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# THE FEATURES OF LAMINAR FLUID MOTION IN THE IMPELLER OF THE CENTRIFUGAL POROUS PUMP

**Розглянуто метод розв'язання задачі руху рідини що не стискається в робочому колесі пористого відцентрового насоса. В рамках запропонованого методу, отримали розвиток теоретичні дослідження, спрямовані на вдосконалення аналітичних залежностей, що дозволяють оцінювати зміни тиску і кінематичних параметріврідини при її ламінарному русі в порожнині пористого тіла відцентрового насосу. Прийнято, що пористе тіло має анізотропні властивості. Прийнята розрахункова схема руху рідини в робочому колесі не враховує втрати енергії при повороті рідини з осьового напрямку в радіальне, а також можливі втрати на вихрові явища у вхідному перерізі насосу. Система рівнянь, що описує рух рідини в пористому колесі, записана в системі полярної координат в припущенні, що зміна параметрів рідини по куту обертання не відбувається. При ламінарному режимі руху фільтраційні характеристики виражаються у вигляді симетричних тензорів другого рангу. Отримано рівняння для статичного тиску рідини та фільтраційної швидкості в пористому робочому колесі пористого відцентрового насоса. Результати, отримані розрахунковим шляхом, і навіть раніше проведені експериментальні дослідження свідчать про їх достатню для практики точність.**

***Ключові слова:*** *пористе тіло, робоче колесо, течія рідини, система рівнянь*

**Рассмотрен метод решения задачи о движении несжимаемой жидкости в рабочем колесе пористого насоса. В рамках предложенного метода, получили дальнейшее развитие теоретические исследования, направленные на совершенствование аналитических зависимостей, позволяющих оценивать изменения давления и кинематических параметров при ламинарном движении жидкости в полости пористого тела. Принято, что пористое тело имеет анизотропные свойства. Принятая расчетная схема движения жидкости в рабочем колесе не учитывает потери энергии при повороте жидкости из осевого направления в радиальное, а также возможные потери на вихреобразные явления во входном сечении. Система уравнений, описывающая движение жидкости в пористом колесе, записана в полярной системе координат в предположении, что изменение параметров жидкости по углу вращения не происходит. При ламинарном режиме движения, фильтрационные характеристики выражаются в виде симметричных тензоров второго ранга. Получены уравнения для статического давления жидкости и фильтрационной скорости в пористом рабочем колесе пористого центробежного насоса. Результаты, полученные расчетным путем, а также ранее проведенные экспериментальные исследования говорят о их достаточной для практики точности.**

***Ключевые слова:*** *пористое тело, рабочее колесо, течение жидкости, система уравнений*

**A method for solving the problem of the motion of an incompressible fluid in the impeller of a porous pump is considered. Within the framework of the proposed method, theoretical studies were further developed, aimed at improving the analytical dependencies, which make it possible to evaluate the changes in pressure and kinematic parameters during the laminar motion of fluid in the cavity of a porous body. It is assumed that the porous body has anisotropic properties. The accepted design scheme of fluid movement in the impeller does not take into account the energy loss when the fluid turns from the axial direction to the radial direction, as well as possible losses due to vortex-like phenomena in the inlet section. The system of equations describing the motion of a liquid in a porous wheel is written in a polar coordinate system under the assumption that there is no change in the parameters of the liquid with respect to the angle of rotation. In the laminar mode of motion, the filtration characteristics are expressed as symmetric tensors of the second rank. Equations are obtained for the static pressure of the liquid and the filtration rate in the porous impeller of a centrifugal pump. The results obtained by calculation, as well as previously conducted experimental studies, indicate that they are accurate enough for practice.**

