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Satbayev University

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ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруды. Web of Science зерттеушілер, авторлар, баспашилар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енүі біздің қогамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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FINITE ELEMENT STUDIES OF FLOW PROCESSES IN HYDROCYCLONES AND LOSS OF HEAD-ON FLOW MIXING

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Abstract. The economic efficiency of hydrocyclone pumping units depends entirely on the amount of specific energy loss during the thickening of the slurry in the hydrocyclone. In many cases, head loss is determined empirically. And this often makes it difficult to design new designs of hydrocyclone pumping units in advance. The problem is exacerbated by the fact that the available scientific results relate to cocurrent flows, while the hydrocyclone pumping unit flows are mostly swirling. Therefore, at the Kuban State Agrarian University (Russia), a study was carried out using mathematical (numerical) and physical methods based on modern hydrodynamics (Computational fluid dynamics, CFD) of mass transfer, liquid and gas flows, as well as other flow processes. The results of the hydrocyclone pressure distribution data obtained during the study, the average velocity of external downdrafts and internal updrafts, were used to determine the head loss in the hydrocyclone. In general, all those issues related to head loss that have been solved for cocurrent (axial) flows should be reconsidered from the point of view of swirling flows. The volume of such works is very large and require huge theoretical and experimental studies. In this regard, this work is only the beginning of a series of similar developments.

Keywords: Hydrocyclone pumping unit, head loss, co-current flow, swirling flow, external downward flow, internal upward flow

© К.Р. Джабагиева¹, Г.В. Дегтярев², А.М. Байтелиева¹, С.М. Лайық^{1*}, Р.А. Пернебаева¹, 2023

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Аннотация. Гидроциклондық сорғы қондырығыларының экономикалық тиімділігі толығымен гидроциклондағы суспензияның қоюлануы кезіндегі менишкіті энергия шығынының мөлшеріне байланысты. Қөптеген жағдайларда эмпирикалық түрде анықталады және бұл көбінесе гидроциклондық сорғы қондырығыларының жана конструкцияларын алдын ала жобалауды қынданатады. Гидроциклондық сорғы қондырығысының ағындары негізінен бұралған ағындарға қатысты қолда бар ғылыми нәтижелер проблеманы қынданатады. Сондықтан Кубань мемлекеттік аграрлық университетінде (Ресей) масса алмасудың, сұйық және газ ағындарының, сондай-ақ басқа да ағындардың заманауи гидродинамикасына (Есептік сұйықтық динамикасы, CFD) негізделген математикалық (сандық) және физикалық әдістерді қолдану арқылы зерттеу жүргізілді. Зерттеу барысында алынған гидроциклон қысымының таралу деректерінің нәтижелері, сыртқы тәмен және ішкі көтерілістердің орташа жылдамдығы гидроциклондағы қысымының жоғалуын анықтау үшін пайдаланылды. Тұастай алғанда, ағымдық (осытқі) ағындар үшін шешілген бас жоғалтуға қатысты барлық мәселелерді айналмалы ағындар түрғысынан қайта қарастырылады. Мұндай жұмыстардың көлемі өте үлкен және орасан зор теориялық және эксперименттік зерттеулерді қажет етеді.

Түйін сөздер: Гидроциклондық сорғы қондырығысы, қысымының жоғалуы, коток ағыны, айналмалы ағын, сыртқы тәмен ағын, ішкі жоғары ағын

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ИССЛЕДОВАНИЯ МЕТОДОМ КОНЕЧНЫХ ЭЛЕМЕНТОВ ПРОЦЕССОВ ПОТОКА В ГИДРОЦИКЛОНАХ И ПОТЕРИ НАПОРА НА СМЕШЕНИЕ ПОТОКА

