual volumetric efficiency were calculated:

$$\eta^{(a)}_{\text{vol.model}} = \frac{Q_{\text{h.model}}}{Q_{\text{model}}}.$$

Table 1. Experimental results (labyrinth seal)
Таблица 1. Результаты экспериментов (уплотнение лабиринтное)

Parameter	Skip mass m, kg				
	1.00	1.67	2.03	3.00	3.70
$p_{s\ \text{model}}$, hPa	11.5	19.3	23.4	34.6	42.7
$t_{\text{h.model}}$, s	2.16	2.71	2.78	4.02	5.93
v_{model}, m³/s	1.80	1.42	1.37	0.94	0.63
$Q_{\text{h.model}}$, m³/h	55.2	43.5	41.9	28.8	19.3
Q_{model}, m³/h	64.2	59.9	56.2	48.6	43.2
$\eta^{(a)}_{\text{vol.model}}$	0.86	0.73	0.75	0.59	0.45
$\eta^{(c)}_{\text{vol.model}}$	0.80	0.73	0.68	0.55	0.44
$\delta\eta_{\text{vol.model}}$, %	+7.5	0	+10.3	+7.3	+2.3

Index (a) – actual, index (c) – calculated (theoretical).

Taking into account the coefficient ζ_c, the leakage ΔQ_{model}, m³/h, through the labyrinth gap was determined for each value of $p_{s\ \text{model}}$:

$$\Delta Q_{\text{model}} = 3600 F_{0\ \text{model}} \sqrt{\frac{2 p_{s\ \text{model}}}{\rho \zeta_c}},$$

where $F_{0\ \text{model}}$ is the area of the gap in the labyrinth, $F_{0\ \text{model}} = 2.63 \cdot 10^{-4}$ m²; ρ is the air density, ρ = 1.2 kg/m³. After that, the calculated (theoretical) volumetric efficiency $\eta^{(c)}_{\text{vol.model}}$ of the installation was calculated:

$$\eta^{(c)}_{\text{vol.model}} = 1 - \frac{\Delta Q_{\text{model}}}{Q_{\text{model}}}.$$

Comparison of $\eta^{(a)}_{\text{vol.model}}$ and the corresponding $\eta^{(c)}_{\text{vol.model}}$ (table 1) gives an idea of the mathematical model adequacy. It can be seen that the actual efficiency is not lower than the calculated one. The relative deviation of $\eta^{(a)}_{\text{vol.model}}$ from $\eta^{(c)}_{\text{vol.model}}$ ($\delta\eta_{\text{vol.model}}$ in table 1) is in the range of 0–10.3%.

The circlips, as expected, significantly improved seal performance (table 2, fig. 3). The lifting speed of the skip, effective air flow and volumetric efficiency of the unit have increased. The leakage is caused by the loose fit of the circlips to the inner wall of the pipeline due to inaccuracies in the shape of its cross-section.

Based on the similarity constants, $\eta_{\text{vol.sample}}$ was calculated for labyrinth and combined seals under a pressure in the discharge pipeline $p_{s\ \text{sample}} = 10$ kPa and different values of the productivity Q_{sample} of the pumpling station. The calculation results are summarized in table 3 and illustrated by the graphs in fig. 4.

To reduce the power consumption of SPW, it is advisable to limit $\eta_{vol.sample}$ to a sufficiently high value. Let the minimum allowable volumetric efficiency $[\eta_{vol}] = 0.95$. The combined seal ensures the fulfillment of the condition $\eta_{vol.sample} \geq [\eta_{vol}]$ for $Q_{sample} \geq 11.5$ m³/s, and the labyrinth – for $Q_{sample} \geq 20$ m³/s.

Table 2. Experimental results (combined seal)
Таблица 2. Результаты экспериментов (уплотнение комбинированное)

Parameter	Skip mass *m*, kg				
	1.00	1.67	2.03	3.00	3.70
$p_{s\ model}$, hPa	11.5	19.3	23.4	34.6	42.7
$t_{h.model}$, s	2.08	2.35	2.54	3.28	3.75
v_{model}, m³/s	1.87	1.64	1.50	1.15	1.00
$Q_{h.model}$, m³/h	57.2	50.1	45.8	35.1	30.5
Q_{model}, m³/h	64.2	59.9	56.2	48.6	43.2
$\eta^{(a)}_{vol.model}$	0.89	0.83	0.81	0.72	0.71

Analysis of the results. When evaluating the experimental results, the features of physical processes in FM should be taken into account. The specificity of aerodynamic phenomena consists in multiple factors influencing the nature of a gaseous medium flow. Therefore, all analytical calculations are of an approximate nature. In addition,