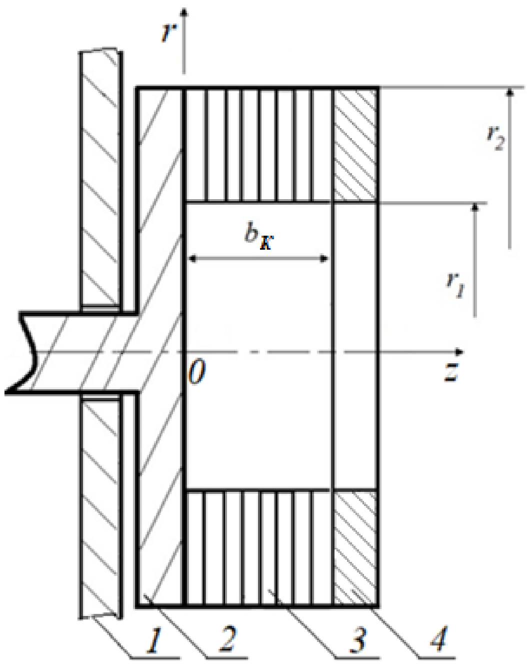
***Key words:*** *porous body, impeller, fluid flow, system of equations*

**Introduction.** The undoubted promise of using pumping units, which include porous bodies, in rocket and space technology, is confirmed by the growing interest, both in the field of scientific and theoretical research, and in the field of their practical application. The absence of pulsation phenomena during the supply of fuel components to the combustion chamber makes it possible to reduce the instability of the fuel combustion process in the chamber and to increase the reliability of the propulsion system. This is especially true for low-consumption fuel systems for low-thrust rocket engines, where it is very important to obtain high head values at low flow rates and guaranteed stability of the feed process. When liquid is supplied to the combustion chamber, the presence of transient processes is characteristic, and as a consequence, it is assumed that there is both a laminar and a turbulent regime of liquid flow in the flow path of the impeller of a porous pump. Thus, consideration of the issue of the laminar flow of liquid in a porous impeller of a centrifugal pump is relevant.

**Review and of literary sources.** For the first time, a systematic approach to the creation of a mathematical model of fluid motion in a porous body was presented in [1]. The study of model flows in a porous medium with rough surfaces was presented in [2], where the boundary conditions for fluid flow were formulated for the case of sliding. A theoretical model of effective gas permeability was developed for the flow of a rarefied gas in a porous medium, and was presented in [3]. Some aspects of the laminar motion of an incompressible fluid in porous bodies were considered in [5 - 7], where it was proposed to express the filtration characteristics of a moving fluid in the form of symmetric tensors of the second rank.

**Method, object and statement of the research problem.** The object of research is the laminar flow of an incompressible fluid.The subject of research is dynamic-type porous centrifugal pumps.The aim of the work is to develop a mathematical model that allows calculating the change in static pressure and fluid velocity in a laminar flow regime in the flow path of the impeller of a porous centrifugal pump of constant width.

**Solution of the problem.** Solving the problem of the motion of an incompressible fluid in a rotating, non-deformable porous wheel having impermeable bearing and cover disks, between which an anisotropic porous body is enclosed, and the housing wall will make it possible to determine the dependence of the pressure and velocity of the fluid on the radius of the wheel. In fig. 1 shows a diagram of the considered porous impeller of a centrifugal pump.




*1 - case, 2 - carrier disk, 3 - porous body, 4 - covering disc*

**Fig.1. The design scheme of a porous impeller of a centrifugal pump**

As a design diagram of the fluid flow in the impeller of a porous pump, it is assumed that the impeller has a constant width $b_K$, the porous body is anisotropic, the porosity of the body is determined by the parameter $m$, the fluid is viscous, not compressible, the effect of resistance from external forces is not taken into account.

Let us assume that the mass resistance force is the sum of the frictional resistance force $R_F$ and the pressure resistance force $R_{DP}$. The pressure force acting on the moving fluid in the cross section of the channel $S$ of the porous annular body is determined from the ratio $R_{DP} = \Delta p \cdot S = S \cdot \left( p_1 - p_2 \right)$, where $p_1$ and $p_2$ are the pressure in the fluid at the inlet and outlet of the porous body.The pressure resistance force has a direction coinciding with the direction of the relative velocity $W$. In the opposite direction, the frictional resistance force $R_F$ will act, which depends on the Re number.The reaction from the action of the pressure resistance force will be directed in the opposite direction of the relative velocity due to the presence of a liquid pressure drop on all particles of the medium.