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Аннотация. Экономическая эффективность гидроциклических насосных установках всецело зависит от величины потери удельной энергии при сгущении гидросмеси в гидроциклоне. Во многих случаях потери напора определяют опытным путем. А это часто затрудняет заранее спроектировать новые конструкции гидроциклических насосных установок. Проблема усугубляется еще тем, что имеющиеся научные результаты относятся к прямоточным потокам, тогда как гидроциклической насосной установке течения в основном закрученные. Поэтому в Кубанском государственном аграрном университете (Россия) проводилась исследование с использованием математических (численных) и физических методов, основанные на современной гидродинамике (Computational fluid dynamics, CFD) массаобмена, потоков жидкости и газа, а также других процессов потока. Результаты данных распределения давления в гидроциклоне, полученных в ходе исследования, средняя скорость внешних нисходящих и внутренних восходящих потоков, использовались для определения потери напора в гидроциклоне. Вообще все те вопросы, связанные с потерей напора, которые нашли решения для прямоточных (осевых) потоков, следует пересмотреть с точки зрения закрученных потоков. Объем таких работ очень большой и требуют проведения огромных теоретических и экспериментальных исследований. В этом плане данная работа является только началом целой серии подобных разработок.

Ключевые слова: гидроциклонная насосная установка, потери напора, прямоточный поток, закрученный поток, внешний нисходящий поток, внутренний восходящий поток

Introduction

One of the important issues in the hydraulics of hydrocyclone pumping units is the determination of the loss of specific energy (head) in the hydrocyclone (Abduramanov, 2011).

The hydrocyclone as a classifying (thickening) apparatus is a short, hollow cylindrical-conical tube, which has found wide application in almost all industries (Imanaliyev et al., 2022). The field of application of hydrocyclones over the past decades has been expanding even faster due to the creation of a new class of vacuum hydrocyclone pumping units (Abduramanov et al., 2006).

A hydrocyclone is an apparatus in which the classification of slurries into constituent components or thickening of the solid phase is carried out (Abduramanov et al., 2000).

In hydrocyclone installations, many technological processes can be carried out (Gutman et al., 1983): classification of homogeneous particles by size, separation of slurry by elements (phases) into two, three or more products;

solid phase thickening, liquid purification from mechanical impurities, separation of slags from non-ferrous metals and others.

In order to perform these processes efficiently in hydrocyclone pumping systems, the head loss must be known (Idelchik, 1975).

The investigated hydrocyclone has the following design characteristics (Zhurba et al., 2003):

- the inlet branch pipe of the hydrocyclone chamber is located perpendicularly relative to its longitudinal axis;
- sand pipe - single-product;
- hydrocyclone chamber – cylindrical-conical;
- drain pipe – solid, single.

The geometric characteristics of the hydrocyclone installation are shown in Figure 1.

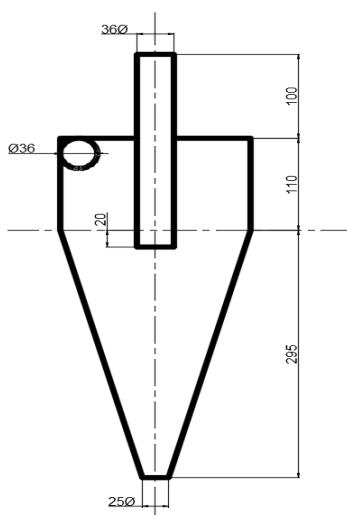


Figure 1 - Geometric characteristics of the hydrocyclone installation

To study the structural characteristics of the hydrocyclone (Computational dynamics fluid, CDF) (Kryazhevsky et al., 2000), its 3D model based on the above geometric characteristics was developed in the software package. The result of which is shown in Figure 2.

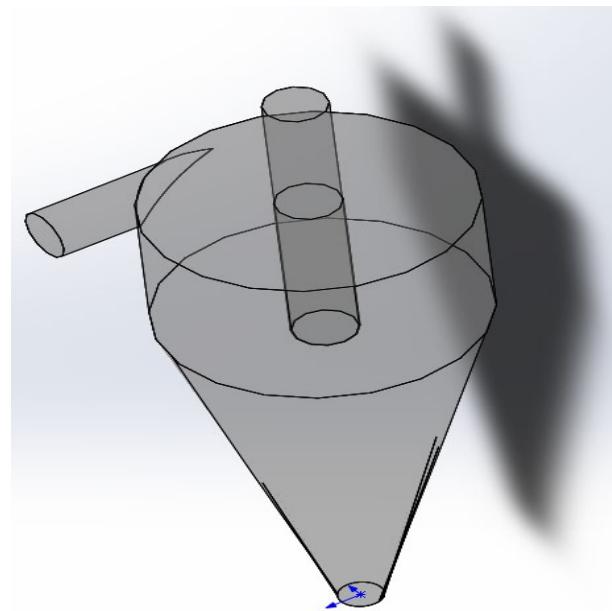


Figure 2-3D model of the hydrocyclone

By means of mathematical modeling in the FlowVision software package, a computational finite element mesh was modeled, which makes it possible to obtain the hydrodynamic characteristics of the hydrocyclone under study during the calculation (Kukolevsky et al., 1981). The result of which is shown in Figure 3. At a pressure at the inlet to the hydrocyclone chamber equal to 70 cm of water column or 6864.2 Pa.

