Mining of Mineral Deposits
Volume 17 (2023), Issue 4, 83-90

https://doi.org/10.33271/mining17.04.083

Influence of the leakage in air supply networks on the efficiency of application of pneumatic backfill equipment

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Abstract

Purpose. Determining the influence of the degree of pneumatic energy losses in the non-hermetic air supply network on the efficiency of using installed equipment in the pneumatic method of waste utilization from mining and beneficiation of minerals. To achieve this purpose, a tightness control device was developed using the method of fixed volumes.

Methods. Using the molecular-kinetic theory of gases, the thermodynamics and hydrodynamics laws, the characteristics of an open thermodynamic system under excess pressure and with a degree of a capillary-type leakage are investigated. Pneumatic energy losses in the pneumatic supply pipeline are determined by the mass of compressed air leaked due to its poor tightness.

Findings. The peculiarities of the tightness control of hollow products by the method of fixed volumes have been summarized. The dependences of non-production losses of compressed air and the corresponding pressure drop on the geometric characteristics of the air supply pipeline, the leakage in supply pipeline, and the time of assessing the degree of leakage have been determined.

Originality. For the first time, the relationship between the parameters of compressed air in an open thermodynamic system under excess pressure during air leakage and its heat exchange with the environment has been revealed. The influence of compressed air leakage in air supply networks on the efficiency of using vibration-pneumatic machines with an annular ejector in backfill technologies has been determined.

Practical implications. The research results can be used to improve the existing or develop the new technological schemes of air supply equipment that use pneumatic energy at mining and metallurgical enterprises. Minimization of energy consumption can significantly expand the scope of application of pneumatic backfilling method.

Keywords: *leakiness, leakages, air supply, energy, pressure, pipeline*

1. Introduction

In modern technological processes of mining enterprises, the waste from mining and beneficiation of minerals in most cases accumulates on the surface. According to the Thermal Energy Technology Institute of the National Academy of Sciences of Ukraine, the development of coal deposits in Ukraine over the course of a past century has led to the accumulation of more than 190 million tons of beneficiation waste. On the other hand, given the depletion of thick seams of minerals in Ukraine, the volume of rocks after winding to the surface is significantly increasing and forming technogenic waste from the extraction of these minerals [1].

To date, Ukraine has accumulated huge amounts of mining and processing waste, which makes the problem of its utilization, especially in mining of flat coal seams and thin-bed seams of ore, extremely urgent, and its solution is possible in two ways:

– reducing or total exclusion of rock winding (using rock to backfill the mined-out space);

– utilization of mining and processing waste accumulated on the mine surface.

Utilization of mining waste and its use for backfilling the mined-out space makes it possible to solve a number of environmental problems including one of the main mining tasks – rock pressure management. In particular, for underground coal mining, it would be appropriate to use technology of leaving waste bottom rocks in the mined-out space without rock winding to mine surface. However, despite the significant advantages of this technology of selective coal mining, it, like many other backfill technologies, is not widely used by Ukrainian mining companies, which is due to a number of reasons:

– the need for high mining rates;

– significant costs for technological processes of transportation of backfill materials from the daylight surface to the mined-out space;

– the lack of effective technical means of backfilling, which are aimed at the possibility of achieving a high density of backfill mass at the lowest possible financial and capital costs.

Received: 3 July 2023. Accepted: 1 November 2023. Available online: 30 December 2023

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

One of the ways to utilize mining waste in the mined-out space is a pneumatic backfill method, which can be used in ore and coal mining industry (at any thickness and dip angles of the seams) when mining mineral deposits by different mining systems. It is possible to solve the current environmental and mining-engineering problems, including rock pressure management, with the help of small-sized backfill equipment, such as a vibration-pneumatic machine with an annular ejector, developed at the Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM of NAS of Ukraine). This design uses the complex influence of vibration-aerodynamic forces on bulky material at the site of its loading into the transportation pipeline. This approach makes it possible to transport various types of bulky materials (including sticky and wet rocks) in various technological processes of mining, primarily in utilization technologies for mining and processing waste in the mined-out space [2], [3].

