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Research into the pressureless flow in hydrotechnical systems at mining enterprises

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Abstract

Purpose. The research purpose is to develop a mathematical model of a pressureless flow in a channel with the occurrence in some areas of overflow layer through the wall. Using this model, it is possible to calculate the overflow layer height and length, as well as the change in flow rate in the channel due to the withdrawal of part of the fluid as a result of the overflow.

Methods. The research uses a comprehensive multi-stage analytical approach. Firstly, in order to develop a mathematical model for a pressureless flow in the channel with the occurrence in some areas of overflow layer through the wall, this research analytically determines the dependence of the flow rate through the channel wall based on formulas for calculating the weir discharge coefficient. At the second stage, a mathematical model of a hydraulic mixture pressureless flow in a rectangular channel with an overflow through the wall is developed to determine the parameters and flow regimes of the stream.

Findings. The dependences of the dimensionless height of the overflow through the channel wall and the effective critical flow depth on the dimensionless current channel length have been obtained for various values of the acting force parameters and the process parameter of the fluid overflow through the channel wall. This made it possible to study the dynamics of changes in these values along the channel for various values of the specified parameters, and to assess the degree of influence of the relevant factors on the characteristics of the pressureless flow along the channel and the process of fluid overflow through wall.

Originality. For the first time, the model of the pressureless flow in the channel is generalized for the case of occurrence in some areas of overflow layer through the wall, when the length and height of the overflow layer are not determined by a hole in the side surface, but are controlled by a decrease in the corresponding flow rate. For the first time, this model makes it possible to calculate the height and length of the overflow layer and the change in the flow rate in the channel due to the withdrawal of part of the fluid as a result of the overflow in cases of overflowing condition of the channel with the stream under unstable and non-calculated flow regimes.

Practical implications. The mathematical model and the calculation results can be used to ensure the environmental safety of the logistics systems of mining enterprises, as well as to assess the volume of the environmental pollution in case of overflowing through the wall of the channels of pressureless hydraulic transportation of waste from mineral processing and metallurgical plants.

Keywords: *channel, overflow, flow, logistics, ecology, pollution, safety, hydraulic mixture*

1. Introduction

Ukraine is in a state of war. To maintain the country's defense capability and provide the economy and industry with its own raw materials, it is necessary to reduce the technogenic burden and increase environmental safety in accordance with the requirements. Significant reserves of minerals are concentrated in Ukraine, the global demand for some of them is met by less than a third, and for some of them our country is a monopolist in Europe and is among the top ten supplier countries in the world [1]-[3]. The mineral and raw material base of Ukraine is one of the richest in the world in the nomenclature of minerals (120 types). It is represented by fuel (coal, oil, gas, oil shale, peat), metallic (iron, manganese, nickel, titanium, uranium, chromium, gold) and non-metallic (rock salt, kaolin, refractory clays, cement raw materials, fluxing limestones, etc.) minerals. This volume is sufficient for the development of domestic industry, focused on the use of its own raw materials [4]-[6].

At the beginning of the 21st century, Ukraine and Australia ranked first in terms of explored iron ore reserves. According to data from the Kryvyi Rih Technical University, in 2000, the total explored iron ore reserves in Ukraine amounted to

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32.597 billion tons, including industrial reserves – 28.124 billion tons. Of these, 68.5% of ores are concentrated in the Kryvyi Rih Iron-ore Basin, in the Kremenchuk iron-ore region the industrial iron ore reserves amounted to 4.65 billion tons, and in Bilozersk – 0.543 billion tons. The Pryazovskyi iron ore region is a reserve base, in which about 3.0 billion tons of explored ore reserves are concentrated, of which 0.9 billion tons are easily enriched high-quality magnetite quartzites [7], [8].

Today, predicted reserves of iron ore raw materials in Ukraine are estimated at approximately 32 billion tons, of which over 70% are concentrated in the Kryvyi Rih Iron-ore Basin. The total availability of balance reserves is over 100 years [9], [10].