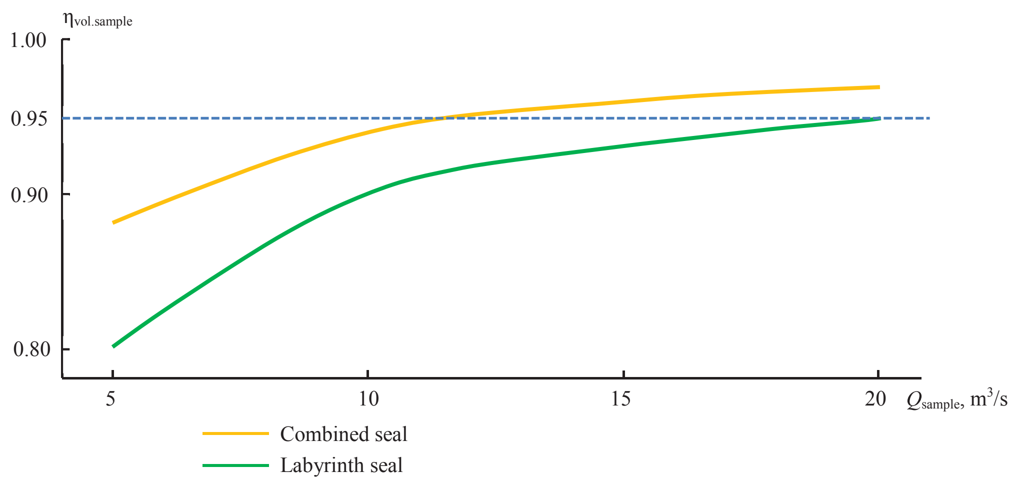

Fig. 4. Dependence between the sample volumetric efficiency on the flow rate
Рис. 4. Зависимость объемного КПД образца от расхода

scaling in terms of similarity, which theoretically ensures the adequacy of the model to the sample, inevitably introduces its own errors in practice. The cumulative influence of these factors results in a discrepancy between the results of physical experiments and the forecast based on theory.

Considering the above, the results of modeling should be considered quite satisfactory, as reflected in table 1 and fig. 3. The actual values of the model volumetric efficiency correspond to the calculated ones with an accuracy adequate for aerodynamics.

The excess of $\eta^{(a)}_{vol.model}$ over $\eta^{(c)}_{vol.model}$ is explained by the fact that the labyrinth seal implemented in the model has a greater aerodynamic resistance as compared to the calculated one.

Table 3. Calculated values $\eta_{vol.sample}$ under $p_{s\ sample}$ = 10 kPa
Таблица 3. Расчетные значения $\eta_{vol.sample}$ при $p_{s\ sample}$ = 10 кПа

Seal type	Productivity Q_{sample}, m^3/s			
	5	10	15	20
Labyrinth	0.80	0.90	0.93	0.95
Combined	0.88	0.94	0.96	0.97

The use of circlips in the seal significantly reduced leakage (table 2, fig. 3). Leakage through the combination seal is due to the pipe cross-section shape error.

Conclusions. The tasks set for SPW physical modeling have been fulfilled. The model study results are as follows.

The convergence of the experimentally obtained volumetric efficiency of the model with their calculated values proved the applicability of SPW mathematical model to calculate the experimental sample.

The volumetric efficiency values of the installation both with a non-contacting seal in the form of a labyrinth and with a combined seal with circlips as a contact component make it possible to consider devices of both types as promising in terms of SPW use.

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Received 23 March 2021

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УДК 622.678.5 DOI: 10.21440/0536-1028-2021-4-64-73

Физическое моделирование скиповой пневмоподъемной установки

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Реферат

Введение. *Работа над шахтными скиповыми пневмоподъемными установками прошла стадию аналитических исследований. Возникла необходимость проверки теоретических положений методами физического моделирования, задачи которого состоят в подтверждении адекватности математической модели и в оценке эффективности различных типов уплотняющих устройств.*
Методика проведения исследования. *Сформулированы этапы физического моделирования, в том числе изготовление модели по критериям геометрического и аэродинамического подобия, построение аэродинамической характеристики установки, проведение экспериментов с бесконтактным и комбинированным уплотнениями и вычисление значений объемного КПД установки на основе полученных экспериментальных данных.*
Результаты исследования. *Определена длительность периода подъема модели скипа с различными массами материала и типами уплотнений. Определены рабочие точки установки в системе координат «расход–давление», вычислены значения объемного КПД применительно к каждой рабочей точке.*
Анализ результатов. *Установлена удовлетворительная сходимость расчетных и экспериментальных параметров физической модели. Объемный КПД модели достиг технически приемлемого уровня. По константам подобия рассчитана ожидаемая величина объемного КПД экспериментального образца шахтной пневмоподъемной установки.*
Выводы. *Результаты исследования модели выявили сходимость экспериментально полученных объемных КПД модели с их расчетными значениями и доказали применимость математической модели для расчета параметров экспериментального образца. Объемный КПД установки как с бесконтактным, так и с комбинированным уплотнением достаточно высок и позволяет рекомендовать исследованные уплотнительные устройства к использованию в установках шахтного пневмоподъема.*

Ключевые слова: *шахтный пневмоподъем; скип; экспериментальный образец; физическая модель; уплотнение; утечка; объемный КПД.*

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Поступила в редакцию 23 марта 2021 года

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Для цитирования: Леонтьев А. А., Таугер В. М., Волков Е. Б., Адас В. Е. Физическое моделирование скиповой пневмоподъемной установки // Известия вузов. Горный журнал. 2021. № 4. С. 64–73 (In Eng.). DOI: 10.21440/0536-1028-2021-4-64-73
For citation: Leontiev A. A., Tauger V. M., Volkov E. B., Adas V. E. Physical modeling of a skip pneumatic winder. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = News of the Higher Institutions. Mining Journal*. 2021; 4: 64–73. DOI: 10.21440/0536-1028-2021-4-64-73