The most common equipment used for pneumatic backfilling the mined-out space of mines is pipeline pneumatic conveying system, in which the compressed air energy is necessary to maintain moving of the material, especially crushed rock, through the pipeline in a suspended state. Domestic and foreign experience in the development and industrial application of all pipeline pneumatic conveying system without exception [4]-[9] shows that their use is constrained by a significant specific consumption of compressed air for production and supply to consumers. Specific electricity consumption for pneumatic conveying of bulky material can reach 4^{-10} kW·h/t, and the costs for wear-out of pipelines and equipment can reach up to 50% of the transportation cost. This is primarily due to the loss of full air pressure for accelerating material transportation and overcoming possible blockages of individual elements of pneumatic conveying equipment.

In pipeline pneumatic conveying system, including the vibration-pneumatic machines, pneumatic energy provides the required performance and transportation distance. The efficiency of such systems in terms of leaving the rock in the mined-out space is determined by a reliable and uninterrupted supply of compressed air. Air supply at mining enterprises is carried out in a centralized manner through main and distribution pipelines or using mobile mine compressors. Regardless of the compressed air production method, its supply to mine consumers requires increased attention to minimizing pneumatic energy losses in the presence of compressed air leakage in air supply systems.

In addition to the use of pneumatic energy in pneumatic backfill technologies, this energy is primarily a vital energy source for deep mines. In some cases, pneumatic energy is the only possible type of energy for mines that are hazardous due to gas or dust, and where sudden coal and air bursts are possible. However, the condition of mine air ducts at operating mining enterprises [10]-[13] necessitates the implementation of specific measures aimed at reducing direct energy consumption, material and technical resources when using compressed air. However, finding the location of compressed air leakage in branched underground air supply networks is difficult and time-consuming.

An analysis in [11] of the ratio between compressed air consumption parameters and past, current, and future costs for it shows that more efficient use of compressed air can reduce the cost of its consumption by up to 8% of the total mining cost. There are known directions aimed at efficient energy management of mine compressed air systems, which are part of large projects and give a certain effect in a short time, but are not stable over time [13]. Today, non-production costs for providing compressed air to mine consumers are quite large [14]-[17] and the problem of reducing them is extremely relevant, given the rising tariff prices of energy resources.

There are various ways to solve the existing problem with the use of pneumatic energy. In particular, in [15], a local comparative analysis method using the correlation between the compressed air supply and its production is proposed to determine the place of inefficient uses of compressed air in an underground mine. At the same time, a regression analysis is used to visualize and quantify the increase in the efficiency of the entire underground compressed air system on the example of the platinum mine underground network. Despite the positive results achieved by applying the underground mine energy management method, it has a number of disadvantages:

– a rather complicated mathematical apparatus of comparative analysis, which requires adjusting the input parameters in accordance with the conditions of each individual mine;

– the need to compare results at many levels;

– attracting additional managers, material and technical resources to identify and prioritize local inefficiency of compressed air in underground mine air supply networks.

One way to improve the reliability and efficiency of mining operations, as well as energy saving in the production, transportation and consumption of compressed air by pneumatic energy consumers, is to minimize compressed air losses by increasing the tightness degree of mine pneumatic network elements. For this purpose, mining enterprises need to increase the requirements for tightness control of compressed air supply systems, especially for pneumatic backfill equipment.

Currently, various methods of detecting and eliminating leakage of liquids and gases in the systems of their supply to consumers have been developed. These methods are aimed at developing reliable ways for detecting and localizing leakage, and each has its own advantages and disadvantages, but in general, any detection of a substance pressure leakage from a system requires work to minimize losses [18]-[20].

The most common and widely used method for determining the leakage degree in pneumatic systems and their parts under excess pressure is the manometric method. This method, which indicates the gas pressure decay in products per unit of time, is also called the "pressure decay" leakage test. At the same time, while hydraulic leakage detection is cheaper, easier and faster to use [18] for pneumatic tests, the sensitivity of "pressure decay" method is limited by the permissible leakage and significantly depends on the influence of changes in ambient temperature and atmospheric pressure. The manometric method, developed at the IGTM of NAS of Ukraine, makes it possible to eliminate the main shortcomings of manometric method of leakage test of technological systems and products. The developed method determines the actual value of neutral gas (compressed air) microleakage using the method of fixed volumes [21], [22].