It should also be noted that today the sustainable development of the Ukrainian economy is impossible without the mining-beneficiation industry. The Kryvyi Rih Iron-ore Basin is the largest in Ukraine, where more than 80% of iron ore raw materials are mined and more than 20% of metallurgical products are produced. The Kryvyi Rih Iron-ore Basin is one of the largest basins in Ukraine, represented by iron ore deposits, the main mining center of the country, located in the Dnipropetrovsk region [11], [12].

The enterprises of the mining-metallurgical industry are the basis of the country's export potential, forming the conditions for the sustainable development of many regions in the country and providing essential revenues to the budget [13]-[16]. At the same time, Ukrainian enterprises pose a potential environmental threat to the regions in which they are located [17]. This threat is very diverse: there is a possibility of pollution of air, aqueous medium, soil, representatives of the flora and fauna existing in this region may suffer losses. One of the threats are the objects of large-scale hydrotechnical construction, which were built in the last century during the greatest development of mining-beneficiation and mining-metallurgical plants. These include: dams, beneficiation waste storage facilities, technical and mine water reservoirs, extensive networks of pipelines and channels for pressureless hydraulic transportation [18]-[20].

The specificity of the technology for processing mineral raw materials at the studied enterprises promotes the use of hydraulic modes of transport, and the location of waste storage facilities in natural lowlands, ravines and gullies creates promising conditions for the use of pressureless hydraulic transport in flumes and channels [21]-[23]. Therefore, on the territory of the country there is not a single mining-beneficiation or mining-metallurgical plant, where channels for pressureless flow of fluid or hydraulic mixture are not used. At some plants, these hydrotechnical structures, which according to the latest scientific trends, are considered as elements of the logistics systems of mining enterprises [24], [25], have a length of more than one kilometer with a depth of up to two meters with a cross-section of three meters wide. The most common cross-sectional shape of such objects is a rectangle, which is conditioned by their construction technologies using standardized reinforced concrete products. Given the terms of use of these structures, which were designed and built almost a century ago, their operation poses an environmental threat. This threat arises as a result of the fluid leakage through fractures in the bottom and walls of the channels, the fluid leakage through the butt seams as a result of their depressurization, the fluid overflow through the channel wall as a result of stream overflowing condition under unstable and non-calculated flow regimes [26]-[29]. In the first two cases, the methodologies for calculating the flow rate and volumes of the lost fluid are known and well-tested in engineering practice [7], [8], [11], while the last case has not been studied scientifically, although it often occurs in practice [30]-[33].

Thus, theoretical and experimental studies of the dependences of the weir discharge coefficient on the dimensionless high-speed head are known, which can be applied at the mining enterprises [28]. But they concern only cases when the overflow layer is bounded by solid surfaces on both sides, while the fluid overflow through the channel wall as a result of stream overflowing condition under unstable and non-calculated flow regimes occurs without such a restriction on the sides. There are known comparisons of experimental data on the operating modes of outlet and overflow channels [29], [30] which provide data on critical heads for such streams. However, the authors do not study the cases where the stream in the critical mode goes beyond the solid channel boundaries, which makes it difficult to use them in the studied case. A theoretical study of the influence of lateral weirs on the process of transporting bottom sediments [32] makes it possible to predict a change in the flow rate along the channel, but does not take into account the peculiarities of the height formation of the overflow layer through the channel wall in the studied case. That is, modern domestic and foreign experts have studied certain elements of mathematical models of processes close to the process of pressureless flow in a channel with an overflow through the wall, which make it possible to construct a mathematical model of this phenomenon, but the model itself has not been developed and tested.

Thus, to ensure the environmental safety of the logistics systems at mining enterprises, it is necessary to develop a mathematical model for pressureless flow in a channel with an overflow through the wall, which would allow calculating the height of the overflow layer, the lifetime of the overflow layer and the change in flow rate in the channel due to the withdrawal of part of the fluid from the channel as a result of the overflowing layer.