Also represented is the movement of the fluid, expressed as a flash of speed. The result of which is shown in Figure 4.

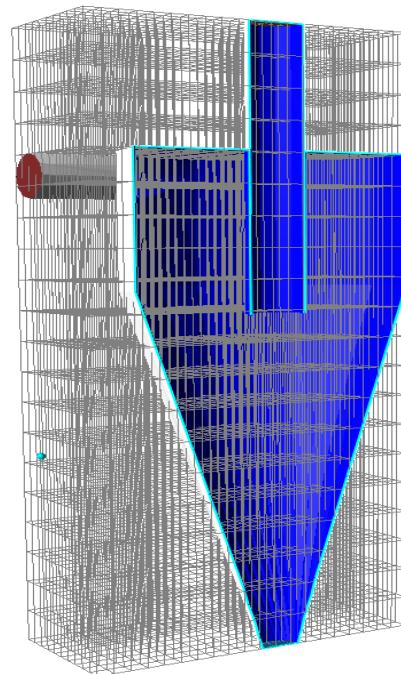


Figure 3 - Calculation mesh of finite elements

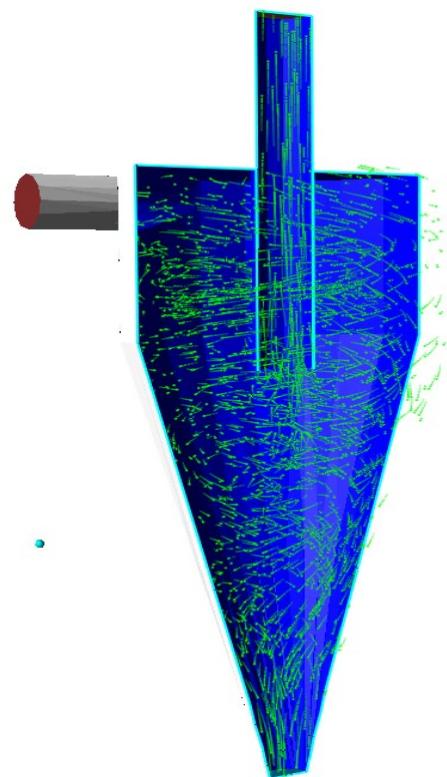
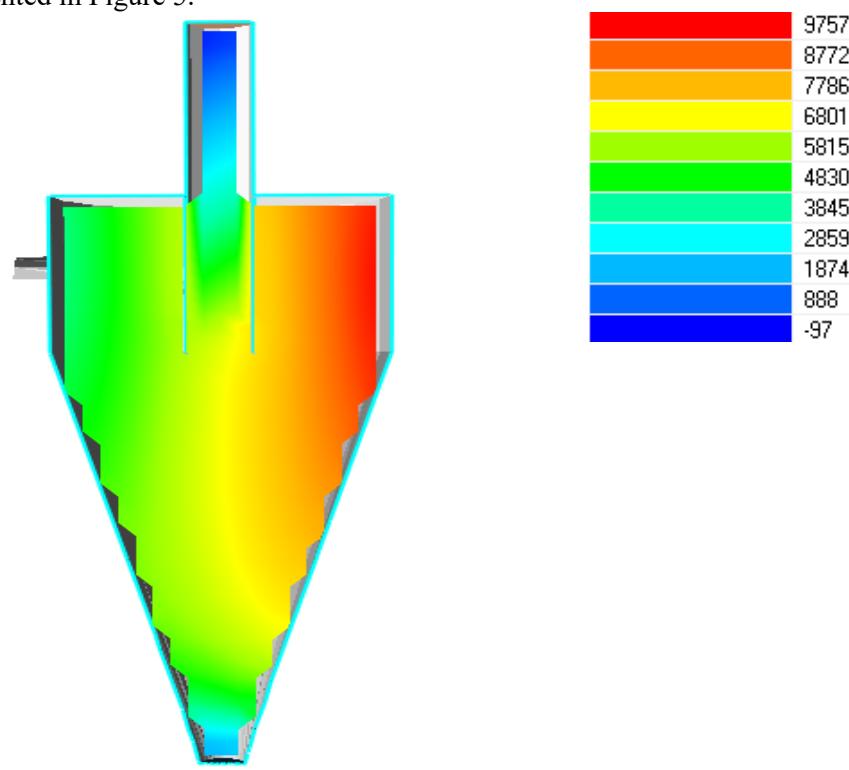


