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# O‘ZGARUVCHAN KESIMGA EGA KANALDA SUYUQLIK OQIMINING NOSTATSIONAR MASALASI

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***Annotatsiya.*** *Mazkur maqolada o‘zgaruvchan kesim yuzali kanallarda suyuqlik oqimining statsionar va nostatsionar harakati matematik modellashtirilgan. Tadqiqotda kichik g‘alayonlar usuli, Gurevich–Xaskind hamda Kuznetsov yondashuvlari asosida nostatsionar oqim parametrlarini aniqlash masalasi ko‘rib chiqilgan. Oqimning kompleks potensiali, tezlik va bosim maydonlarini aniqlash uchun analitik formulalar keltirilgan hamda erkin chegara uchun kinematik va dinamik shartlar hosil qilingan. Torayuvchi kanalda pulsatsiyalanuvchi oqimlarning xossalari tahlil qilinib, bosim amplitudasi va fazasining Struxal soniga bog‘liqligi o‘rganilgan. Tadqiqot natijasida kanalning siqilish zonasida yuzaga keladigan uyurmalik oqim parametrlarini hisoblashning analitik usuli ishlab chiqilgan hamda uyurmasiz oqimni ta’minlaydigan kanal shaklini aniqlash usuli taklif etilgan.*

***Kalit so‘zlar:*** *o‘zgaruvchan kesimli kanal, nostatsionar oqim, statsionar oqim, kichik g‘alayonlar usuli, Gurevich–Xaskind usuli, kompleks potensial, suyuqlik dinamikasi, erkin chegara, uyurmalik oqim, bosim amplitudasi, Struxal soni, Keldish–Sedov formulasi, matematik model, kanal geometriyasi, analitik yechim.*

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# НЕСТАЦИОНАРНАЯ ЗАДАЧА ТЕЧЕНИЯ ЖИДКОСТИ В КАНАЛЕ ПЕРЕМЕННОГО СЕЧЕНИЯ

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***Аннотация.*** *В данной статье математически моделируется стационарное и нестационарное поведение течения жидкости в каналах с переменным поперечным сечением. Рассматривается задача определения параметров нестационарного течения на основе метода малых возмущений, подходов Гуревича–Хаскинда и Кузнецова. Представлены аналитические формулы для определения комплексных потенциальных, скоростных и давленых полей течения, а также выведены кинематические и динамические условия для свободной границы. Проанализированы свойства пульсирующих течений в сужающемся канале, изучена зависимость амплитуды и фазы давления от числа Струхале. В результате исследования разработан аналитический метод расчета параметров турбулентного течения, возникающего в зоне сжатия канала, и предложен метод определения формы канала, обеспечивающей турбулентное течение.*

***Ключевые слова****: канал с переменным поперечным сечением, нестационарное течение, стационарное течение, метод малых возмущений, метод Гуревича–Хаскинда, комплексный потенциал, гидродинамика, свободная граница, турбулентное течение, амплитуда давления, число Струхала, формула Келдыша–Седова, математическая модель, геометрия канала, аналитическое решение.*

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# UNSTEADY PROBLEM OF FLUID FLOW IN A CHANNEL OF VARIABLE CROSS-SECTION

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***Abstract.*** *This article mathematically models the stationary and unsteady behavior of fluid flow in channels with variable cross-sections. The study considers the problem of determining unsteady flow parameters based on the method of small disturbances, Gurevich–Haskind and Kuznetsov approaches. Analytical formulas are presented for determining the complex potential, velocity and pressure fields of the flow, and kinematic and dynamic conditions for the free boundary are derived. The properties of pulsating flows in a narrowing channel are analyzed, and the dependence of the pressure amplitude and phase on the Struxhal number is studied. As a result of the study, an analytical method for calculating the parameters of the turbulent flow that occurs in the compression zone of the channel is developed, and a method for determining the channel shape that ensures turbulent flow is proposed.*

