РЕСУРСОЗБЕРІГАЮЧІ ЕЛЕКТРОТЕХНОЛОГІЇ СІЛЬСЬКОГОСПОДАРСЬКОГО ВИРОБНИЦТВА

УДК 614.89:537.868

CALCULATION OF THE MICRO FLOW RATE AT THE SURFACE OF A BALL MODELING EMBRYO

M. Kundenko[1], Y. Vitkovsky[1], Kui Jiao[2]

[1]Харківський національний технічний університет сільського господарства імені Петра Василенка,
[2]School of Mechanical Engineering State Key Laboratory of Engines, Yaguan Rd, Tianjin, China

Expressions are obtained for the mean time value of microflow velocities near the boundary of biological objects (embryo, sperm). These results are the basis for modeling the process of mass transfer of particles of a cryo-preservative medium to the surface of biological objects in the presence of acoustic oscillations.

Introduction. The effect of increasing cryoresistivity was obtained on a very limited set of biological objects: germ cells and nuclear-free blood cells [3].

The possibilities of using ultrasound in cryoconservation of sperm of farm animals are practically not covered. The mechanisms of ultrasonic action on cryobiological systems are also not investigated. Considering this, it is advisable to investigate the possible mechanisms of action of ultrasonic waves in order to optimize the conditions of low-temperature preservation of such biological objects as sperm of farm animals.

This will improve the efficiency of methods for freezing and warming biological objects (sperm cells, embryos, etc.) and identify approaches to the use of ultrasonic waves in cryoconservation of biological objects. An important issue here is the possibility of a physico-mathematical description of the interaction of ultrasonic waves with a cryo-conservation medium containing biological objects.

One of the defining factors in determining the speed of microflows arising in the presence of a sound wave is the vibrational velocity of medium particles in the vicinity of the boundary surface of a biological object. However, in practice, the geometric dimensions of a biological object can be significantly (by several orders of magnitude) smaller than the length of the sound wave. Biological objects are modeled by a geometric body in the form of an ellipsoid of rotation (elongated spheroid).

It is known [1] that one of the main mechanisms of diffusion of particles of a cryopreserving medium to the surface of a biological object (embryo, sperm) is micro-currents arising under the action of acoustic vibrations. The presence of these microflows indicates that the average time mass flow is zero.

The magnitude of the constant component of the velocity (it is assumed that in the absence of acoustic oscillations of the cryo-preservative medium was at rest) of the micro-flow is less than the amplitude of the vibrational velocity in the acoustic wave. Numerous experimental results [3,7] show that the process of mass transfer is determined by diffusion resulting from the presence of a concentration difference between the layer of the medium immediately adjacent to the surface of a biological object (embryo, sperm) and the thickness of the medium.

Thus, the task is to determine the speed of a microflow $\vec{V}_2$ in the vicinity of a biological object based on the construction of a solution to the problem

Research methodology. We will assume that such a complex environment takes up some volume. Since the biological objects under consideration have sufficiently small geometrical dimensions, it is natural to assume that the influence of the forces of gravity and inertia on their movement is negligible. Therefore, it can be assumed that biological objects move locally together with the surrounding cryo - preservative medium. In addition, we will assume that the average distance between biological objects is large compared with their linear dimensions. Therefore, the process of formation of a microflow near one biological object does not approximately depend on the existence of others and, as shown in section 2, is completely determined by the exciting acoustic wave. In this case, you can use the results given in [5,6] and obtain the following expression for the effective viscosity coefficientof the liquid formed by the cryo - preservative medium and biological objects. Consider the case of a biological object in the form of an ellipsoidal spheroid (sperm model) [2]. For further calculations, it is convenient to introduce spheroidal coordinates associated with an ellipsoidal spheroid according to the formulas

$$x = c\sqrt{\left(\xi^2-1\right)\left(1-\eta^2\right)}\cos\varphi,$$
$$y = c\sqrt{\left(\xi^2-1\right)\left(1-\eta^2\right)}\sin\varphi,$$
$$z = c\,\xi\,\eta\,. \qquad (1)$$

Here, $c = \sqrt{a^2 - b^2}$, a and b - respectively, the major and minor semiaxes of the spheroid. Coordinates ξ, η, φ change in intervals $\xi \in [1, \infty]$, $\eta \in [-1, 1]$, $\varphi \in [-\pi, \pi]$. The equation of the boundary surface of a biological object in spheroidal coordinates (1) has the following form

$$\xi = \xi_0 = \frac{a}{\sqrt{a^2-b^2}}. \qquad (2)$$

Since the microflows are realized in a small neighborhood of a biological object and the tangential components of the velocity of a microflow are zero on its surface, it is natural to assume that these components are zero in a small neighborhood of a biological object. Therefore, we will assume that the speed of a microflow $\vec{V}_2$ is directed along the normal to the surface of a biological object.

$$\vec{V}_2 = V_{\xi 2}\ \vec{e}_\xi\ . \qquad (3)$$

In addition, we can neglect the dependence on the azimuthal coordinate φ $\left(\frac{\partial}{\partial \varphi} \equiv 0\right)$. Since the biological object is symmetric with respect to the major and minor axes, we have

$$div\,\vec{V}_2 = \frac{1}{c\left(\xi^2-\eta^2\right)}\ \frac{\partial}{\partial \xi}\left(\bar{V}_{\xi 2}\sqrt{\left(\xi^2-\eta^2\right)\left(\xi^2-1\right)}\right), \qquad (4)$$

$$rot\vec{V}_2 = -\ \frac{\sqrt{1-\eta^2}}{c\left(\xi^2-\eta^2\right)}\ \frac{\partial}{\partial \eta}\left(V_{\xi 2}\ \sqrt{\xi^2-\eta^2}\right)\vec{e}_\varphi . \qquad (5)$$