The research purpose is to develop a mathematical model of a pressureless flow in a channel with the occurrence in some areas of overflow layer through the wall, which would allow calculating the height and length of the overflow layer, as well as the change in flow rate in the channel due to the withdrawal of part of the fluid as a result of the overflowing condition.

2. Methods

Achieving the purpose set in the introduction requires considering the well-known mathematical models for pressureless flow in a channel, providing for the fluid flow rate along the length of the flow through the side surface in the direction perpendicular to it. It is necessary to adapt the dependences for determining the flow rate through the channel wall, taking into account the dependences of the flow rate coefficient when fluid overflows through weirs, as well as to modernize the corresponding terms of the model equations. The research purpose is also to develop an algorithm for solving the system of equations obtained in the development of a mathematical model for pressureless flow in a channel with the occurrence in some areas of overflow layer through the wall, and to obtain the dependences of the height, length of the overflow layer, as well as the flow rate in the channel due to the withdrawal of part of the fluid as a result of the overflowing condition.

When constructing a model for the homogeneous fluid flow in a channel, the following assumptions are used [24], [26], [33]-[35] (Figs. 1-3):

– the fluid is ideal and heavy;

– the fluid velocity does not change through the layer thickness;

– the fluid is considered homogeneous, which corresponds to the case of flowing water or a low-concentration hydraulic mixture with solid particles less than 0.1 mm in diameter;

– the channel has a rectangular cross-section, the geometric parameters of which are unchanged along the length;

– the occurrence of a friction force between the fluid and the solid surfaces of the channel is taken into account using Pavlovsky’s formula;

– the vertical component in the overflow layer velocity is neglected; for the flow in the channel and in the overflow layer, the provisions of the “not deep water” theory are valid;

– the flow is symmetrical with respect to the longitudinal axis of the channel;

– it is assumed that there is no influence of wind and solar radiation on the free flow surface; there is an instant increase in the flow height in the cross-section where the overflow layer occurs.

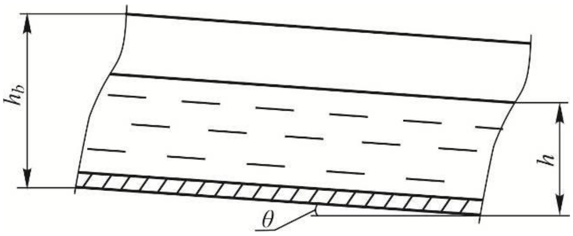

Figure 1. Longitudinal channel section with normal pressureless flow: h – stream depth, m; h$_b$ – geometric channel depth; θ – the angle of the channel inclination to the horizon

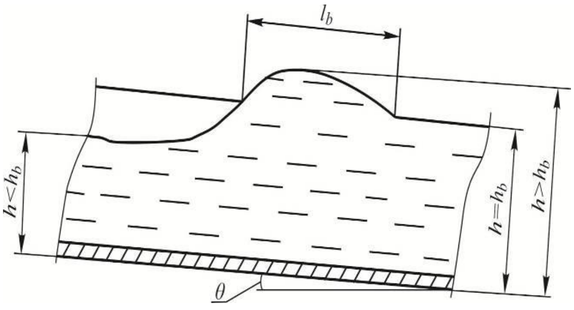

Figure 2. Longitudinal channel section with pressureless flow in the channel with overflow through the wall: l$_b$ – the length of the channel on which the fluid flows over the wall

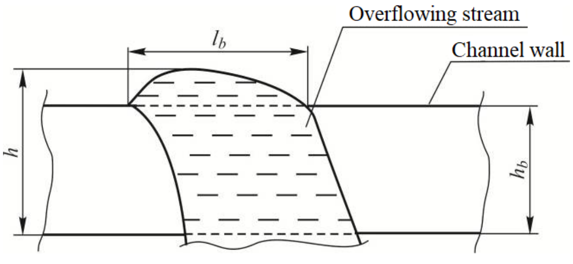

Figure 3. A view of pressureless flow in a channel with an overflow through the wall