Taking a constant value of the pressure gradient along the length of the porous body, the reaction force from the action of the pressure resistance force will be written in the form:

$$R_R = \left(p_1 - p_2\right) \cdot S \cdot \left(1 - m\right).$$

The pressure drop acting on the liquid is balanced by the resistance and reaction force $R_R$, and the pressure resistance force, and $R_R = R_{DP}$. Therefore, the equation for the equilibrium of a liquid in a porous element can be written in the form:

$$\left(p_1 - p_2\right) S = R_F + \left(p_1 - p_2\right) S \left(1 - m\right).$$

Hence, the mass force of friction resistance is $R_F = \left(p_1 - p_2\right) \cdot S \cdot m$. We divide the forces of resistance of friction and pressure to the mass of the liquid, we get the next:

$$R_T = \frac{R_{TP}}{M} = \frac{p_1 - p_2}{l\rho} \text{ and } R_Д = \frac{R_{ДВ}}{M} = \frac{\left(1 - m/m\right)\left(p_1 - p_2\right)}{l\rho}.$$

The total mass resistance force can be written as: $R = \dfrac{\left(p_1 - p_2\right)}{l\rho m}$.

When a fluid moves in a rotating porous wheel, a large pressure gradient from centrifugal forces acts. The porosity of the porous element is taken such that it corresponds to the properties of an isotropic porous body. Therefore, only the mass frictional drag force is taken into account, and the pressure drag force is taken into account in the equations. For a porous wheel, the projections of the mass force of pressure resistance on the polar axes $r$ and $\varphi$ will be, respectively,

$$R_{DP}(r) = \frac{\partial p}{\partial r}\frac{\left(1 - m\right)}{\rho m} \text{and} R_{DP}(\varphi) = \frac{\partial p}{\partial \varphi}\frac{\left(1 - m\right)}{r\rho m}.$$

Considering the above, the system of equations describing the motion of a fluid in a porous wheel in a polar coordinate system has the form:

$$Vr\frac{\partial Vr}{\partial r} + \frac{1}{r}V\varphi\frac{\partial Vr}{\partial \varphi} - \frac{1}{r}V^2\varphi = -\frac{m}{\rho}\frac{\partial p}{\partial r} + R_r m^2, \tag{1}$$

$$rVr\frac{\partial V\varphi}{\partial r} + V\phi\frac{\partial V\varphi}{\partial \varphi} + V\varphi Vr = -\frac{m}{\rho}\frac{\partial p}{\partial \phi} + rR_\varphi m^2, \tag{2}$$

$$\frac{\partial\left(rVr\right)}{\partial r} + \frac{\partial V\varphi}{\partial \varphi} = 0, \tag{3}$$

where:

- *Vr* and *Vφ* are the radial and circumferential components of the absolute fluid filtration rate, r and φ are polar coordinates;
- *Rr* and *Rφ* are the projections of the mass resistance force *R* porous wheel in radial and circumferential directions.

The mass force of frictional resistance can be written as:

$$\vec{R} = -\left(C + K \cdot W\right) \cdot \vec{W} ,$$

where:

- $\vec{W}$ – filtration relative speed of fluid movement in a porous wheel;
- *C* and *K*– tensors of hydraulic resistance for laminar and turbulent filtration, respectively, which have the form:

$$\left|C\right| = \begin{vmatrix} Crr & C\varphi r \\ Cr\varphi & C\varphi\varphi \end{vmatrix}, \ \left|K\right| = \begin{vmatrix} Krr & K\varphi r \\ Kr\varphi & K\varphi\varphi \end{vmatrix}.$$