Figure 4 - Fluid movement expressed as a flash of speed

The data on pressure distribution in the hydrocyclone chamber are expressed by filling pressure and are presented in Figure 5.



Picture 5 - Filling from pressure

For a detailed analysis of the hydrodynamic characteristics, graphs of pressure and velocity modulus are presented (Fig. 6). These graphs were built in sections, the beginning of which is taken from the drain pipe.

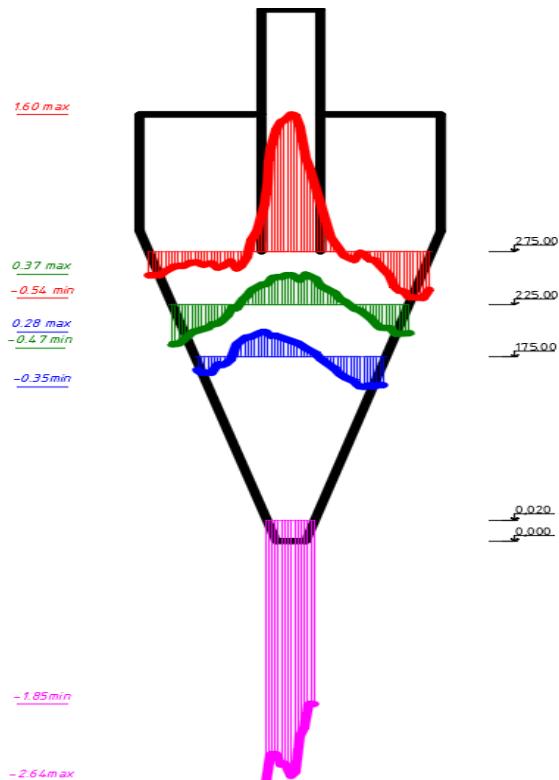


Figure 6 - Graphs of velocities in the section at around 20, 175.225.275 mm

When determining the head loss of a hydrocyclone, the velocities of the internally ascending and externally descending flows were used based on the hydrodynamic parameters of the hydrocyclone at a level of 275.00 mm (Fig. 7).

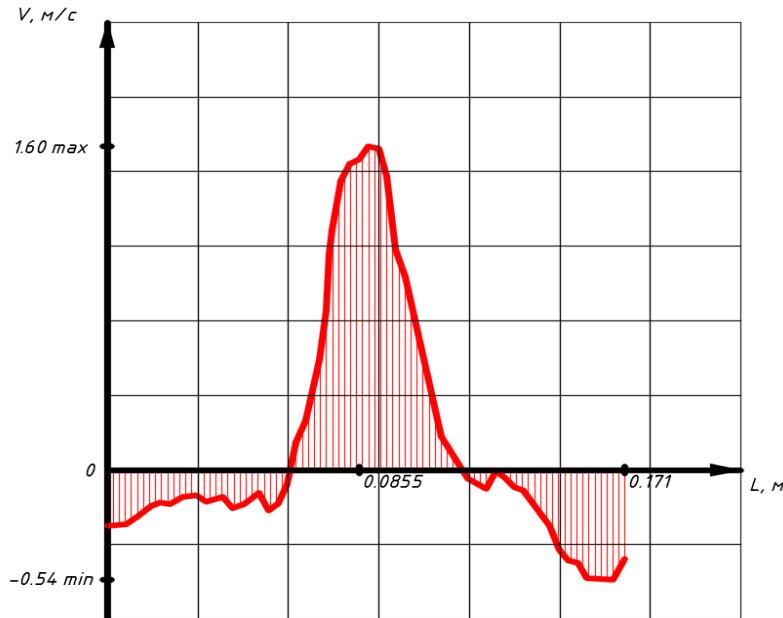


Figure 7 - Graph of speed at around 275.00 mm

The speeds obtained by mathematical modeling and the distribution of pressure in the hydrocyclone chamber are more consistent with the parameters obtained experimentally. Therefore, the above features of the flows in the hydrocyclone will be used in determining the head loss (Kiselev et al.,).