The scientific research results, published in peer-reviewed publications by domestic and foreign specialists in hydraulics [28]-[32] make it possible, taking into account the above assumptions, to propose a well-known model of pressureless flow with fluid removal through the bottom for the description of the flow through an open channel when an overflow occurs through its wall [24], [33]-[35]:

$$\frac{dh}{ds}=\frac{\sin\theta-i_f-\dfrac{2\alpha_k}{gb^2}\dfrac{Q}{h^2}\Phi(Q,h)}{1-\dfrac{\alpha_k Q^2}{gb^2h^3}}; \qquad (1)$$

$$\frac{dQ}{ds}=(Q,h); \qquad (2)$$

$$\Phi=(Q,h)-\wp\mu' b\bar{s}\sqrt{\frac{2(p_B-p_A)}{\rho}+2g(h+d)+\frac{\alpha_k Q^2}{b^2h^2}}; \qquad (3)$$

$$i_f=\frac{C_f}{2gb^3}\cdot\frac{\left[2h+b\left(1-\bar{s}\right)\right]}{h^3}Q^2; \qquad \wp=sign\left(p_B-p_A\right), \qquad (4)$$

where:

h – stream depth, m;

s – current channel length;

θ – the angle of the channel inclination to the horizon;

i_f – hydraulic inclination of the stream;

α_k – Coriolis coefficient (from 1.10 to 1.15);

Q – volume flow rate of fluid through the current cross-section of the stream;

$\Phi(Q, h)$ – a function that takes into account the removal or inflow of fluid volumes through the stream bottom;

b – channel width, m;

$\bar{s}$ – the relative area of the holes in the channel bottom;

μ' – a coefficient of the flow rate through holes in the bottom;

p_B – pressure above the free surface of the stream, Pa;

p_B – pressure under the channel bottom, Pa;

ρ – fluid density;

d – the characteristic geometric size of the holes in the channel bottom;

C_f – the coefficient of hydraulic friction of the stream against the channel bottom;

$\wp$ – coefficient that takes into account the direction of mass transfer at the channel bottom when adding fluid to the stream $\wp=-1$, when the fluid is withdrawn – $\wp=1$;

sign – sign function.

In the studied case, unlike the model (1)-(4), the fluid withdrawal does not lead to a change in the friction conditions and the solid surface, since the overflow occurs through the top, and the flow rate of the fluid leaving the channel is determined according to the well-known formulas of hydraulics, which are used to calculate the overflow layer parameters [28], [35]-[37]. Taking into account this and the assumptions made, the Formulas of the model (1)-(4), after appropriate transformations, take the following form:

$$\frac{dh}{ds}=\frac{\sin\theta-i_f-\dfrac{4\sqrt{2}\mu\alpha_k Q}{b^2h^2\sqrt{g}}\left(h-h_b\right)^{3/2}}{1-\dfrac{\alpha_k Q^2}{gb^2h^3}}; \qquad (5)$$

$$\frac{dQ}{ds} = -\mu\sqrt{8g}\left(h-h_b\right)^{3/2}; \tag{6}$$

$$Q_0 = -\mu\sqrt{8g}\int_0^{l_b}\left(h-h_b\right)^{3/2} ds; \tag{7}$$

$$i_f = \frac{C_f}{2g}\cdot\frac{2h+b}{b^3h^3}Q^2, \tag{8}$$

where:

μ – a coefficient of the flow rate through the channel wall;

h_b – geometric channel depth;

Q_0 – volume flow rate of fluid through the channel wall;

l_b – the channel length on which the fluid overflow through the wall occurs (Figs. 2, 3).