Let's accept, $C\varphi r = Cr\varphi$ and $K\varphi r = Kr\varphi$. In projections onto the cylindrical coordinate axes, the expressions for the mass frictional drag forces are:

$$R_{TP}(r) = -\left(Cir + Kir \cdot W\right) \cdot Wi , \ R_{TP}(\varphi) = \left(Ci\varphi + Ki\varphi \cdot W\right) \cdot Wi .$$

In the case of choosing a coordinate system that coincides with the main axes of the hydraulic resistance tensor, the expressions for *C* and *K* will take the form:

$$\left|C\right| = \begin{vmatrix} Crr & 0 \\ 0 & C\varphi\varphi \end{vmatrix}, \ \left|K\right| = \begin{vmatrix} Krr & 0 \\ 0 & K\varphi\varphi \end{vmatrix},$$

and the projections of the mass frictional drag force will be written in the form:

$$R_{TP}(r) = -\left(Crr + Krr \cdot W\right) \cdot Wr , \ R_{TP}(\varphi) = \left(C\varphi\varphi + K\varphi\varphi \cdot W\right) \cdot W\varphi .$$

The projections of the portable filtration velocity of the liquid on the radial and circumferential directions, respectively, are:

$$Wr = Vr \text{ и } W\varphi = m \cdot \omega \cdot r - V\varphi .$$

The absolute value of the portable fluid filtration rate has the form:

$$W = \sqrt{\left(m\omega r - V\varphi\right)^2 + \left(Vr\right)^2} .$$

Let us take into account that $\frac{\partial V\varphi}{\partial \varphi}=\frac{\partial Vr}{\partial \varphi}=\frac{\partial p}{\partial \varphi}=0$, since the fluid flow is symmetric along the φ coordinate. In these equations, the velocities *Vr* and *Vφ*, as well as the pressure, depend only on the radius, then the equations of motion are transformed into differential equations of the form:

$$\frac{1}{m}Vr\frac{dVr}{dr}-\frac{1}{m}\frac{(V\varphi)^2}{r}=-\frac{m}{\rho}\frac{dp}{dr}-\left(Crr+Krr\sqrt{(m\omega r-V\varphi)^2+(Vr)^2}\right)Vrm, \quad (4)$$

$$\frac{1}{m}Vr\frac{dV\varphi}{dr}-\frac{1}{m}\frac{(V\varphi Vr)}{r}=\left(C\varphi\varphi+K\varphi\varphi\sqrt{(m\omega r-V\varphi)^2+(Vr)^2}\right)(m\omega r-V\varphi)m, \quad (5)$$

$$\frac{d}{dr}\left(rVr\right)=0. \quad (6)$$

The boundary conditions are accepted as follows:

$$r = r_1 = Const;\ V\varphi(r_1) = Const;\ Vr(r_1) = Const;\ p(r_1) = Const.$$

From the equation of continuity, taking into account the boundary conditions, the projection of the absolute velocity on the radial direction is determined from the relations:

$$\frac{\partial Vr}{\partial r}=-\frac{Vr}{r},\ Vr=\frac{Vr(r_1)\cdot r_1}{r}=\frac{Const}{r}.$$

Substituting the obtained expression *Vr* into the system of equations of motion, we finally obtain:

$$\frac{dp}{dr}=\frac{Const^2}{m^2r^2}+\frac{\rho}{m^2}\frac{(V\varphi)^2}{r}-\left(Crr+Krr\sqrt{r^2(m\omega r-V\varphi)^2+Const^2}\right)\frac{Const\ r}{\rho}, \quad (7)$$

$$\frac{dV\varphi}{dr}=-\frac{V\varphi}{r}+\left(\frac{\left(C\varphi\varphi r+K\varphi\varphi\right)}{Const}\sqrt{r^2(m\,\omega\cdot r-V\varphi)^2+Const^2}\right)(m\omega r-V\varphi)m^2, \quad (8)$$

$$\frac{d\left(rVr(r_1)\right)}{dr}=0. \quad (9)$$

For a laminar fluid flow, the quantity of the $K\cdot W\cdot\vec{W}$ is much less than $C\cdot\vec{W}$, and can be neglected. We take the following notation:

$$a=\frac{C\,m^2}{n},\ b=C\cdot m^3\cdot\omega/n,\ d=\frac{\rho n^2}{m^2},\ h=\left(C\rho n\right),\ q=\left(\frac{\rho}{m^2}\right),\ n=Vr(r_1)\cdot r_1.$$

