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The calculation of heat exchange processes in the conveying pipe of a skip pneumatic winder

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Abstract

Introduction. *The article considers thermodynamic processes in the conveying pipe of a skip pneumatic winder.*

Research aim *is to analyse the establishment of temperature regime of pipeline's operation and estimate the influence of air refrigeration on the velocity of a skip in the conveying pipe of a skip pneumatic winder.*

Methodology. *A mathematical model has been built of "mining blower–skip–lifting pipeline–surrounding media" system, which will make it possible to get the dependence of conveying medium temperature and loaded skip velocity on depth. The formulae are introduced to estimate pipeline wall heating and air refrigeration inside the pipeline. The ratio has been found, which makes it possible to determine the time of heating upon the expiry of which the process of heat exchange in the initial part of the pipe will be steady.*

Results. *The relevance of the problems has been justified. Dependences of air-flow rate and air velocity in the pipeline on the vertical height coordinate are presented together with skip winding velocity variation conditioned by air flow refrigeration. The solution to the inverse problem is described: the calculation of air blowing station capacity required to provide the calculated value of average velocity, the results of which will allow to determine the value of mining blower capacity which provides for skip calculated average winding velocity, predetermined cycle duration, and unit capacity.*

Summary. *The ratios, obtained as a result of the calculation, make it possible to determine the value of mining blower capacity required to provide for skip calculated average winding velocity, predetermined cycle duration, and unit capacity.*

Ключевые слова: *winder; skip; pneumatic system; pipeline; heat exchange processes; mathematical model; mine winding.*

Introduction. Increase in the depth of deposits and the capacity of heading machines and shearers demands larger skip capacities and winding velocity. Limited operational characteristics of cable winders condition the need for the alternative means of mine winding with higher specific capacity. The analysis of various means of transport clearly indicates the potentials of the specific type of pneumatic container conveying – skip pneumatic winders [1–5].

When developing the systems with gaseous conveying medium, the problems arise associated with the determination of the influence of physical, particularly thermodynamic, properties of a medium on the system parameters. Mathematical description of the units of heavy duty with the motion cycle being strictly determined is extremely challenging. Mine winding systems must run at a steady pace, and with high energy load, pipeline length being hundreds of meters. In such conditions, in the mathematical model of a system, it is essential to take into account physical effects, connected with the properties of air of both enclosing and conveying medium.

Methodology. Mathematical model of *mining blower–skip–lifting pipeline–surrounding media* system will make it possible to get the dependence of conveying medium temperature and loaded skip velocity on depth. The indicated dependences in turn will make it possible to determine the velocity of a container in the depth function.

Thus, mathematical description of thermodynamic processes made in this work will become the constituent part of the calculation of skip pneumatic winder duty cycle duration.

The analysis of heat exchange processes. Air blowing station delivers flow into the conveying pipe, the temperature of the flow is significantly higher than the surrounding air. This fact is explained by energy loss when pressurising with blower rotor active elements. Modern mining blowers *SIEMENS* have got the coefficient of efficiency of 80–85 % [6, 7], and this number reduces with the increase of head capacity of a unit. Although it is rather high for a turbomachine, about 20 % of the unit's power is expended to heat gas.

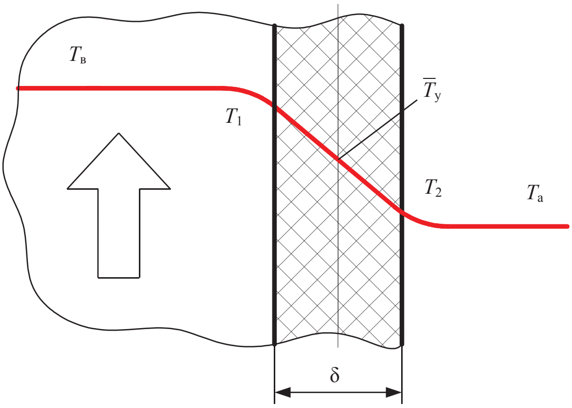

Fig. 1. A fragment of the pipe's wall
Рис. 1. Фрагмент стенки трубы

Heated air comes to the conveying pipeline under pressure and conveys the loaded skip to the surface. As a result of heat exchange the pipeline gets hot, while the air under the skip cools. This is an isobaric process; temperature drop is accompanied by air density growth and winding velocity reduction.