***Keywords:*** *channel with variable cross-section, unsteady flow, steady flow, small perturbation method, Gurevich–Haskind method, complex potential, fluid dynamics, free boundary, turbulent flow, pressure amplitude, Struchal number, Keldysh–Sedov formula, mathematical model, channel geometry, analytical solution.*

## Kirish

Hozirgi kunda respublikamiz hududidagi oʻzgaruvchan kesimli kanallarda suvning nostatsionar oqimi gidravlik va geometrik parametrlarini aniqlash masalalari yetarli darajada oʻrganilmagan. Bunday kanallarda oqimning murakkab tuzilishi natijasida uyurmali va kavitatsion zonalar hosil boʻlib, ushbu sohalarda loyqa choʻkindilarining toʻplanishi oqim strukturasining buzilishiga hamda kanal devorlarining yemirilishiga sabab boʻladi. Natijada gidrotexnik inshootlarda gidrodinamik bosim va tezlik pulsatsiyalari ortib, suv sathining pasayishi kuzatiladi, bu esa inshootlarning xavfsiz va ishonchli ishlashiga salbiy ta'sir koʻrsatadi.

Shu munosabat bilan oʻzgaruvchan kesimli kanallarda hosil boʻladigan uyurmali maydonlarning oʻlchamlarini aniqlash hamda nostatsionar oqim sharoitida gidravlik bosim va tezlik maydonlarini hisoblash usullarini takomillashtirish muhim ilmiy-amaliy ahamiyat kasb etadi. Mazkur masala gidrotexnika inshootlari, irrigatsiya va melioratsiya tizimlari hamda gidroenergetika obyektlarining samarali va barqaror faoliyatini ta'minlashda dolzarb vazifalardan biri hisoblanadi.

Oʻzgaruvchan kesimga ega kanallarda suyuqlik oqimining stasionar masalalari siqilmaydigan ideal suyuqliklar nazariyasi doirasida keng oʻrganilgan boʻlib, ular asosan Jukovskiy metodi asosida tadqiq etilgan.

Biroq nostatsionar oqim sharoitida yuzaga keladigan gidravlik jarayonlarni tavsiflash va ularning asosiy parametrlarini aniqlash masalalari yetarli darajada tadqiq qilinmagan. Shu bois ushbu tadqiqotning maqsadi oʻzgaruvchan kesimli kanallarda nostatsionar oqim sharoitida gidravlik hisoblash usullarini takomillashtirishdan iborat.

## Materiallar va uslublar

Mazkur kanaldagi suyuqlik oqimining nostatsionar masalasi esa kichik gʻalayonlar usuliga asoslangan va Gurevich–Xaskind usuli deb nomlanuvchi metod yordamida tadqiq etilgan [1; 2].

Koʻrilayotgan jarayon uchun nostatsionar masalaning formulasi quyidagicha ifodalanadi. Vaqtning boshlangʻich momentida suyuqlik egallagan $D_o$ soha aniq aniqlanadi. Ushbu chegaraning

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bir qismi qattiq devor (kanal devori) bilan cheklangan, qolgan qismi esa erkin sathdan iborat bo‘ladi. Qattiq sirt sharti va erkin sathdagi bosim ma’lum bo‘lgani sababli, vaqt o‘tishi bilan o‘zgaradigan oqim parametrlarini aniqlash vazifasi qo‘yiladi.

Kichik g‘alayonlar usulining umumiy tavsifini keltiramiz [3; 4].

Faraz qilaylik, $w(z)$-stasionar oqimning kompleks potensiali bo‘lsin. Amalda ushbu bog‘lanish quyidagi parametrik ko‘rinish orqali ifodalanadi:

$$w_0(u), \qquad z = z_0(u)\,, \tag{1}$$

bu yerda “u”- kanonik soha bo‘lib, unga fizik tekislik va boshqa sohalar konformal akslantiriladi. Endi stasionar oqimga $\varepsilon$ kichik parametr orqali ifodalangan quyidagi shakldagi kichik g‘alayon qo‘shamiz:

$$\left.\begin{aligned} z(t)&=z_0+\varepsilon z_1(z_0,t),\\ w(z,t)&=w(z_0)+\varepsilon w_1(z_0,t),\\ v(z,t)&=\vartheta_0(z_0)+\varepsilon\vartheta_1(z_0,t),\\ P(z,t)&=P_0(z_0)+\varepsilon P_1(z_0,t)\end{aligned}\right\}, \tag{2}$$

bu yerda: *z*- nostatsionar oqim sohasidagi fizik koordinata; *w*- nostatsionar oqimning kompleks potensiali. $\overline{\vartheta} = \vartheta e^{i\theta}$ kompleks tezlik; $\theta$ - tezlik vektorining *x* o‘qi bilan hosil qilgan burchagi; P - bosim.

“*u*” parametrik o‘zgaruvchini hisobga olgan holda, nostatsionar masala yechimi xuddi stasionar masaladagi kabi quyidagi ikkita funksiya orqali aniqlanadi:

$$z = z(u,t), \qquad w(u,t)\,.$$

Ushbu funksiyalarni kichik g‘alayonlar usuliga ko‘ra quyidagicha ifodalash mumkin:

$$\begin{gathered} z = z_0(u) + \varepsilon z_1(u,t)\\ w = w_0(u) + \varepsilon w_1(u,t)\,. \end{gathered}$$

Xuddi shunday, suyuqlik oqimi tezligi va bosimini mos ravishda quyidagicha ifodalash mumkin:

$$\begin{gathered} \overline{v}(u,t) = \overline{\vartheta}_0(u) + \varepsilon\overline{\vartheta}_1(u,t)\\ P(u,t) = P_0(u) + \varepsilon P_1(u,t)\,. \end{gathered}$$

Ma’lumki, bosim Koshi–Lagranj integralidan aniqlanadi.

$$P + \rho\left(\frac{\partial\varphi}{\partial t} + \frac{1}{2}\left|\vartheta\right|^2\right) = c(t)\,,$$

bu yerda: $\rho$ -suyuqlik zichligi; $\varphi$ - nostatsionar oqimning tezlik potensiali; $c(t)$ - vaqtga bog‘liq funksiya.

Shunday qilib, $z_1, w_1, \vartheta_1, p_1$ to‘rtta parametrdan faqat ikkitasi erkin o‘zgaruvchi bo‘lib, ular orqali qolgan parametrlarni hisoblash muhim ahamiyatga ega. Biz bu metodning kichik tafsilotlariga to‘xtalmay, A.V. Kuznetsov tomonidan rivojlantirilgan va soddalashtirilgan ko‘rinishidan foydalanishga harakat qilamiz [5;6].

Faraz qilaylik, bizda ma’lum bir masalaning stasionar yechimi mavjud bo‘lsin. Endi stasionar yechimdan katta farq qilmaydigan nostatsionar oqim masalasini ko‘rib chiqamiz. Bu yerda nostatsionarlik kanaldagi suyuqlik oqimi tezligining kichik g‘alayonli o‘zgarishlari natijasida yuzaga keladi.

Nostatsionar oqimning kompleks potensiali quyidagicha ifodalanadi:

$$w = w_0 + w_1\,. \tag{3}$$

Endi esa $w(u,t)=\varepsilon w_1=\varphi(u,t)+i\Psi(u,t)$ uchun chegaraviy masalani belgilaymiz. Biz $u=u_0$ ekanligini inobatga olib, doimiy deb hisoblaymiz (haqiqatdan ham kanal devori o‘zgarmas deb qabul qilinadi). (3)-tenglamadan foydalanib, suyuqlik sohasida suyuqlik tezligini quyidagicha ifodalashimiz mumkin:

$$\overline{\vartheta}(\overline{r},t)=\overline{\vartheta}_0(\overline{r})+\Delta\varphi(\overline{r},t)\,, \tag{4}$$