Then, expressing the mass force of resistance in the form of Darcy's law, the system of equations of motion we can be written in the following form:

$$\frac{dp}{dr} = \frac{n^2\rho}{m^2r^3} + \frac{\rho}{m^2}\frac{(V\varphi)^2}{r} - Crr\frac{n\rho}{r}, \tag{10}$$

$$\frac{dV\varphi}{dr} = -\frac{V\varphi}{r} + \frac{C\varphi\varphi m^2 r}{n}\left(m\omega r - V\varphi\right), \tag{11}$$

$$\frac{d\left(rVr(r_1)\right)}{dr} = 0\,. \tag{12}$$

Let us consider the case of a porous centrifugal wheel with constant filtration characteristics, when *Crr*= *Cφφ* = *C* = *const*. Taking this condition into account, the system of equations of motion will be written in the form:

$$\frac{dp}{dr} = \frac{d}{r^3} + q\frac{(V\varphi)^2}{r} - \frac{h}{r}, \tag{13}$$

$$\frac{dV\varphi}{dr} = br^2 - V\varphi\left(\frac{1}{r} + ar\right), \tag{14}$$

$$\frac{d\left(rVr(r_1)\right)}{dr} = 0\,. \tag{15}$$

The equation is a first-order linear differential equation that can be solved using the method of variations of arbitrary constants. We solve the homogeneous differential equation (14). The solution to the differential equation is obtained in the form:

$$V\varphi = \frac{e^{-ar^2}C_1}{r},$$

where $C_1$ is a constant.

We substitute the obtained expression for the velocity $V\varphi$ into a homogeneous differential equation, as a result we obtain next:

$$C_1' = \frac{dC_1}{dr} = br^3e^{ar^2}\,.$$

Let's integrate this equation. As a result of integration, we get:

$$C_1 = \frac{2b}{a^2}\left(\frac{ar^2}{2}e^{\frac{ar^2}{2}} - e^{\frac{ar^2}{2}} + C_2\right),$$

where $C_2$ is the constant of integration.

We substitute all the obtained components into the equation for the velocity $V\varphi$

$$V\varphi = \frac{br}{a} - \frac{2b}{a^2 r} + \frac{2b}{a^2 r} e^{-\frac{ar^2}{2}} C_2 .$$

Thus, after the transformation, we have an expression for the constant of integration $C_2$, which makes it possible to obtain a solution to the equation for the desired velocity:

$$C_2 = \frac{V\varphi(r_1) a^2 r_1}{2b} e^{\frac{ar_1^2}{2}} - \left( \frac{ar_1^2}{2} - 1 \right) e^{\frac{ar_1^2}{2}} .$$

Taking into account the previously adopted designations, the equations for the velocity $V\varphi$ will have the following form:

$$V\varphi = m\omega r - \frac{2\omega Vr(r_1) r_1}{mC} \frac{1}{r} + \left( \frac{2\omega Vr(r_1) r_1}{mC} - m\omega r_1^2 \right) e^{\frac{Cm^2 r_1}{2Vr(r_1)}} e^{-\frac{Cm^2 r^2}{2Vr(r_1) r_1}} \frac{1}{r} .$$

To solve the differential pressure equation (13), we substitute the obtained equation for the velocity $V\varphi$ into it, and take into account the previously adopted designations. Then the equation for determining the pressure will take the following form:

$$\frac{dp}{dr} = \frac{d}{r^3} + \frac{q}{r^3} \left( \frac{br}{a} - \frac{2b}{a^2 r} + \frac{2b}{a^2 r} C_2 e^{-\frac{ar^2}{2}} \right) - \frac{h}{r^2} .$$