Summing up the basis for the expression for calculating the hydraulic inclination of the stream to Equations (5)-(8) and performing the appropriate transformations with the successive introduction of dimensionless variables, the mathematical model can be written in the following form:

$$\frac{dy}{dl} = \frac{1-Ap^2-A_\mu p y^{3/2}}{1-p^2}, \tag{9}$$

$$\frac{dp}{dl} = -\frac{A_\mu}{2}y^{3/2}; \tag{10}$$

$$y = \frac{h-h_b}{h_b}; \quad p = \left(\frac{h_k}{h_b}\right)^{3/2}; \quad l = \frac{s\sin\theta}{h_b}; \quad h_k = \sqrt[3]{\frac{\alpha_k Q^2}{gb^2}};$$

$$A = \frac{C_f\left(0.5+m\right)}{\alpha_k\sin\theta}; \quad A_\mu = \frac{2\sqrt{8\alpha_k}\,\mu}{\sin\theta}m; \quad m = \frac{h_b}{b},$$

where:

y – the dimensionless height of the overflow through the channel wall;

p – effective dimensionless critical flow depth;

l – dimensionless current channel length;

A – the parameter of acting forces, the ratio of the hydraulic friction force and the force that ensures the fluid stream flow;

A_μ – a parameter that takes into account the occurrence of fluid overflow through the channel wall;

m – geometric channel parameter.

The initial conditions for the system of Equations (9) and (10) will be:

$$y\left(l=0\right) = y_0; \quad p\left(l=0\right) = p_0, \tag{11}$$

where:

y_0 – the initial value of the dimensionless height of the overflow through the channel wall;

p_0 – the initial value of the effective dimensionless critical flow depth.

Model (9) and (10) with conditions (11) is studied when the initial values for corresponding parameters are changed in the following intervals $0.1 \le y_0 \le 0.9$ and $0.125 \le p_0 \le 0.354$ for typical ranges of changes in values (Table 1).

3. Results and discussion

The system of Equations (9) and (10) under the initial Conditions (11) cannot be solved by an analytical method. Therefore, numerous methods are used to obtain a solution, namely, the solution of the system of differential equations by the Euler method.

Table 1. Limits of an interval of parameter changes in model (9)-(11)

Parameter		Interval limits	
Name	Designation	Lower	Upper
Flow rate coefficient through the channel wall	μ	0.475	0.645
Angle of the channel inclination to the horizon	θ	0°	30°
Coriolis coefficient	α_k	0.980	2.300
Hydraulic friction coefficient	C_f	0.030	0.300
Geometric channel parameter	m	0.500	2.000

Calculations using Formulas (9)-(11) make it possible to obtain the dependences of the dimensionless height of the overflow through the channel wall and the effective critical flow depth on the dimensionless current channel length for various values of the acting forces parameter and the process parameter of the fluid overflow through the channel wall (Figs. 4, 5).