bu yerda; $\vec{r}=\vec{r_0}+\vec{\delta}-D_t$ sohadagi ma’lum bir nuqtaning radius-vektori, ($\vec{\delta}$ -nuqtaning statsionar chegara nisbati bo‘yicha siljishi, $\vec{r_0}$ -statsionar chegaraning radius-vektori) o‘zgaruvchan chegaraning o‘tmaslik sharti asosida, A.V. Kuznetsov tomonidan chegara sirtidagi normal tezlik quyidagi formula yordamida hisoblanadi:

$$\frac{\partial\varphi_1}{\partial\eta}=\frac{\partial\delta_\eta}{\partial t}+\frac{\partial}{\partial s}(\vartheta_\tau\delta_\eta)\,, \tag{5}$$

bu yerda $\overline{r},\overline{n}-D_0$ chegaradagi urunma va normal ortlar; $\delta_n=\overline{\delta}\cdot\overline{n}-\vec{\delta}$ vektorning normaldagi proeksiyasi; $S-D_0$ konturning yoy uzunligi; $\vartheta_\tau-D_0$ chegaradagi urunma tezlik.

(5) shart erkin chegara uchun o‘rinli, ammo undagi $\delta_n$ ni bundan buyon η bilan belgilaymiz, u noma’lum erkin chegarada $ds=ds_0=\dfrac{d\varphi_0}{\vartheta_k}$ bo‘lgani uchun erkin chegaradagi kinematik shartni quyidagicha yozishimiz mumkin

$$\frac{\partial\varphi}{\partial n}=\frac{\partial\eta}{\partial t}+\vartheta_K^2\frac{\partial\eta}{\partial\varphi_0}=D\eta\,\cdot \tag{6}$$

(4)-tenglamadan foydalanib, Koshi–Lagranj integralidan $\overline{r}=\overline{r_0}+\overline{\delta}$ nuqtada 0 gacha bo‘lgan aniqlik darajasida suyuqlik bosimini hisoblashning tarkibiy ifodasi quyidagicha keltiriladi:

$$p(\overline{r_0}+\vec{\delta},t)=p_0(\overline{r_0})-\rho\left(\frac{\partial\phi}{\partial t}+(\vec{\vartheta}\cdot\triangle\varphi)+\vartheta_n\frac{\partial\vartheta}{\partial s}\delta_\tau\right). \tag{7}$$

(7)-tenglamadagi barcha hadlar statsionar chegaralarda hisoblanadi. Ushbu formula erkin chegarada dinamik shartni quyidagi shaklda ifodalash imkonini beradi:

$$\frac{\partial\varphi}{\partial t}+\vartheta_K^2\frac{\partial\varphi}{\partial\varphi_0}+\vartheta_K^2 x\eta=0 \tag{8}$$

(6) va (8) dan $\eta$ ni yo‘qotsak,

$$\vartheta_K^3\frac{\partial\varphi}{\partial n}=D\left[\frac{\partial\varphi_0}{\partial\theta_0}D\varphi\right] \tag{9}$$

ni hosil qilamiz.

Bu yerda

$$D=\frac{\partial}{\partial t}+\vartheta_\kappa^2\frac{\partial}{\partial\varphi_0}\,,$$

$\theta_0-$ statsionar oqimda tezlik vektorining x o‘qi bilan hosil qilgan burchagi. M.I. Gurevich va M.D. Xaskind keyingi hisob-kitoblarni soddalashtirish maqsadida (8) tenglamadan $\vartheta_K^2 x\eta$ hadni chiqarib tashlab, quyidagi soddalashtirilgan ko‘rinishga keldilar [3; 4]:

$$\frac{\partial\varphi}{\partial t}+\vartheta_K^2\frac{\partial\varphi}{\partial\varphi_0}=0 \tag{10}$$