A key factor in the technological efficiency of using any equipment is the reliability of its operation [23]-[27], which is estimated over a period of time by the probability of failure-free operation of this equipment. This quantitative indicator of reliability is a function of a dimensionless failure rate of a system or element. Failure rate in applied reliability theory is determined by the following distribution laws relative to failure-free operation time:

– the exponential law;
– the normalized law using the Laplace function;
– the Weibull law using its and gamma functions;
– the Rayleigh law.

The IGTM of NAS of Ukraine has studied the vibration-pneumatic machine with an annular ejector for utilization of waste from mining and processing of minerals using the exponential law of its uptime distribution relative to the failure rate. Studies have shown that in the air supply network, in the presence of compressed air leakage from 10 to 40%, the distribution of this equipment uptime relative to the failure rate is in the range from 0.5 to 0.9. The uptime increases with increasing compressed air supply volume and decreases with increasing its specific volume consumption due to the presence of leakage in the air supply networks [28].

For equipment using pneumatic energy, reliability indicators depend primarily on the specific flow rate and pressure of compressed air in air supply networks. In turn, the compressed air consumption in mine pneumatic networks depends on the pressure drop, which is affected by the leakages of these networks and the number of pneumatic energy consumers. The Ontario Mining Association once undertook a compressed air leakage management project that costed $ 532000 to prevent leakage in compressed air lines at various types of underground mines (FNX Mining's McCredy West nickel mine, Inco Copper Cliff South CVRD nickel mine, and Teck Cominco/Barrick Gold's Williams gold mine) and, as a result, to save energy. The goal of this project was not only a comprehensive audit of using and saving electricity in air supply networks, but also ways to improve the reliability and the efficiency of pneumatic equipment by preventing compressed air leakage [14].

The purpose of this paper is to determine the peculiarities of assessing the influence of the air supply network leakage on the reliability of pneumatic backfill equipment, which is carried out by the method of tightness control of hollow products with fixed volumes.

In accordance with the research purpose, it is necessary to solve the problem of scientific substantiation and development of a highly efficient and highly accurate method for tightness control of mine pneumatic network elements and to develop a method for calculating the impact of pneumatic energy losses on the reliability and efficiency of pneumatic backfill equipment for wider use of this method during utilization of mining and beneficiation waste in the mined-out space.

2. Methods

2.1. Vibration-pneumatic machine with an annular ejector

A vibration-pneumatic machine (VPM) with an annular ejector, the general view of which is shown in Figure 1, is a small-sized (up to 0.4 m in height and up to 200 kg in weight) pneumatic conveying vehicle that belongs to site pipeline pneumatic conveying systems and moves any type of bulky materials over a distance of up to 120 m. Depending on the geological and mining-technical conditions of backfilling the mined-out space, it is necessary to supply the compressed air with a pressure from 0.2 to 0.4 MPa and an air flow rate from 25 to 50 m^3/min into the VPM in a stable mode for transporting the rock [2], [3].

Figure 1. General view of vibration-pneumatic machine with an annular ejector

2.2. Tightness control of hollow products using the fixed volume method

Tightness control of hollow products using the fixed volume method involves measuring the temperature and pressure of a control neutral gas (compressed air) [21], [22] in a closed volume thermostat with two vessels (compensation and reference) of equal volumes placed in it and a device for measuring the pressure drop between them (Fig. 2).

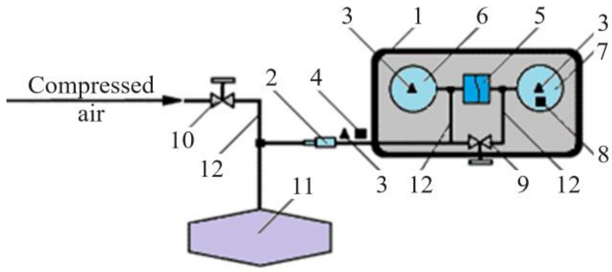

Figure 2. Functional scheme of tightness control by the method of fixed volumes: 1 – thermostat; 2 – inlet fitting; 3 – temperature sensors; 4 – barometric pressure sensor; 5 – device for measuring pressure drop; 6, 7 – compensation and reference vessels; 8 – absolute air pressure sensor in the reference vessel; 9, 10 – locking equipment; 11 – test object; 12 – pneumatic system

For the viscous regime of gaseous substance leakage from overpressure product with rigid walls and a constant leakage degree we have:

– the capillary-type gas leakage through leaky areas of product can be assumed to be steady and laminar due to the low leakage rate;

– the dynamic gas viscosity coefficient is constant due to small temperature and pressure gradients;

– the geometric parameters of the total leakage locations are constant.