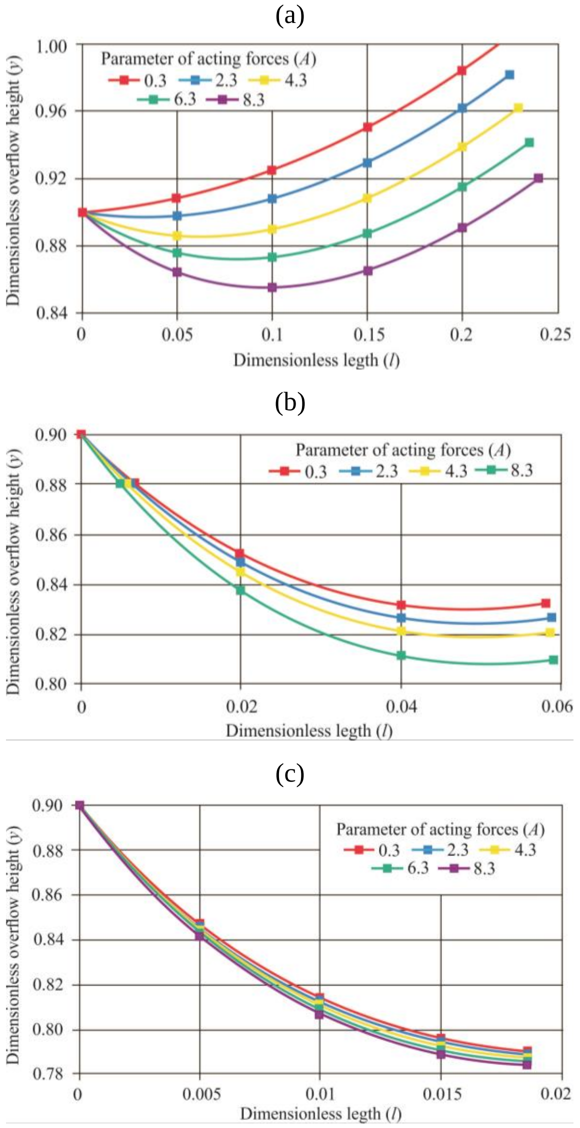

Figure 4. Dependence of the dimensionless height of the overflow through the channel wall (y) on the dimensionless length (l) at different values of the acting forces (A) parameter, when the parameter that takes into account the occurrence of fluid overflow through the channel wall is: (a) $A_\mu = 3$; (b) $A_\mu = 13$; (c) $A_\mu = 43$

This makes it possible to study the dynamics of changes in the values of y and p along the channel for various values of the parameters A and A_μ.

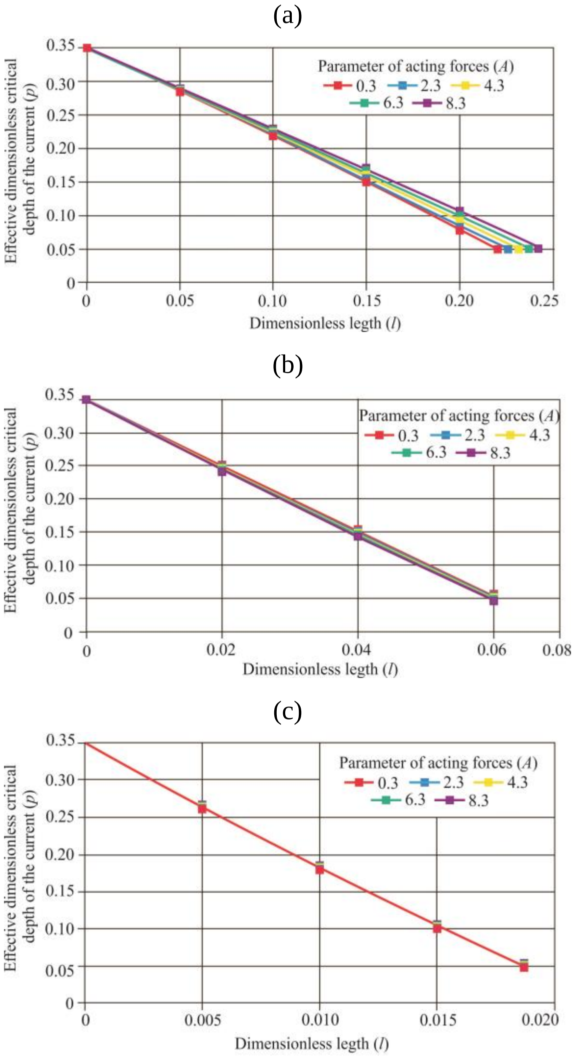

Figure 5. Dependence of the effective dimensionless critical flow depth (p) on the dimensionless length (l) at various values of the acting forces (A) parameter, when the parameter that takes into account the occurrence of fluid overflow through the channel wall is: (a) $A_\mu = 3$; (b) $A_\mu = 13$; (c) $A_\mu = 43$