Head loss due to flow mixing

This type of pressure loss occurs in the conical part of the apparatus, where the movement of each of the flows occurs with a variable flow rate along the path (Salakhov, 1968).

Consider two sections, I-I and II-II, separated from each other at a distance, for a time $\Delta t = 1c$ interval. Then, based on the theorem on the change in momentum, we have (Ternovsky et al., 1994):

$$\rho(\alpha_2 \bar{g}_{z_2}^2 \omega_2 - \alpha_1 \bar{g}_{z_1}^2 \omega_1) = F \quad (1)$$

where, $\bar{g}_{z_1}, \bar{g}_{z_2}$ – average values of axial speeds, respectively, in sections I and II;
 ω_1, ω_2 – cross-sectional area, respectively, in I and II sections;
 ρ – liquid density;
 F – total acting force.

Without taking into account friction forces $\alpha_1 \approx \alpha_2 \approx 1$ and with expression (1), it has the form (Bradly, 1965)

$$\rho g_{z_2}^2 \omega_2 - \rho g_{z_1}^2 \omega_1 = p_1 \omega_1 - p_2 \omega_2 \quad (2)$$

where, p_1, p_2 – average pressure values, respectively, in sections I and II.

As is known for rotational motion (Svarovsky L., 1977)

$$\frac{dh}{dr} = \frac{g_{\phi}^2}{gr}, \quad (3)$$

where, g_{ϕ} – tangential speed;

r – arbitrary radius.

Substituting the values into this equation and integrating it, you can get the head loss over a given section (piezometric head increment). Let us determine the head loss separately for the downward and upward flows (Abdiramanov et al., 2016):

1a) for the downstream, we rewrite formula (2) in a different form

$$\rho g_{z_{2H}}^2 \omega_{2H} - \rho g_{z_{1H}}^2 \omega_{1H} = p_{1H} \omega_{1H} - p_{2H} \omega_{2H}, \quad (4)$$

where the indices 1H and 2H refer to the downward flow in sections I and II (Abduramanov, 1987):

if we assume that pressure is the sum of its piezometric and centrifugal components, then

$$p_{1H} = \rho gh_{1H} + \rho gh_{luH} \quad (5)$$

$$p_{2H} = \rho gh_{1H} - \rho gdz + \rho gh_{2uH}. \quad (5')$$

For determination h_{luH} we integrate equation (3) with a known value $g_{\phi H}$

$$g_{\phi H} = g_{\phi cr} \left(\frac{r_u}{r} \right)^n$$

Within the change of dr from rw to rc, the height dh changes from h1H to h1c, therefore, from equation (3) (Sun et al., 2020)

$$h_{1H} - h_{luH} = \int_{r_w}^{r_u} \frac{g_{\phi cr}^2}{gr} \left(\frac{r_u}{r} \right)^{2n} dr = \frac{g_{\phi cr}^2}{2gn} \left(\frac{r_u^{2n}}{r_w^{2n}} - 1 \right), \quad (6)$$

$$\text{or} \quad h_{luH} = h_{1H} - \frac{g_{\phi cr}^2}{2gn} \left(\frac{r_u^{2n}}{r_w^{2n}} - 1 \right).$$

$$\text{Differently} \quad h_{luH} = h_{1H} + \frac{g_{\phi cr}^2}{2gn} - \frac{g_{\phi cr}^2}{2gn} \frac{r_u^{2n}}{r_w^{2n}},$$

where rc is the radius of the cyclone in the given section;

– near-wall tangential velocity;

rw is the radius of the Abduramanov quasi-surface.