Let us integrate the resulting expression. Considering the initial conditions $r = r_1$; $V\varphi = V\varphi(r_1) = const$ equation of the form:

$$\Delta p = \frac{\rho \left( Vr(r_1) r_1 \right)^2}{2m^2 r^2} + \frac{\omega^2 r^2 \rho}{2} - \left( \frac{4\omega^2 Vr(r_1) r_1 \rho}{m^2 C} \right) \ln(r) -$$
$$\left( \frac{2\omega^2 \left( Vr(r_1) r_1 \right)^2 \rho}{m^4 C^2} \right) \frac{1}{r^2} + \left( \frac{4\omega^2 \left( Vr(r_1) r_1 \right) \rho}{m^2 C} - 2\omega^2 \rho r_1^2 \right) e^{\frac{Cm^2 r_1}{2Vr(r_1)}} \int_{r_1}^{r} \frac{1}{r} e^{-\frac{Cm^2 r^2}{2Vr(r_1) r_1}} dr -$$
$$- \left( \frac{8\omega^2 \left( Vr(r_1) r_1 \right)^2 \rho}{m^4 C^2} - \frac{4\omega^2 \left( Vr(r_1) r_1 \right) \rho}{m^2 C} r_1^2 \right) e^{\frac{Cm^2 r_1}{2Vr(r_1)}} \int_{r_1}^{r} \frac{1}{r^3} e^{-\frac{Cm^2 r^2}{2Vr(r_1) r_1}} dr +$$
$$\frac{\rho}{m^2} \left( \frac{2\omega \left( Vr(r_1) r_1 \right)}{mC} - m\omega r_1^2 \right)^2 e^{\frac{Cm^2 r_1}{2Vr(r_1)}} \int_{r_1}^{r} \frac{1}{r^3} e^{-\frac{Cm^2 r^2}{2Vr(r_1) r_1}} dr - C\rho \left( Vr(r_1) r_1 \right) \ln(r)$$

.

Finally, we obtain a system of equations that allows us to calculate the values of pressures and velocities along the radius of the impeller of a porous centrifugal pump in the form:

$$\begin{aligned} p(r) = {} & pr(r_1) + \frac{\rho\left(Vr(r_1)r_1\right)^2}{2m^2r^2} + \frac{\omega^2r^2\rho}{2} - \left(\frac{4\omega^2 Vr(r_1)r_1\rho}{m^2C}\right)\ln(r) - \\ & \left(\frac{2\omega^2\left(Vr(r_1)r_1\right)^2\rho}{m^4C^2}\right)\frac{1}{r^2} + \left(\frac{4\omega^2\left(Vr(r_1)r_1\right)\rho}{m^2C} - 2\omega^2\rho r_1^2\right)e^{\frac{Cm^2r_1}{2Vr(r_1)}}\int_{r_1}^{r}\frac{1}{r}e^{-\frac{Cm^2r^2}{2Vr(r_1)r_1}}dr \\ & -\left(\frac{8\omega^2\left(Vr(r_1)r_1\right)^2\rho}{m^4C^2} - \frac{4\omega^2\left(Vr(r_1)r_1\right)\rho}{m^2C}r_1^2\right)e^{\frac{Cm^2r_1}{2Vr(r_1)}}\int_{r_1}^{r}\frac{1}{r^3}e^{-\frac{Cm^2r^2}{2Vr(r_1)r_1}}dr + \\ & \frac{\rho}{m^2}\left(\frac{2\omega\left(Vr(r_1)r_1\right)}{mC} - m\omega r_1^2\right)^2 e^{\frac{Cm^2r_1}{2Vr(r_1)}}\int_{r_1}^{r}\frac{1}{r^3}e^{-\frac{Cm^2r^2}{2Vr(r_1)r_1}}dr - C\rho\left(Vr(r_1)r_1\right)\ln(r) \end{aligned} \quad (16)$$