The study of heat exchange processes between the heated flow and pipe wall and between the pipe wall and the atmosphere provide for the solution of two problems:

– pipeline operation temperature conditions establishment;

– the estimation of air cooling influence on skip velocity.

The first problem is relevant because it is essential to determine whether pipes made of polymeric composite materials, precisely of fibreglass, are able to function at calculated temperatures.

As the skip elevates, flow cooling leads to air density growth and corresponding consumption reduction, which impacts on the velocity of a container. The determination of dependence between the loaded skip velocity and its coordinate will make it possible to calculate an average velocity of winding and the duty cycle of the unit.

Fig.1 represents a fragment of the pipe's wall. Notation: $T_в$ – air flow temperature at the outlet of the mining blower; T_1, T_2 – the temperature at the internal and external surfaces of the wall correspondingly; T_a – the temperature of the atmosphere; δ – the thickness of the wall.

The pipe's wall is cylindrical, but as long as its thickness is much less than the internal diameter *d*, the calculation can be performed using formulae for a plane wall with no significant errors.

Heat flow density q through the wall is [8]

$$q = k(T_{\text{в}} - T_{\text{a}}),$$

where k – the coefficient of heat exchange.

The value of the heat exchange coefficient is determined by the formula

$$k = \left(\frac{1}{\alpha_{\text{в}}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_{\text{a}}} \right)^{-1},$$

where $\alpha_{\text{в}}$ – is the coefficient of the internal flow heat transmission to the wall; α_{a} – the coefficient of heat transmission from the wall to the atmosphere; λ – the coefficient of heat conductivity of polymeric composite materials.

The temperatures of the internal and the external surfaces of the wall are determined according to the formulae:

$$T_1 = T_{\text{в}} - \frac{q}{\alpha_{\text{в}}};$$
$$T_2 = T_{\text{a}} + \frac{q}{\alpha_{\text{a}}}. \qquad (1)$$

Formulae (1) provide the value of maximum temperature T_1, the impact of which the material at the inlet of the pipeline is exposed to; formulae (1) make it possible to calculate average wall heating temperature $\bar{T}_{\text{y}}$ (fig. 1) in the condition of the steady-state heat exchange:

$$\bar{T}_{\text{y}} = \frac{T_1 + T_2}{2}.$$

Of interest is the time of heating, after which the process of heat exchange in the initial part of a pipe will be steady.

The problem of unsteady-state heat exchange calculation is rather labour-intensive [9]. Taking into account that at the present stage of investigation, heavy demands are not imposed on the accuracy, we will confine ourselves to rough estimate.

Let us make some assumptions:

– there is no heat transmission from the external surface of the pipe to the atmosphere ($\alpha_{\text{a}} = 0$);

– the pipe heats to temperature $\bar{T}_{\text{y}}$ throughout the length.

Then, for a minor fragment with a mass m and internal surface area s of the pipe near the entry end, the following equality is true

$$cmd\Delta T' = \alpha_{\text{в}} s \Delta T' dt, \qquad (2)$$

where c – the specific heat capacity of polymeric composite materials; $\Delta T' = T_{\text{в}} - \bar{T}_{\text{y}}$ – the difference of flow and pipe temperatures at a time; $d\Delta T'$ – pipe temperature increment in a time dt.

The relation $\delta \ll d$ between the thickness and the internal diameter d of the pipe means that internal and external diameters of the pipe are similar in value, consequently,

$$m \cong \rho s \delta, \qquad (3)$$

where ρ – the density of polymeric composite materials.

Substitution of (3) into (2) eliminates undetermined parameters m and s:

$$c\rho\delta d\Delta T' = \alpha_{\text{в}}\Delta T'dt,$$

from which

$$\frac{d\Delta T'}{\Delta T'} = \frac{\alpha_{\text{в}}}{c\rho\delta}dt. \tag{4}$$

Integration of (4) makes it possible to find temperatures difference dependence on the time for the initial conditions $(t = 0;\ \Delta T' = \Delta T_0 = T_{\text{в}} - T_{\text{a}})$:

$$\Delta T' = \Delta T_0\left(1 - \exp\left(-\frac{\alpha_{\text{в}}t}{c\rho\delta}\right)\right). \tag{5}$$

Having expressed t in terms of (5), we get the unknown duration t_{y} of pipe heating up to the average temperature $\bar{T}_{\text{y}}$:

$$t_{\text{y}} = -\frac{c\rho\delta}{\alpha_{\text{в}}}\ln\left(1 - \frac{T_{\text{в}} - \bar{T}_{\text{y}}}{\Delta T_0}\right). \tag{6}$$

Formulae (5) and (6) provide a rough idea of the dynamics of wall heating process.