Given the above, such a regime of gaseous substance leakage from the product corresponds to the relations for an incompressible liquid [29]-[31], primarily the Poiseuille equation.

The actual product leakage value is determined by the change in air mass in the compensation vessel (hermetic and thermally insulated vessel) taking into account the actual change in air pressure and temperature in the tested product (non-hermetic vessel). The IGTM of NAS of Ukraine has developed a fixed volume leakage test device (DLTFV) using the manometric method for determining actual leakage. When testing a prototype using this device, the error in determining the leakage degree of the tested product did not exceed 17% with a permissible error of 20% [22].

2.3. Determination of the relationship between compressed air parameters in an open thermodynamic system

When determining the relationship between the compressed air parameters in an open thermodynamic system (Fig. 2), the following ratios, obtained using the molecular kinetic theory of gases and the laws of [21], [22], are used:

$$\left(m_{c,b}+\Delta m_c\right)m_{p,b}\Delta T_c T_{p,b}=\left(m_{c,b}\Delta m_p-\Delta m_c m_{p,b}\right)\times \times T_{c,b}T_{p,b}+m_{c,b}\left(m_{p,b}+\Delta m_p\right)T_{c,b}\Delta T_p; \quad (1)$$

$$\Delta T_c=\frac{m_{c,b}\Delta m_p-\Delta m_c m_{p,b}}{m_{p,b}\left(m_{c,b}+\Delta m_c\right)}T_{c,b}+ +\frac{m_{c,b}\left(m_{p,b}+\Delta m_p\right)}{m_{p,b}\left(m_{c,b}+\Delta m_c\right)}\cdot\frac{T_{c,b}}{T_{p,b}}\Delta T_p; \quad (2)$$

$$\Delta m_c=m_{c,b}\left[\left(\frac{\Delta\bar{P}}{P_b}+1\right)^{1/k}-1\right]; \quad (3)$$

$$\Delta m_p=m_{p,b}\left[\left(\frac{\Delta\bar{P}}{P_b}+1\right)^{1/n}-1\right], \quad (4)$$

where:

$m_{c,b}$ and $m_{p,b}$ – initial air mass values in the compensation vessel and in the product (test object), kg;

Δm_c and Δm_p – changes in air masses in the compensation vessel and in the product, kg;

$T_{c,b}$ and $T_{p,b}$ – initial values of air temperature in the compensation vessel and in the product, K;

ΔT_c and ΔT_p – changes in air temperature in the compensation vessel and in the product, K;

$\Delta\bar{P}$ – time-averaged drop in air pressure in the system, Pa;

P_b – initial value of air pressure in the system, Pa;

k and n – adiabatic and polytropic coefficients.

In terms of physics, leakage flow or leakage refers to the inleakage flow power of a substance located inside an object. In the International System of Units (SI), the leakage flow rate is specified in Pa·m^3/s = W. The real conditions for leakage test of products using DLTFV correspond to the characteristics of the viscous regime of gaseous substance flow. For this flow regime, the value of $\delta > 10^{-5}$ W, and the gaseous substance pressure in the product P_b during the tests is $P_b > 10^5$ Pa, which causes the gas to leak into the atmosphere. The sensitivity threshold $\delta_{\min}$ (the lowest inleakage flow value) in the compression method (with excess pressure) of implementing the manometric method of testing products for leaks is determined as follows [22]:

$$\delta_{\min}=\frac{\Delta P_{\min}V_p}{\tau}, \quad (5)$$

where:

$\Delta P_{\min}$ – lower bound of pressure drop measurement, Pa;

V_p – the product volume, m^3;

τ – the time of product testing for leakage, s.

To assess the product leakage degree by the manometric method in practical calculations, the generalized formula [22] is used in accordance with Equality (1):

$$\delta=\frac{\left(P_{p,b}-P_{p,e}\right)V_p}{\tau}=\Delta P_\tau V_p, \quad (6)$$

where:

$P_{p,b}$ – gas pressure in the product at the beginning of testing, Pa;

$P_{p,e}$ – gas pressure in the product at the end of testing, Pa;

ΔP_τ – gas pressure drop in the product per unit of time (pressure drop rate).