$$V\varphi = m\omega r - \frac{2\omega Vr(r_1)r_1}{mC}\frac{1}{r} + \left(\frac{2\omega Vr(r_1)r_1}{mC} - m\omega r_1^2\right)e^{\frac{Cm^2r_1}{2Vr(r_1)}}e^{-\frac{Cm^2r^2}{2Vr(r_1)r_1}}\frac{1}{r}. \quad (17)$$

$$\dot{m} = \rho SVr = const\,. \quad (18)$$

The integrals included in expression (16) must be determined by numerical methods for given values of the radii. To determine the velocities and pressures of a liquid in a centrifugal wheel, a filtration characteristic of a porous body is required.

**Analysis of the obtained results.** During the theoretical study, it was assumed that the porosity of the porous body was isotropic and did not depend on the radius. This greatly simplified the starting point for theoretical research.

In fig. 2 shows the results of calculations of the relative velocity $V\varphi$, depending on the relative radius and porosity of the porous body.

The case when the value of porosity *m* = 1 will correspond to the impeller of a disk pump, with an inter-disk space equal to $b_K$, which is confirmed by the theoretical provisions in [7].

As noted earlier, in real designs of porous impellers, the porous body is anisotropic, and the calculated values for each radius must be determined based on the value of the actual porosity. Previous experimental studies to determine the dependences of pressure drops and fluid velocities in porous bodies at different angles of pouring samples, confirmed that the filtration characteristics expressed by second-rank tensors in a laminar flow regime are determined with sufficient accuracy for practice [5].

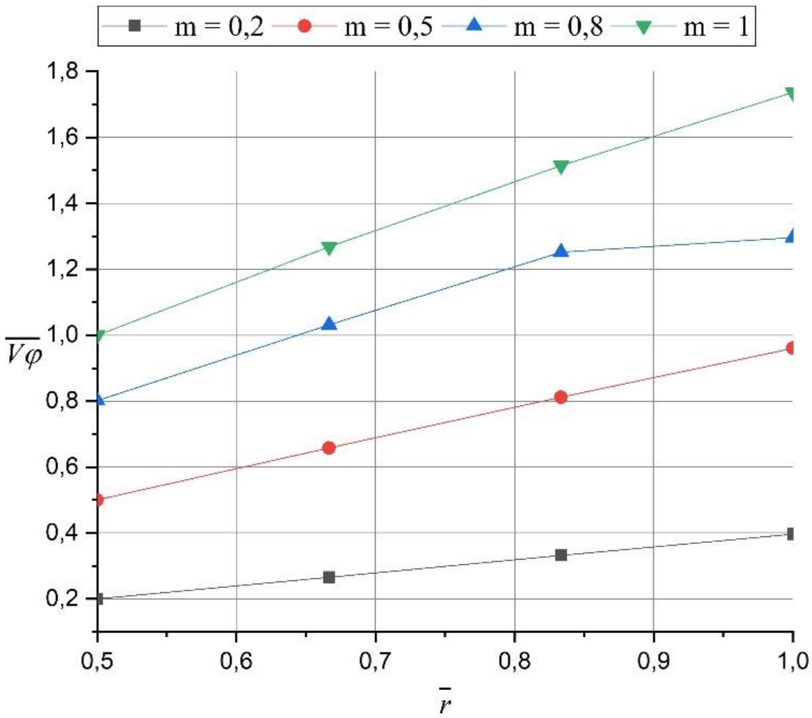



**Fig. 2. The dependence of the relative speed of the $\overline{V\varphi}$ on the relative radius of the impeller $\bar{r}$ and the porosity of the porous body *m***

**Conclusions.** As a eventually of the theoretical studies, the following results were obtained:

- on the basis of the model of the laminar motion of a viscous incompressible fluid in the flow path of a porous pump rotating in a stationary body, relations for determining the parameters of the fluid along the radius of the impeller are obtained;
- the proposed mathematical model can be used as a basis for the numerical solution of laminar fluid flow in the impeller of a porous pump.

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