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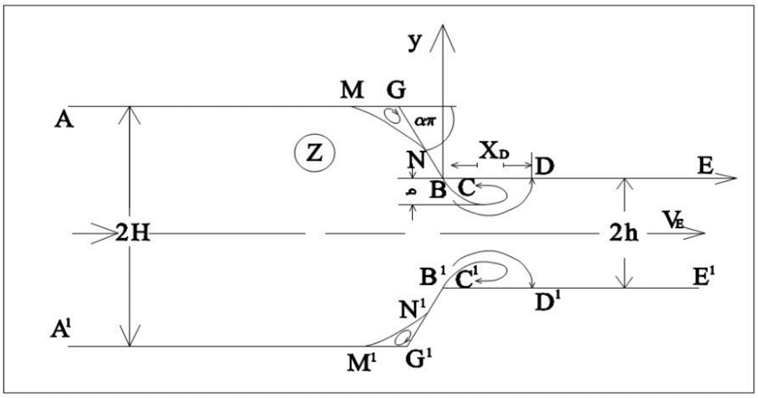
(5), (6) va (10) chegara shartlari kanonik sohada $w(u,t)$ ni aniqlash uchun chegaraviy masalani belgilash imkonini beradi. Bunda, ushbu funksiyaning boshlang‘ich qiymati, cheksiz uzoqdagi nuqtadagi sharti (agar oqim sohasi cheksizgacha cho‘zilgan bo‘lsa) hamda oqimchaning qattiq chegaradan ajraladigan nuqtadagi sharti oldindan ma’lum bo‘lishi zarur.




**1-rasm. Torayuvchi kanalda suyuqlik oqimining sxemasi.**

**Natijalar va muhokama**

Torayuvchi kanalda suyuqlik oqimining barqaror holatini tahlil qilish (1-rasm) va kichik tebranishlar usulini qo‘llash orqali, kanalning cheksiz uzoq nuqtasida suyuqlik tezligining ortishi natijasida yuzaga keladigan nostatsionar oqimlarni o‘rganish mumkin

$$V_A(t) = U + \vartheta(t) \,.$$

Kanalning cheksiz uzoq nuqtasida statsionar tezlik holatidagi garmonik (pulsatsiyalanuvchi) oqim qonuni muhandislik hisoblarida katta ahamiyatga ega

$$\vartheta(t) = \vartheta^* \cdot e^{jkt}\,, \tag{11}$$

bu yerda: $k$ – tebranish chastotasi, $j$ – vaqtinchalik shartli birlik.

$\tau = \dfrac{Ut}{H}$ o‘lchovsiz miqdorni kiritib, (11) -tenglamani quyidagi shaklda ifodalash mumkin:

$$\vartheta(t) = \vartheta^* \cdot e^{j\omega\tau}\,. \tag{12}$$

Bunda

$$\omega = \frac{kH}{U}\,.$$

Nostatsionar oqim masalasining keyingi hisoblash jarayonlarini soddalashtirish maqsadida, $MN$ konturi qattiq devor sifatida qabul qilinadi va ushbu devor bo‘ylab $\dfrac{\partial\tilde{\varphi}}{\partial n} = 0$ deb olinadi.

Shunda $\dfrac{\partial\tilde{w}}{\partial u}$ funksiyasi uchun chegaraviy shartlar quyidagi ko‘rinishda ifodalanadi.

$$\operatorname{Im}\frac{d\tilde{w}}{du} = 0, \quad -\infty < u < -1, \quad 1 < u < \infty. \tag{13}$$

Erkin chegarada bosimning doimiy bo‘lishi shartidan quyidagi natija hosil bo‘ladi.

$$\operatorname{Re}\frac{d\tilde{w}}{du} = -C_1 e^{-\frac{j\omega}{V_k^2}\varphi_0}\frac{d\tilde{\varphi}}{d\varphi_0}, \qquad u \in [-1,1] \tag{14}$$