2.4. Influence of the leakage degree in air supply networks on the pneumatic energy non-production losses

As an example, consider the influence of leakage in air supply networks when using VPM with an annular ejector in combination with a compressor unit. The principle block diagram of the use of DLTFV to assess the air supply pipeline leakage rate during repair and maintenance work is shown in Figure 3. It is necessary to use DLTFV according to the instructions for its operation when compressor is working, valve 2 is open and valve 5 is closed (Fig. 3).

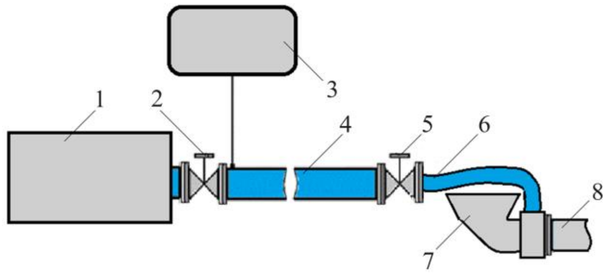

Figure 3. Principle block diagram of using DLTFV to assess the air supply pipeline leakage rate of theVPM: 1 – compressor; 2, 5 – shut-off valves; 3 – DLTFV; 4 – air supply pipeline; 6 – VPM flexible hose; 7 – VPM with annular ejector; 8 – VPM pipeline pneumatic conveying system

The technical characteristics of the compressor correspond to the specified compressed air parameters necessary for the reliable functioning of the VPM with an annular ejector:

– volumetric productivity given for initial conditions, Q_p = 50 m^3/min;

– final pressure, nominal, abs. P_f = 0.9 MPa;

– final temperature T_f = 333 K.

At the output of the compressor unit, the mass per second productivity of compressed air supply to consumers is:

$$M_f=\frac{Q_p P_f}{60RT_f}, \quad (7)$$

where:

R = 287.14 J/(kg·K) – universal gas constant of air.

Due to the pressure loss ΔP in the air supply network elements, compressed air, which can be used for pneumatic backfilling the mined-out space, enters the VPM with an annular ejector with a mass flow rate per second:

$$M_{sup}=\sqrt{\frac{\bar{F}^2}{RT_{sup}}\left\{\frac{1}{4}\left(P_f+\frac{RT_f M_f^2}{P_f\bar{F}^2}\right)^2-\left[P_f+\Delta P-\frac{1}{2}\left(P_f+\frac{RT_f M_f^2}{P_f\bar{F}^2}\right)\right]^2\right\}},$$

where:

$\bar{F}$ – the cross-sectional area averaged over the air supply pipeline length (Fig. 3), m^2;

T_{sup} – the temperature of the compressed air supplied to the pneumatic energy consumer, K.

In general, when calculating and analyzing air supply systems, it is necessary to know how their temperature, pressure and air flow rate change, taking into account cooling, leakage and drags. In the case of assessing the leakage degree in the air supply pipeline during repair and maintenance work, the movement of air in it occurs only due to the presence of leakages. In the case of assessing the degree of leakage of the air supply pipeline during repair and maintenance work, the air flows in it occur only due to the presence of leakages. Therefore, the influence of drag can be neglected and it can be assumed that non-production pneumatic energy losses are caused only by the influence of leakages in the air supply pipeline.

If in the last equality we designate:

$$P_\Sigma = P_f + \frac{RT_f M_f^2}{P_f \bar{F}^2}, \quad (8)$$

and pressure losses in the air supply network elements are considered according to the Equation (6) as:

$$\Delta P = \frac{\delta\tau}{V_p} = \frac{\delta\tau}{L\bar{F}},$$

which are determined during time τ only by leakage δ in the air supply pipeline of length L with total free volume V_p, then, taking into account Equality (7), the second mass non-production compressed air losses are:

$$\Delta M = M_f - M_{sup} = \frac{Q_p P_f}{60RT_f} - \bar{F} \times \sqrt{\frac{1}{RT_{sup}}\left[\frac{P_\Sigma^2}{4} - \left(P_f + \frac{\delta\tau}{L\bar{F}} - \frac{P_\Sigma}{2}\right)^2\right]}. \quad (9)$$