Knowing that (Wang et al., 2018)

$$g_{\phi cr} = \delta g_{Z_{rec}} \left(1 - \frac{Z}{T} \right)^m; \quad (7)$$

$$r_u = kz + r_{rec};$$

and

$$r_{w1} = k_1 z + r_{cb} = k_1(z - a) + r_{cb}$$

where,

$$K = \operatorname{tg} \alpha; K_1 = \operatorname{tg} \beta$$

we rewrite formulas (5) and (5') in the form

$$p_{1H} = \rho g \left[h_H + 2\delta_1^2 \frac{g_{nec}^2}{2g} \left(1 - \frac{z}{T} \right) \left(\frac{kz + r_{nec}}{k_1 z + r_{cb}} - 1 \right) \right]; \quad (8)$$

$$p_{2H} = \rho g \left[h_H - dh_H + 2\delta_1^2 \frac{g_{nec}^2}{2g} \left(1 - \frac{z + dz}{T} \right) \left(\frac{k(z + dz) + r_{nec}}{k_1(z + dz) + r_{cb}} - 1 \right) \right]. \quad (8')$$

The cross-sectional areas of the external (peripheral, external) flow are determined from the equality:

$$\omega_{1H} = \Pi(r_{u_1}^2 - r_{w_1}^2); \quad (9)$$

$$\omega_{2H} = \Pi(r_{u_2}^2 - r_{w_2}^2). \quad (9')$$

The average values of axial velocities in these sections will be:

$$\bar{g}_{Z_{1H}}^2 = \bar{g}_{nec}^2 \left(1 - \frac{z}{T} \right); \quad (10)$$

$$\bar{g}_{Z_{2H}}^2 = \bar{g}_{nec}^2 \left(1 - \frac{z + dz}{T} \right). \quad (10')$$

Substituting values $p_1, p_2, \bar{g}_{Z_{2H}}, \omega_{1H}, \omega_{2H}$ into formula (4) and carrying out a series of transformations at ($\omega_{1H} \equiv \omega_{2H} = \omega_H$) $p_{1H} - p_{2H} \equiv \rho g dh_H$ you can write:

$$dh_H = \frac{g_{nec}^2}{g} \frac{dz}{T},$$

From where, after integration, we get (Haicai L. V., and et all, 2018):

$$h_H = \frac{2z}{T_k} \frac{g_{nec}^2}{2g} + C.$$

then $Z=0$, head loss $h_{wH} = 0$, so the constant of integration $C=0$, means

$$h_H = \frac{2z}{T_k} \frac{g_{nec}^2}{2g} = \zeta_{nec} \frac{g_{nec}^2}{2g}, \quad (11)$$

where,

$$\zeta_{nec} = \frac{2z}{T_k}.$$

1b) for the upward flow, formula (2) takes the form

$$p_{1B}\omega_{1B} - p_{2B}\omega_{2B} = \rho \bar{g}_{Z_{2B}}^2 \omega_{2B} - \rho \bar{g}_{Z_{1B}}^2 \omega_{1B} \quad (12)$$

where, $p_{1B} = \rho gh_b + \rho gh_{1B}$

h_{1B} is determined by integrating formula (3) with (Ibrayev T.T., and et all, 2022).

$$\begin{aligned} \bar{g}_\varphi &= \bar{g}_{\varphi w} \left(\frac{r_w}{r_x} \right)^n \\ h_{1B} &= \int_{r_{cb}}^{r_w} \frac{\bar{g}_{\varphi w}^2 \left(\frac{r_w}{r_x} \right)^{2n}}{gr_x} dr_x = \frac{1}{n} \left(\frac{r_w^{2n}}{r_{cb}^{2n}} - 1 \right) \frac{\bar{g}_{\varphi w}^2}{2g} + h_{cb} \end{aligned} \quad (13)$$

means

$$p_{1B} = \rho g \left\{ h_b + \frac{\bar{g}_{\varphi w}^2}{2gn} \left(\frac{r_w^{2n}}{r_{cb}^{2n}} - 1 \right) \right\} + p_{cb}, \quad (14)$$

where $\bar{g}_{\varphi w}$ - tangential velocity of fluid particles on the line of zero axial velocities [22, b.335],

$$\bar{g}_{\varphi w} = A \bar{g}_{bx} \left(\frac{R_u}{r_{cb} + kz_B} \right)^{\frac{1}{2}};$$

$$p_{1_B} = \rho g \left\{ h_B + \frac{1}{2gn} A^2 g_{_{BX}}^2 \frac{R_u}{r_{cb} + kz_B} \left(\frac{r_{cb} + k_z}{r_{cb}} - 1 \right) \right\}; \quad (15)$$

$$p_{2_B} = \rho g \left\{ h_B - dh_B + \frac{1}{2gn} A^2 g_{_{BX}}^2 \frac{R_u}{r_{cb} + k(z_B + dz_B)} \left[\frac{r_{cb} + k(z + dz)}{r_{cb}} - 1 \right] \right\}. \quad (15')$$