Bunda

$$w = \tilde{w}e^{-j\omega\tau}\,.$$

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Tashqi ta’sir ostida yuzaga kelgan oqimni ifodalash usuli $\frac{d\tilde{w}}{du}$ funksiyaning $u=0$ nuqtada oddiy qutbga ega bo‘lishini talab qiladi. Ushbu holatni, shuningdek (13) va (14) chegaraviy shartlarni e’tiborga olib, umumlashtirilgan Keldish–Sedov formulasidan foydalanish orqali aralash chegaraviy masalaning yechimini quyidagi ko‘rinishda yozish mumkin: [7;9]

$$\frac{d\tilde{w}}{du}=\frac{1}{\sqrt{u^2-1}}\left[\frac{C_1}{\pi}\int_{-1}^{1}\sqrt{\frac{1-\xi}{1+\xi}}\frac{(\xi+d)e^{-\frac{j\omega\lambda^2\varphi_0(\xi)}{Q}}}{(a-\xi)(\xi-u)}d\xi+\frac{C_2}{u-a}\right], \tag{15}$$

bu yerda $\lambda=\frac{U}{V_k}$; $C_2$ (11) dan aniqlanadi

$$C_2=\frac{Q\vartheta^*\cdot\sqrt{a^2-1}}{\pi U}. \tag{16}$$

$C_1$- qiymati $\frac{d\tilde{w}}{du}$ funksiyaning $u=1$ nuqtasida cheklangan bo‘lishi shartidan aniqlanadi.

$$\frac{C_1}{\pi}\int_{-1}^{1}\frac{(\xi+d)e^{-\frac{j\omega\lambda^2\varphi_0(\xi)}{Q}}}{\sqrt{1-\xi^2}(a-\xi)}d\xi+\frac{C_2}{a-1}=0.$$

Bu holat oqimning ajralish nuqtasida nostatsionar tezlikning cheklangan bo‘lishini ko‘rsatadi. Shundan kelib chiqib, oxirgi tenglamadan quyidagi ifoda aniqlanadi:

$$C_1=\frac{Q\vartheta^*}{U}\sqrt{\frac{a+1}{a-1}}\frac{1}{I(1,\omega)}, \tag{17}$$

bunda

$I(1,\omega)=I(u,\omega)/u=1$

$$I(u,\omega)=\int_{-1}^{1}\sqrt{\frac{1-\xi}{1+\xi}}\frac{(\xi+d)e^{-\frac{j\omega\lambda^2\varphi_0(\xi)}{Q}}}{(a-\xi)(u-\xi)}d\xi.$$

(16)va (17) formulalarini (15) formulaga qo‘yib, quyidagini olamiz

$$\frac{d\tilde{w}}{du}=\frac{Q\vartheta^*}{\pi U(u-a)}\sqrt{\frac{a^2-1}{u^2-1}}\left[1-\left(\frac{a-u}{a-1}\right)\frac{I(u,\omega)}{I(1,\omega)}\right] \tag{18}$$

$$\frac{dz}{du}=\frac{Q}{\pi V_k}\left[\frac{a+1}{a+d}\right]\frac{(u+d)EXP\left[\pi\left(\frac{(1+\alpha)}{F(-1)}F(u)-i\alpha\right)\right]}{(u-a)(u+1)}. \tag{19}$$

(19) va (18) formulalar yordamida biz nobarqaror tezlikni hisoblaymiz

$$\frac{dw}{dz}=\frac{du}{dz}\frac{d\tilde{w}}{du}e^{j\omega\tau}=\frac{Q\vartheta^*}{\lambda q_E}\sqrt{\frac{a^2-1}{u^2-1}}\left[\frac{u+1}{u+d}\right]\left[1-\left(\frac{a-u}{a-1}\right)\frac{I(u,\omega)}{I(1,\omega)}e^{-\pi\left[\frac{(1+\alpha)}{F(-1)}F(u)-i\alpha\right]+j\omega\tau}\right]. \tag{20}$$

Bo‘shliqning nostatsionar chegarasini aniqlash uchun tezlik nolga teng bo‘ladigan $D$ nuqtaning abssissasini aniqlash zarur. $\frac{\partial W}{dz}=0$ shartidan esa quyidagi ifoda hosil qilinadi:

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$$1+\frac{du}{dw_0}\frac{d\tilde{w}}{du}e^{j\omega\tau}=0, \tag{21}$$

ya'ni,

$$\sqrt{\left(\frac{a+1}{a-1}\right)\left(\frac{u-1}{u+1}\right)}\left(\frac{u+d}{a+d}\right)+\frac{\vartheta^*}{U}\left[1-\left(\frac{a-u}{a-1}\right)\frac{I(u,\omega)}{I(1,\omega)}\right]e^{j\omega\tau}=0. \tag{22}$$

D nuqtaning abssissasi

$$\frac{x_D}{H}=\frac{U}{\pi V_k}\left[\frac{a+1}{a+d}\right]\mathrm{Re}\int_{-d}^{1}\frac{\left[1+du+\sqrt{(d^2-1)(u^2-1)}\right]\left[gu-1+\sqrt{(g^2-1)(u^2-1)}\right]^{\alpha}}{(a-u)(u+1)(u-g)^{\alpha}}du. \tag{23}$$

(23) tenglama yordamida aniqlanadi, bunda integralning pastki chegarasi sifatida $d$ qiymati (22) tenglamadan olinadi.

Oldingi masalada bo'lgani kabi, ko'rib chiqilayotgan kanalda suyuqlikning nostatsionar oqimi vaqtida bosimning ortishi (25) formula yordamida aniqlanadi. $\frac{\partial\varphi}{\partial\varphi_0}$ qiymati esa

$$\frac{dw_0}{du}=\frac{Q}{\pi}\left[\frac{a+1}{a+d}\right]\frac{(u+d)}{(u-a)(u+1)}. \tag{24}$$

(24) va (18) formulalar asosida hisoblanadi. $\frac{\partial\varphi}{\partial t}$ funksiyani (18) formuladan foydalanib aniqlash mumkin, ammo uni funksiyasi uchun aralash chegaraviy masalaning yechimini yozish orqali yanada sodda usulni topish mumkin:

$$\tilde{F}(u)=\frac{j\omega U}{H}\tilde{w}+V_0^2\frac{d\tilde{w}}{dw_0}, \tag{25}$$

bu yerda $V_0$ - barqaror oqim tezligining moduli hisoblanadi.

Chunki

$$\begin{aligned}&\mathrm{Im}\tilde{F}(u)=0, && -\infty<u<-1,\\ &\mathrm{Re}\tilde{F}(u)=0, && -1\le u\le 1,\\ &\mathrm{Im}\tilde{F}(u)=\begin{cases}\frac{j\omega U}{H}\tilde{C}_1 & 1<u<a,\\ 0, & a\le u<\infty\end{cases}\end{aligned}. \tag{26}$$

Doimiy $\tilde{C}_1$ kattalik suyuqlik oqimining qo'shimcha nostatsionar sarf koeffitsientini ifodalaydi.

$$C_1=\tilde{C}_1e^{j\omega\tau}=\frac{Q\vartheta^*}{U}e^{j\omega\tau},$$

bundan

$$\tilde{C}_1=\frac{Q}{U}\vartheta^*.$$

Keyinchalik, ushbu shartlarga mos ravishda tuzilgan analitik funksiya quyidagi shaklga ega bo'ladi.

$$\tilde{F}(u)=\frac{j\omega U\vartheta^*}{\pi}\sqrt{u^2-1}\int_1^a\frac{d\xi}{\sqrt{\xi^2-1}(\xi-u)}$$

yoki

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$$\tilde{F}(u) = \frac{j\omega U \vartheta^*}{\pi} \ln\left| \frac{a-u}{a\,u - 1 + \sqrt{(a^2-1)(u^2-1)}} \right|. \qquad (27)$$

(27) dan va $\tilde{F}(u)$ ta'rifdan quyidagi kelib chiqadi

$$j\frac{\omega U}{H}\tilde{\varphi} = \frac{j\omega U \vartheta^*}{\pi} \ln\left| \frac{a-u}{a\,u - 1 + \sqrt{(a^2-1)(u^2-1)}} \right|, \ |u| > 1$$