The average volumetric non-production compressed air loss $\Delta\bar{Q}$ per minute is:

$$\Delta\bar{Q} = \frac{60\Delta MRT_f}{P_f}. \quad (10)$$

3. Results and discussion

3.1. Characteristics of an open thermodynamic system under excess pressure and with capillary-type leakage degree

The fixed volume method for tightness control of hollow products assumes the presence of a system of connected vessels, one of which is leaky (test object), and the other is sealed and thermally insulated (compensation vessel). The change in pressure and temperature of the gaseous medium in this system during the test is compared with the corresponding parameters in the reference vessel (Fig. 2). In this case, the test object has a capillary-type leakage degree and diffusion leakage of the gaseous medium occurs from it.

The research studies possible physical processes of the distribution of thermodynamic parameters in a system of connected vessels, in which gas leakage from a leaky vessel occurs under the following conditions:

– the ambient temperature does not change;

– the gas in the leaky vessel has time to cool down due to heat exchange with the external air environment, where its temperature decreases;

– there is an increase in gas pressure in a leaky vessel due to heat exchange with the external air environment, where its temperature increases.

During the step-by-step study of the physical processes occurring in the studied system of connected vessels, the following results have been obtained:

– a change in the gas mass of a leaky vessel due to its leakage, taking into account heat exchange with the external environment, causes a change in gas pressure in a sealed and thermally insulated vessel, which causes a corresponding change in the gas mass of this vessel;

– in the system, changes in gas mass occur with continuous equalization of its temperature fields due to the presence of a thermostat (Fig. 2), while the values of the total changes in temperature and gas mass depend on the value of the temperature change in the external air environment and gas pressure due to its leakage;

– the heat exchange of the system with the external environment does not affect the actual amount of gas mass leakage and the heat is distributed between the change in the internal gas energy and the work performed.

The total gas microflow leakage from a leaky vessel of constant volume and a constant leakage degree is considered by analogy with the steady-state laminar flow of a viscous incompressible fluid through a cylindrical pipe of circular cross-section. Studies performed using Ratios (1)-(6) and the results presented in [22] have shown that:

– in a system of connected vessels, one of which is leaky, and the other is sealed and thermally insulated, a mutual redistribution of gas parameters occurs, during which the gas parameters in the leaky vessel change according to the polytropic law, and are transformed into changes in the gas parameters in the sealed thermally insulated vessel according to the adiabatic law;

– at the same excess gas pressure in a system of connected vessels, one of which is leaky and influenced by the external air environment, and the other is sealed and thermally insulated, there is an invariance in the gas mass leakage value from the leaky vessel due to a capillary-type leakage depending on the temperature and pressure of the external air environment;

– in the power of gas leakage flow from a closed-volume product that is under excess control gas pressure and has a capillary-type leakage degree, there is a physical constant ΔP_τ, which determines the pressure drop rate, the numerical value of which is determined by the product design, the control gas type and the measuring equipment used to assess the product total leakage degree.

In terms of its physical content, the pressure drop constant of a gaseous substance corresponds to the time constant of this substance flow: a value determined by multiplying the product volume by the ratio of the pressure difference on both sides of the substance flow to the substance flow rate as a result of leakage.

3.2. Influence of compressed air leakage in air supply networks on non-production pneumatic energy losses

One of the economic efficiency components when using VPM with an annular ejector for utilization of mining and beneficiation waste at mining enterprises is non-production costs for supplying pneumatic energy. These costs primarily depend on the pressure drop, which is affected by leakages in air supply networks and the number of pneumatic energy consumers.

As an example, consider the influence of the leakage degree in the air supply pipeline (compressed air pressure drop) when using VPM with an annular ejector in combination with a compressor unit in accordance with the scheme shown in Figure 3.

Figure 4 shows graphical dependences of the minute-averaged volumetric non-production losses of compressed air and the corresponding pressure drop on the air supply pipeline leakage degree, taking into account its length and the above technical characteristics of the compressor. Dependences are constructed using Equations (5), (9), (10) and Notations (8) for initial conditions: $\bar{F}$ = 0.0314 m^2 (for ∅ 0.2 m); T_{sup} = 303 K; τ = 4 h.