By analogy with the external flow, and the areas of the internal (paraxial) flow in sections I and II, respectively, are equal to:

$$\omega_{1_B} = \Pi(r_{w_1}^2 - r_{cb_1}^2);$$

$$\omega_{2_B} = \Pi(r_{w_2}^2 - r_{cb_2}^2).$$

The average values of the axial velocities of the internal flow in sections I and II are equal.

$$\bar{g}_{Z_{1_B}}^2 = \bar{g}_{Z_{cI}}^2 \left(\frac{z}{h_B} \right)^{2n};$$

$$\bar{g}_{Z_{2_B}}^2 = \bar{g}_{Z_{cI}}^2 \left(\frac{z + dz}{h_B} \right)^{2n}.$$

Substituting values $p_{1_B}, p_{2_B}, \omega_{1_B}, g_{Z_{1_B}}, g_{Z_{2_B}}$ in (12) and, as before, the gently sloping $k_1 \approx k$, ($\omega_{1_B} \approx \omega_{2_B}$), $n = 0.5$, $p_{1_B} - p_{2_B} = \rho g d h_B$ find:

$$dh_B = \frac{\rho}{\rho g} g_{cI}^2 \frac{dz}{h_B}.$$

$$\text{From where, after integration, we get } h_{wB} = \frac{2z}{h_B} \frac{g_{cI}^2}{2g} + C.$$

If $Z \rightarrow 0$ head loss $h_{wB} \Rightarrow 0$, hence the constant of integration $C=0$.

Means

$$h_{wB} = \frac{2z}{h_B} \frac{g_{cI}^2}{2g} = \zeta_{wB} \frac{g_{cI}^2}{2g}, \quad (16)$$

where,

$$\zeta_{wK} = 2 \frac{z}{h_K} = 2 \left(\frac{z}{h_K} - \frac{a}{h_K} \right)$$

The total pressure loss for mixing the flow in the conical part of the hydrocyclone $h_{w.c.} = h_{wH} + h_{wB} = \frac{2z}{T} \frac{g_{nec}^2}{2g} + \frac{2z}{h_B} \frac{g_{cI}^2}{2g}$

$$\text{or } h_{w.c.} = \zeta_{nec} \frac{g_{nec}^2}{2g} + \zeta_{wB} \frac{g_{cI}^2}{2g}.$$

Since intensive mixing occurs precisely in the conical part, where $z \rightarrow H_k$, $z \rightarrow h_B$, then finally we have