The results of numerical calculations (Fig. 4) indicate that the stream depth decreases along the channel length at all parameter values of occurrence of fluid overflow through the channel wall (A_μ) from 13 to 43, regardless of the value of the acting forces parameter (A). At the same time, when the parameter value of occurrence of fluid overflow through the channel wall is less than 13, then the value of the stream depth along the channel length first decreases, and after reaching a certain distance, it begins to increase. This tendency takes place for all values of the acting forces parameter. It should be noted that for smaller values of this parameter, the decrease in flow rate at the beginning of the channel is less noticeable than for larger parameter values. This effect can be explained by a change in the fluid flow rate due to the fluid overflow through the channel wall, which affects both the fluid volume in the channel and the hydraulic stream resistance. The results of numerical calculations (Fig. 5) indicate that, regardless of the value of the acting force parameters and the parameter of occurrence of fluid overflow through the channel wall, the fluid flow rate along the channel decreases. This nature of the change in parameters is fully consistent with the logic of the studied process, which proves the correspondence of the developed model to the studied phenomenon. It should be noted that the velocity of a decrease in the flow rate along the channel length remains constant for all the studied cases, but is variable depending on the value of the parameter that takes into account the occurrence of fluid overflow through the channel wall. It follows from Figure 4 that with an increase in this parameter value, the velocity of a decrease in the fluid flow rate along the channel length increases, while the influence of the acting forces parameter on this value can be neglected within the limits of calculations with engineering accuracy.

Having the results of numerical calculations (Figs. 4, 5), and taking into account Expression (7), the parameters of the pressureless flow in the channel, namely the height and flow rate of the flow in the channel, as well as the fluid flow rate through the channel wall, can be calculated by the following Formulas:

$$h = \left(1 + y(l)\right) h_b\,; \quad Q = p(l)\sqrt{\frac{g b^2 h_b^3}{\alpha_k}}\,; \qquad (12)$$

$$Q_0 = -\frac{\mu h_b \sqrt{8g}}{\sin\theta}\int_0^{l_0} y^{3/2}(l)\,dl\,; \quad l_0 = \frac{l_b}{h_b}\sin\theta\,, \qquad (13)$$

where:

l_0 – the channel length on which the fluid overflow through the wall occurs.

Equations (9), (10) and (13), together with the initial conditions (11), represent a mathematical model of a pressureless flow in the channel with the occurrence in some areas of an overflow layer through the wall. Expressions (12) indicate that this model makes it possible to calculate the height and length of the overflow layer and the change in the flow rate in the channel due to the removal of part of the fluid as a result of the overflow. The results of calculations performed using this mathematical model make it possible to study the dependence of the flow depth and the fluid flow rate along the channel for various values of the acting forces parameter and the parameter of fluid overflow through the channel wall.

Thus, the mathematical model, which is proposed and studied in the paper, can be used to ensure the environmental safety of the logistics systems of mining enterprises, in which there are pressureless flows in channels with an overflow through the wall. Such use involves calculating the overflow layer height and the lifetime of the overflow layer, which determines the volume of environmental pollution, and assessing the change in flow rate in the channel due to the removal of part of the fluid from the channel as a result of the overflow layer, which determines the level of change in technological production performance. To do this, as can be seen from Formulas (12) and (13), it is necessary to determine analytically the dependences of the dimensionless height of the overflow through the channel wall and the effective dimensionless critical flow depth on the dimensionless length for various values of the acting forces parameter and the process parameter of the fluid overflow through the channel wall. The presence of such analytical dependences will simplify the study of the dependence of process parameters on a variety of criteria and determination of optimal parameters by methods of mathematical analysis without the use of numerical mathematics algorithms. It is also interesting to determine the maximum value of the process parameter of the fluid overflow through the channel wall, at which the influence of the acting forces parameter on the dependence of the dimensionless height of the overflow through the channel wall on the dimensionless length can be neglected.