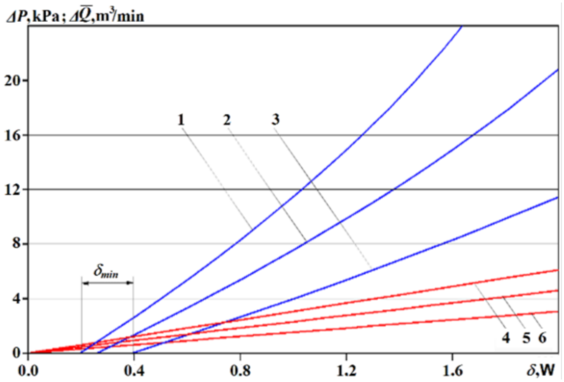

Figure 4. Dependence of time-averaged volumetric non-production losses of compressed air and pressure drop on the air supply pipeline leakage degree, taking into account its length: 1, 2, 3 – volumetric flow rates for pipeline lengths (L), equal to 150 m (1), 200 m (2), 300 m (3), respectively; 4, 5, 6 – pressure drop for pipeline lengths (L), equal to 150 m (4), 200 m (5), 300 m (6), respectively

Analysis of the dependences in Figure 4 shows that with an increase in the free volume of the air supply pipeline (due to an increase in its length at $\bar{F}$ = const):

– the minute-averaged volumetric non-production losses of compressed air, which are approximated by polynomials of the 3rd degree with the approximation reliability value $R^2 \to 1$, decrease. At the same time, there is a minimum permissible leakage degree of the air supply pipeline $\delta_{\min}$, at which, despite a slight pressure drop of an average volumetric non-production loss $\Delta\bar{Q} \to 0$, the value of $\delta_{\min}$ increases;

– the compressed air pressure drop decreases in direct proportion to δ, in which the proportionality factor decreases.

The calculation results of the influence of compressed air leakage in the air supply pipeline for the given initial data show that in the range of changes of 0.2 W ≤ δ ≤ 2 W, the compressor volumetric productivity loss can reach 50% or even more depending on the free volume of pipeline used for supplying pneumatic energy. Such a state of pneumatic energy supply of VPM with an annular ejector can significantly interfere with the reliable functioning of this equipment.

Successive variation of the initial data during the analysis of the influence of compressed air leakages on ΔP and $\Delta\bar{Q}$ in the air supply pipeline at L = const does not change the qualitative nature of the dependences ΔP, $\Delta\bar{Q}$ and shows the following:

– a change in temperature T_{sup} does not significantly change the initial numerical values of ΔP and $\Delta\bar{Q}$;

– a change in time τ according to a directly proportional change in the initial numerical values ΔP causes a decrease (at $\tau\downarrow$) or an increase (at $\tau\uparrow$) to $\Delta\bar{Q} \to Q_p$ of the corresponding initial numerical values of $\Delta\bar{Q}$ according to their polynomial dependence on $\delta \geq \delta_{\min}$;

– the change in the area averaged along the length according to the inversely proportional change of the initial numerical values ΔP causes an increase (at $\bar{F}\downarrow$) to $\Delta\bar{Q} \to Q_p$ or a decrease (at $\bar{F}\uparrow$) of the corresponding initial numerical values according to their polynomial dependence on $\delta \geq \delta_{\min}$.

Electricity tariffs for industrial enterprises are different, depending on the energy distribution company, the voltage class and have a tendency of constant growth. This leads to an increase in non-production financial costs for the pneumatic energy loss during its transportation through the air supply network of pipelines.

4. Conclusions

During repair and maintenance work at mining enterprises, reducing the leakage degree of mine pneumatic network elements and minimizing compressed air losses are among the solutions to the problem of increasing the reliability and efficiency of mining operations, as well as energy saving in the production, transportation and consumption of compressed air. Assessing the impact of leakages from compressed air supply pipelines on the efficiency of using pneumatic backfill equipment, in particular ejector-type pneumatic conveying system significantly expands the scope of application of backfill technologies at mining enterprises.

Reducing the leakage degree of mine pneumatic network elements and minimizing compressed air losses during repair and maintenance work at mining enterprises is one of the options for solving the problem of increasing the reliability and efficiency of mining operations, as well as energy saving in the production, transportation and consumption of compressed air.