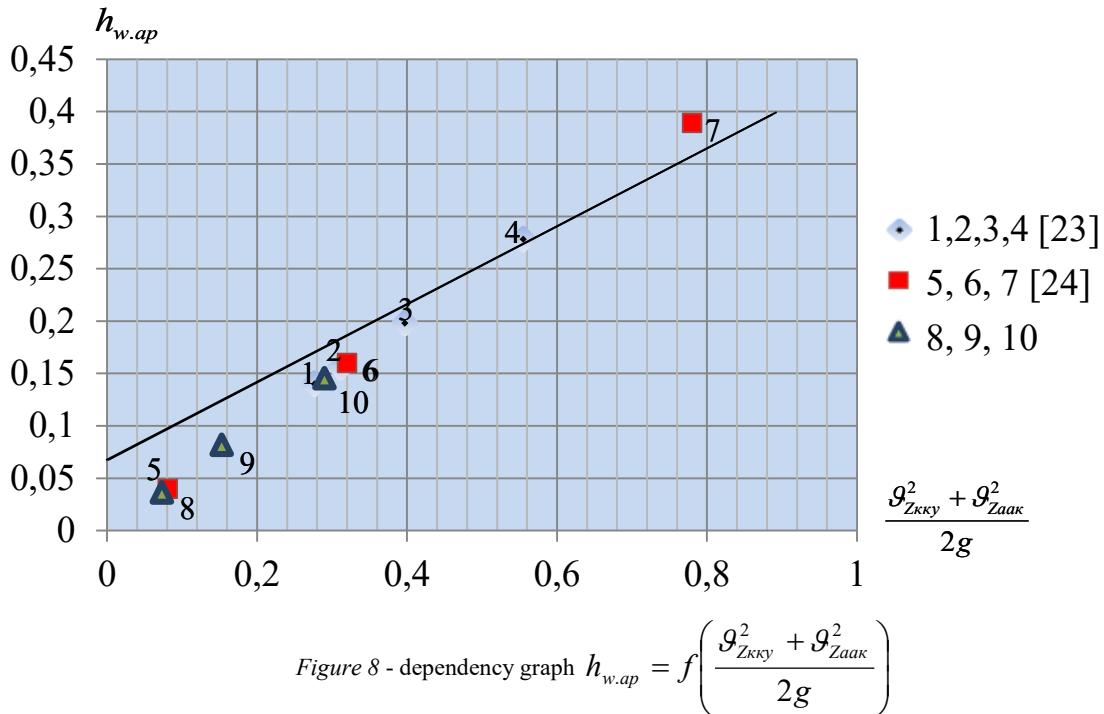
$$h_{w.c.} = 2 \frac{g_{Znne}^2}{2g} + 2 \frac{\bar{g}_{Zcc}^2}{2g} = 2 \left(\frac{g_{Znne}^2 + g_{Zcc}^2}{2g} \right) \quad (17)$$

The results of determining the pressure loss for mixing the flow in the conical part of the hydrocyclone based on the data of experimental studies are shown in the table (Table 1) and plots are plotted (Fig. 8).

Table 1 - Definitions according to the formula for the loss of pressure for mixing the flow in the conical part of the hydrocyclone.

Nº	$g_{z_{KKY}}$	$g_{z_{AAK}}$	$h_{w.ap}$	$\frac{g_{Z_{KKY}}^2 + g_{Z_{AAK}}^2}{2g}$
Experimental data of A. Abduramanov				

1	1,33	0,97	0,2765	0,14
2	1,35	1,11	0,31169	0,1557
3	1,39	1,40	0,397	0,198
4	1,41	1,86	0,555	0,278
Experimental data of A.I. Zhangarin				
5	2,39	1,39	0,780	0,389
6	1,41	1,08	0,32	0,16
7	0,71	0,54	0,081	0,04
Experimental data of K. Zhabagieva				
8	0,27	0,8	0,073	0,0364
9	0,40	1,2	0,153	0,082
10	0,54	1,6	0,29	0,1455



As you can see (Fig. 8) $h_{w.ap}$ the pressure loss for mixing the flow in the conical part of the hydrocyclone

depends on the speed $\left(\frac{g_{ZKKy}^2 + g_{Zaak}^2}{2g}\right)$ downstream and upstream.

Conclusion

To study the structural characteristics of the hydrocyclone (Computational dynamics fluid, CDF), its 3D model based on the above geometric characteristics was developed in the software package.

Using mathematical modeling in the FlowVision software package, a computational finite element mesh was modeled, which makes it possible to obtain the hydrodynamic characteristics of the hydro cyclone under study during the calculation. Also represented is the movement of the fluid, expressed as a flash of speed.

For a detailed analysis of hydrodynamic characteristics, graphs of pressure and velocity modulus are presented.

In determining the head loss of a hydrocyclone, the velocities of internally ascending and externally descending flows were used based on the hydrodynamic performance of the hydrocyclone at a level of 275.00 mm.

As a result, a formula was found for determining the pressure loss when mixing flows, based on the experimental data, the pressure loss in the hydrocyclone was found, and a dependency graph was constructed.

The results of our study will be used in the study of energy issues in the use of hydro cyclone pumping units. The formula for determining the head loss during mixing flows will be used by researchers in the study of head loss in various designs of hydrocyclones and hydrocyclone pumping units.

The results of our research can be used to determine the pressure loss in new hydro cyclone pumping units, filter cyclones, filter cyclone pumping units, vacuum hydro cyclone pumping units, single-surface and double-surface vortex jet apparatuses, hydro cyclone-jet apparatuses.

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