Study of heat processes influence on the winding velocity. It is convenient to build rough dependence of flow temperature on the coordinate of arbitrary cross-section of a pipe with the help of the equation by V. T. Shukhov [10], reduced to

$$\Delta T = \Delta T_0 \exp\left(-\frac{k\pi d}{Mc_{\text{в}}}x\right), \tag{7}$$

where ΔT – flow temperature rise over the temperature of the atmosphere at a height of x from the pipe's entry end; ΔT_0 – the same but in the entry end (at the outlet of the mining blower); M – air mass flow rate under the loaded skip; $c_{\text{в}}$ – the specific heat capacity of air in the pipeline; x – the distance between the entry and arbitrary cross-sections of a pipe.

Using Gay-Lussac law [11, 12] and formula (7), we get the dependences of air-flow rate Q and air velocity v in the pipeline on the coordinate x:

$$Q = Q_0\left[1 - \frac{\Delta T_0}{273}\left(1 - \exp\left(-\frac{k\pi d}{Mc_{\text{в}}}x\right)\right)\right];$$

$$v = v_0\left[1 - \frac{\Delta T_0}{273}\left(1 - \exp\left(-\frac{k\pi d}{Mc_{\text{в}}}x\right)\right)\right];$$

$$v_0 = \frac{4Q_0}{\pi d^2}, \tag{8}$$

where Q_0, v_0 – consumption and average velocity at the entry end of a pipeline.

Not taking into account the periods of acceleration and braking of a skip, we get flow rate which is average for the shaft depth:

$$\overline{v} = \frac{v_0}{H}\int_0^H \left[1-\frac{\Delta T_0}{273}\left(1-\exp\left(-\frac{k\pi d}{Mc_{\text{в}}}x\right)\right)\right]dx;$$

from which

$$\overline{v} = v_0\left[1-\frac{\Delta T_0}{273}+\frac{\Delta T_0 Mc_{\text{в}}}{273k\pi dH}\left(1-\exp\left(-\frac{k\pi dH}{Mc_{\text{в}}}\right)\right)\right], \qquad (9)$$

where H – the length of a pipeline, roughly the size of the depth of a mine shaft.

According to (9), it is convenient to determine the average winding velocity of a skip during the calculation of the duty cycle of the unit.

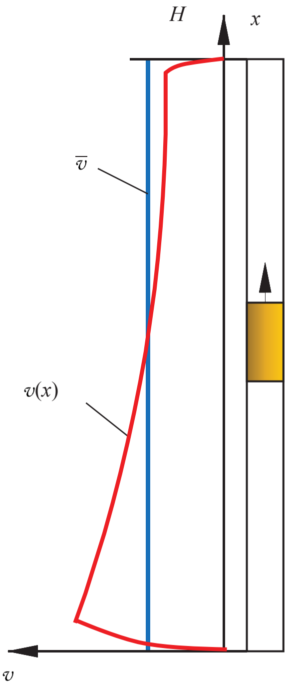

Fig. 2. Variation of flow velocity in the pipeline: $v(x)$ – dependence between velocity and x-coordinate; $\overline{v}$ – average velocity

Рис. 2. Изменение скорости потока в трубопроводе: $v(x)$ – зависимость скорости от координаты x; $\overline{v}$ – средняя скорость

Fig. 2 illustrates skip winding velocity variation conditioned by air flow cooling.

Air mass flow rate under the loaded skip is

$$M = \rho_t Q_0. \qquad (10)$$

In (10) ρ_t – the density of air at the outlet of a mining blower is

$$\rho_t = \rho_{0t}\frac{p_0+\Delta p}{p_0} = \rho_{0t}\left(1+\frac{\Delta p_{\text{г}}}{p_0}\right),$$

where ρ_{0t} – the density of air under the atmospheric pressure and temperature which the air gets after passing through the mining blower; p_0 – the atmospheric pressure; $\Delta p_{\text{г}}$ – overpressure under the loaded skip.

Overpressure $\Delta p_{\text{г}}$ is calculated by the following formula

$$\Delta p_{\text{г}} = \frac{4(m_{\text{и}}+m_{\text{с}})g}{\pi d^2},$$

where $m_{\text{и}}$, $m_{\text{с}}$ – the mass of mineral and the proper weight of a skip correspondingly; g – gravitational acceleration; d – internal diameter of pipelines.