Determining the ratios between the compressed air parameters in an open thermodynamic system under excess pressure, during air leakage and its heat exchange with the surrounding air environment has made it possible to develop the most advanced method of the tightness control of hollow products by pressure decay. This method is based on the principle of thermally insulated fixed volumes, in which scientific novelty is combined with original technical and design solutions. The studies have revealed that it is possible to determine with high accuracy the degree of actual total leakage value of air supply networks at low pressure, taking into account real changes in the parameters of the surrounding air environment.

It is shown that the dependences of the pressure decay and time-averaged volumetric non-production losses of compressed air in an air supply pipeline of a constant length on its leakage degree, which is not less than the minimum permissible value, have the form of a 3rd degree polynomial. The coefficients of these polynomials are determined by the tightness control time and the length-averaged area of the pipeline. The method for assessing the impact of air supply network leakage degree on non-production pneumatic energy losses makes it possible to obtain permissible tightness ranges of air supply systems depending on their free volume, in which these losses are minimal.

The research results can be used in the development of innovative technological schemes for the use of VPM with an annular ejector for the utilization of mining waste and beneficiation of minerals at mining and metallurgical enterprises.

Acknowledgements

The research results have been obtained within the framework of a contract between the Konstruktorske Biuro Pivdenne imeni M.K. Yanhelia and the Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine "Development of methods and technical means of tightness control without the use of helium and a vacuum chamber. Manufacturing of an experimental sample of the device", state registration No. 0197U015488, as well as during the implementation of the Research Work III-63-12 "Physicochemical mechanics of geotechnological systems: identification of parameters and control", state registration No. 0112U000493 funded by the National Academy of Sciences of Ukraine. Authors express their gratitude to the management of the Konstruktorske Biuro Pivdenne imeni M.K. Yanhelia for their support and assistance related to the designing and approval of the tightness control device. Authors also express their gratitude to the staff of the tightness control laboratory of the Vyrobnyche Obiednannia Pivdennyi Mashynobudivnyi Zavod imeni O.M. Makarova for their consultations and technical assistance in experimental studies. In addition, the authors express special gratitude to the editorial office of the journal for their useful suggestions and advice taken into account by the authors when finalizing the manuscript.

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Оцінка впливу ступеня негерметичності повітропостачальних мереж на ефективність застосування пневматичного закладного устаткування

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Мета. Встановлення впливу ступеня втрат пневматичної енергії в негерметичній повітропостачальній мережі на ефективність використання закладного устаткування при пневматичному способі утилізації відходів видобутку і збагачення корисних копалин. Для досягнення цієї мети розроблено пристрій контролю герметичності за методом фіксованих об'ємів.

Методика. За допомогою молекулярно-кінетичної теорії газів, законів термодинаміки та гідродинаміки досліджено характеристики відкритої термодинамічної системи, що знаходиться під надлишковим тиском і має ступінь негерметичності капілярного типу. Втрати пневматичної енергії в пневмопостачальному трубопроводі визначаються за величиною маси стисненого повітря, що витекло через його негерметичність.

Результати. Узагальнено особливості контролю герметичності порожнистих виробів за методом фіксованих об'ємів. Встановлено залежності невиробничих втрат стисненого повітря та відповідного падіння тиску від геометричних характеристик повітропостачального трубопроводу, наявності в ньому витоків та часу проведення оцінки ступеня його негерметичності.

Наукова новизна. Вперше встановлено взаємозв'язок параметрів стисненого повітря у відкритій термодинамічній системі, що знаходиться під надлишковим тиском, під час витоку повітря з системи та її теплообміну з оточуючим середовищем. Визначений вплив витоків стисненого повітря в мережах повітропостачання на ефективність використання вібраційнопневматичних машин з кільцевим ежектором в технологіях закладних робіт.

Практична значимість. Результати досліджень можуть бути реалізовані при вдосконаленні існуючих або розробці нових технологічних схем повітропостачання устаткування, що використовує пневматичну енергію, на підприємствах гірничо-металургійного комплексу. Мінімізація енерговитрат значно розширить область застосування пневматичного способу закладання.

Ключові слова: *негерметичність, витоки, повітропостачання, енергія, тиск, трубопровід*