4. Conclusions

An analysis of the obtained calculation results indicated in the paper makes it possible to draw the following conclusions:

1. With an increase in the dimensionless flow length, in the entire range of changing values, the effective dimensionless critical flow depth, that is, the fluid flow rate in the channel, decreases. The nature of this dependence is close to linear, and also has no extrema and intersection points. The influence of the acting forces parameter on the nature of this dependence and the value of the effective dimensionless critical depth is almost unnoticeable, and further research is needed to determine the influence of the process parameter of the fluid overflow through the channel wall.

2. The nature of the dependence of the dimensionless height of the overflow through the channel wall on the dimensionless current length significantly depends on the process parameter of the fluid overflow through the channel wall. At lower values of the process parameter of the fluid overflow through the channel wall, this dependence is extremal, as evidenced by the minimum of curves at values of the dimensionless current length close to 0.1. In this case, the height of the overflow layer along the channel increases. With an increase in the values of this parameter, the dependence of the dimensionless height of the overflow through the channel wall on the dimensionless current length loses its extreme character, and the height of the overflow layer along the channel decreases. The influence of the acting forces parameter on the nature of this dependence remains throughout the entire range of changing values, but with an increase in the value of the process parameter of the fluid overflow through the channel wall, the influence of the value of the acting forces parameter on the value of the dimensionless height of the overflow through the channel wall significantly decreases.

3. The velocity of a decrease in the flow rate along the channel length remains constant for all the studied cases, but is variable depending on the value of the parameter that takes into account the occurrence of fluid overflow through the channel wall. It has been determined that as this parameter value increases, the velocity of a decrease in the fluid flow rate along the channel length increases, while the influence of the acting forces parameter on this value can be neglected within the limits of calculations with engineering accuracy.

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Дослідження безнапірної течії в гідротехнічних системах гірничих підприємств

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Мета. Метою дослідження є створення математичної моделі безнапірної течії в каналі з існуванням на деяких ділянках шару переливу через борт, яка б дозволяла розраховувати висоту й довжину шару переливу та змінення витрати в каналі за рахунок видалення частини рідини через перелив.

Методика. При проведенні дослідження в роботі використано комплексний багатоетапний аналітичний підхід. Спочатку з метою створення математичної моделі безнапірної течії в каналі з існуванням на деяких ділянках шару переливу через борт в цій роботі аналітично визначено залежність витрати через борт каналу на основі формул для розрахунку коефіцієнту витрати водозливів. На другому етапі розроблено математичну модель безнапірної течії гідросуміші в прямокутному каналі з переливом через борт для визначення параметрів та режимів течії потоку.

Результати. Отримано залежності безрозмірних висоти переливу над бортом каналу та ефективної критичної глибини течії від безрозмірної поточної довжина каналу для різних значень параметрів діючих сил та параметру процесу перетікання рідини через борт каналу. Це дозволило дослідити динаміку змінення цих величин вздовж каналу при різних значеннях вказаних параметрів, та оцінити ступінь спливу відповідних факторів на характеристики безнапірної течії вздовж каналу та процес перетікання рідини через його борт.

Наукова новизна. Вперше модель безнапірної течії в каналі узагальнена на випадок існування на деяких ділянках шару переливу через борт, коли довжина та висота шару переливу не визначається отвором у боковій поверхні, а регулюється зменшенням відповідної витрати. Ця модель вперше дозволяє розрахувати розраховувати висоту й довжину шару переливу та змінення витрати в каналі за рахунок видалення частини рідини через перелив у випадках переповнення каналу потоком при несталих та не розрахункових режимах течії.

Практична значимість. Математична модель та результати розрахунків можуть бути використані для забезпечення екологічної безпечності логістичних систем гірничих підприємств, а також для оцінки обсягів забруднення навколишнього середовища при переливі через борт каналів безнапірного гідравлічного транспорту відходів збагачення корисних копалин та промислових відходів металургійних комбінатів.

Ключові слова: *канал, перелив, течія, логістика, екологія, забруднення, безпека, гідросуміш*