The formula by V. T. Shukhov is devised for horizontally oriented pipe, that is why a question arises about it applicability to the vertical pipeline. In [13], heat transmission coefficient α_{a} dependence on the coordinate of a point on the wall of a vertical pipe is shown. Thus, the applicability of the case under consideration is well founded.

Inverse problem solution also becomes possible, which is necessary for design calculation of a unit: the calculation of capacity Q_0 of an air blowing station, which is necessary to provide calculated value of average velocity $\overline{v}$.

Substitution of (8) and (10) into (9) allows to get the following expression

$$\bar{v} = \frac{4Q_0}{\pi d^2}\left[1-\frac{\Delta T_0}{273}+\frac{\Delta T_0\rho_t Q_0 c_{\text{в}}}{273k\pi dH}\left(1-\exp\left(-\frac{k\pi dH}{\rho_t Q_0 c_{\text{в}}}\right)\right)\right], \tag{11}$$

which is an equation towards Q_0 under the predetermined $\bar{v}$.

The complexity of equation (11) solution comes from the fact that the unknown value is a part of the exponent's index. With the account of the approximate character of calculations it is advisable to consider that the following equality holds

$$-\frac{k\pi dH}{\rho_t Q_0 c_{\text{в}}} \approx -\frac{k\pi dH}{\rho_0 \bar{Q} c_{\text{в}}},$$

where $\bar{Q}$ – relative air flow rate, determined according to the average velocity:

$$\bar{Q} = \bar{v}\frac{\pi d^2}{4}.$$

Then (11), after algebraic transformations, will be written as the following equation

$$Q_0^2 + AQ_0 - B = 0$$

with the positive root

$$Q_0 = \sqrt{\frac{A^2}{4}+B}-\frac{A}{2}, \tag{12}$$

where

$$A = \left(\frac{273}{\Delta T_0}-1\right)\frac{k\pi dH}{\rho_t c_{\text{в}}\left[1-\exp\left(-\frac{k\pi dH}{\rho_0 \bar{Q} c_{\text{в}}}\right)\right]};$$

$$B = \frac{68,3\bar{v}k\pi^2 d^3 H}{\Delta T_0 \rho_t c_{\text{в}}\left[1-\exp\left(-\frac{k\pi dH}{\rho_0 \bar{Q} c_{\text{в}}}\right)\right]}. \tag{13}$$

Summary. The ratios (11), (12), and (13) make it possible to determine the value of mining blower capacity required to provide for skip calculated average winding velocity, predetermined cycle duration, and unit capacity.

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Расчет теплообменных процессов в подъемном трубопроводе скиповой пневмоподъемной установки

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Реферат

Введение. *В статье рассмотрены термодинамические процессы, происходящие в подъемном трубопроводе скиповой пневмоподъемной установки.*

Цель работы. *Проанализировать установление температурного режима эксплуатации трубопровода и оценить влияние охлаждения воздуха на скорость движения скипа в подъемном трубопроводе скиповой пневмоподъемной установки.*

Методология. *Составлена математическая модель системы «воздуходувка–скип–подъемный трубопровод–окружающая среда», которая позволит получить зависимости температуры транспортирующей среды и скорости груженого скипа от глубины. Выведены формулы для оценки нагрева стенки трубопровода и охлаждения воздуха внутри трубопровода. Найдено соотношение, позволяющее определить время нагрева, по истечении которого процесс теплообмена на начальном участке трубы станет установившимся.*

Результаты. *Обоснована актуальность поставленных задач. Приведены зависимости объемного расхода и скорости воздуха в трубопроводе от координаты высоты, а также изменения скорости подъема скипа, обусловленного охлаждением воздушного потока. Описано решение обратной задачи: вычисление производительности воздухонагнетательной станции, которая необходима для обеспечения расчетного значения средней скорости, результаты которого позволят определить значение подачи воздуходувки, обеспечивающей расчетную среднюю скорость подъема скипа, заданную продолжительность цикла и производительность установки.*

Выводы. *Полученные в рамках расчета соотношения дают возможность определить значение подачи воздуходувки, необходимое для обеспечения расчетной средней скорости подъема скипа и заданных продолжительности цикла и производительности установки.*

Ключевые слова: *подъемная установка; скип; пневмосистема; трубопровод; теплообменные процессы; математическая модель; рудничный пневмоподъем.*

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