Olingan ifodalarni bosim formulaga qo'llash orqali quyidagi natijaga erishamiz:

$$\frac{\Delta P}{\rho V_k^2} = \frac{\vartheta^* e^{j\omega\tau}}{U}\left[ \frac{j\omega\lambda^2}{\pi} \ln\left| \frac{a-u}{a\,u - 1 + \sqrt{(a^2-1)(u^2-1)}} \right| - \right.$$

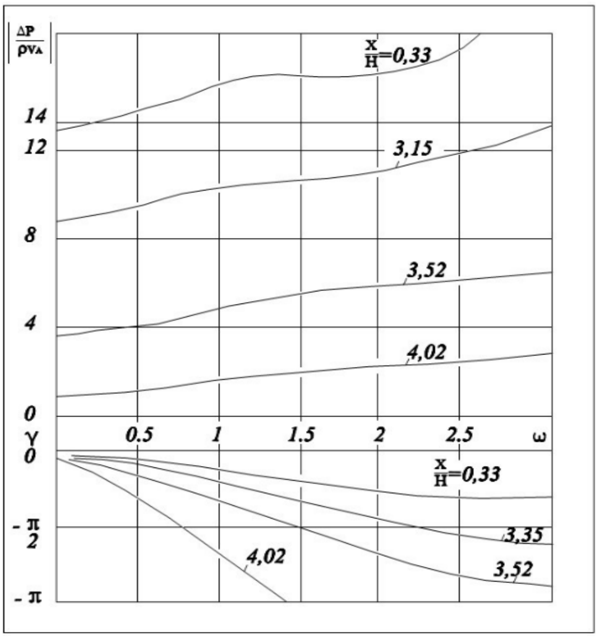
$$\left. -\left(1 - \frac{V_0^2}{V_k^2}\right)\sqrt{\frac{a-1}{a+1}}\sqrt{\frac{u+1}{u-1}}\left(\frac{a+d}{u+d}\right)\left[1 - \left(\frac{a-u}{a-1}\right)\frac{I(u,\omega)}{I(1,\omega)}\right]\right]$$

(28)

bunda $\lambda = \dfrac{U}{V_k}$ teng (28) formulani quyidagicha yozishimiz mumkin.

$$\frac{\Delta P}{\rho V_k^2} = n_0 e^{j(\omega\tau + \gamma)}$$

Amplituda $n_0$ va fazaning o'zgarish burchagi γ ning Struxal soni ω ga bog'liqligi VDO kanal devoridagi turli nuqtalarda 2-rasmda tasvirlangan.




**2-rasm. Nostatsionar harakatda bosim moduli va fazaning o'zgarish burchagi $\gamma$ ning Struxal soni $\omega$ ga bog'liqligi.**

Hisoblash grafiklaridan ko‘rinib turibdiki, teshikdan masofa $\frac{x}{H}$ £ oshgan sari bosim o‘zgarishi so‘nuvchi xususiyatga ega bo‘ladi [1; 2; 4; 11].

## Xulosa

O‘zgaruvchan kesim yuzali kanalda suyuqlik oqimining matematik modeli taklif etildi. O‘zgaruvchan kesim yuzali kanalda suyuqlikning uyurmalik oqimi hisobga olgan holdagi statsionar va nostatsionar harakati masalasining analitik yechimi olindi. Kanalning siqilish zonasida yuzaga keladigan uyurmalik oqim geometrik o‘lchamlarini kanalning siqilish parametri $x/H$ va oqim tezligiga bog‘liq ravishda hisoblashning analitik usuli keltirildi. O‘zgaruvchan kesim yuzali kanalning uyurmasiz oqimni ta’minlaydigan shaklining kanal geometriyasiga va oqim tezligiga bog‘liq ravishda aniqlash usuli yaratildi.

Masalada olingan natijalar nasos stansiyalarining ekspluatatsiyasida va loyihalashda muhim ahamiyatga ega. Chunki uyurmalik zonaning geometrik o‘lchamlarini va ularni nostatsionar tezlikka bog‘liq holda o‘zgarishini aniqlash nasos stansiyalarining ish rejimiga ta’sir qilishi aniqlangan.

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