After a series of transformations, we obtain an equation for determining the speed of a microflow $\vec{V}_2 = \bar{V}_{\xi 2}\ \vec{e}_\xi$

$$V_{\xi 1} = \frac{A\,B\,e^{-\alpha c \xi}}{2\,c^2 \rho_0 \xi}\times$$

$$\times\left[\cos\left(k_0 c\,\xi - \omega t\right)\left(\frac{1}{\xi}+\alpha\,c\right)+k_0 c\,\sin\left(k_0 c\,\xi-\omega t\right)\right]\times$$

$$\times\sqrt{\frac{\xi^2-1}{\xi^2-\eta^2}}\ . \qquad (6)$$

We now determine the change in density ρ_1.

$$\frac{\partial \rho_1}{\partial t} = -\ \frac{\rho_0}{c\left(\xi^2-\eta^2\right)}\ \frac{\partial}{\partial \xi}\left(V_{\xi 1}\sqrt{\left(\xi^2-\eta^2\right)\left(\xi^2-1\right)}\right). \qquad (7)$$

After a series of transformations, limited to members of the order ξ^{-2}, and integrating over time we get

$$\rho_1 = \frac{AB\,c\,e^{-\alpha c \xi}\,\xi}{2\,\omega\left(\xi^2-\eta^2\right)}\times$$

$$\times\left[\left(k_0^2-\alpha^2\right)\sin\left(\xi\,c\,k_0-\omega t\right)+2\,\alpha\,k_0\cos\left(k_0 c\xi-\omega t\right)\right]. \qquad (8)$$

Now it is necessary to determine the value $\overline{\rho_1 V_{1\xi}}$ - the average value for the oscillation period of the exciting acoustic wave.

$$\bar{V}_{\xi 2}\sqrt{\left(\xi^2-\eta^2\right)\left(\xi^2-1\right)} = -\ \frac{A^2B^2e^{-2\alpha\xi}\,k_0\left(k_0^2+\alpha^2\right)}{8\rho_0^2\,\omega c^2\left(\xi^2-\eta^2\right)}\times$$

$$\times\sqrt{\left(\xi^2-\eta^2\right)\left(\xi^2-1\right)}+D_2\ , \qquad (9)$$

where D_2 is an arbitrary value that does not depend on the variable ξ.

Thus, we have the following expression for the normal component of the microflow velocity

$$\bar{V}_{\xi 1} = -\ \frac{A^2B^2e^{-2\alpha\xi c}\,k_0\left(k_0^2+\alpha^2\right)}{8\rho_0^2\,\omega c^2\left(\xi^2-\eta^2\right)}+$$

$$+\ \frac{D_2}{\sqrt{\left(\xi^2-\eta^2\right)\left(\xi^2-1\right)}}\ . \qquad (10)$$

After calculating we obtain the final expressions for the micro-flow velocity in the vicinity of the surface of a biological object, where the value D_1 is given by the formula

$$D_1 = \sqrt{\left(\xi_0^2-\eta^2\right)\left(\xi_0^2-1\right)}\ \frac{ABe^{-\alpha c\xi_0}}{2\rho_0\,c^2}\left[\frac{1}{\xi_0}\left(\frac{1}{\xi_0}+\alpha c\right)+\right.$$

$$\left.+\ \frac{ABe^{-\alpha c\xi_0}\,k_0\left(k_0^2+\alpha^2\right)}{4\,\omega\left(\xi_0^2-\eta^2\right)\rho_0}\right].$$

First of all, we note that the average speeds of a microflow takes the maximum value on the surface of a biological object (sperm, embryo), therefore the basic expression for determining the average speed of microflows is finally

$$\bar{V}_э = \frac{1}{\pi\,f\,R}\ \sqrt{\frac{\mathrm{P}\,c_0}{2\,S_э\,\rho_0}}\ . \qquad (11)$$

We obtain the expression for the micro-flow rate for the average value of the micro-flow rate in the case of a biological object - sperm,

$$\bar{V}_c = \frac{\sqrt{\frac{\mathrm{P}c_0}{2S_c\,\rho_0}}}{\pi fa\left(1+\frac{1}{2\sqrt{1-\left(\frac{b}{a}\right)^2}}\,\ell n\,\frac{b}{a\left(1+\sqrt{1-\left(\frac{b}{a}\right)^2}\right)}\right)}, \qquad (12)$$

where a and b - are respectively the major and minor axes of an ellipsoidal spheroid simulating sperm;

S_c - is the surface area of the sperm.

Based on the obtained expressions (11) and (12) for microflow velocities, numerical calculations were

performed. The dependences of the speed of microflows on the magnitude of the sound power of the exciting acoustic wave and its frequency were investigated. Sound power varied within $P = 1 \div 5$ мкWт, and frequency within $f = 10 \div 50$ кHz. The results of calculations of the microflow velocities for the embryo depending on the magnitude of sound power at various values of the frequency of the exciting sound wave showed the following. At a fixed frequency of the acoustic wave, the speed of the microflow monotonously increases with increasing sound power.

So in the case of a biological object of the type of sperm at the speed of the micro-flow $\bar{V}_c = 546 \frac{\text{м}}{s}$, the thickness of the boundary layer is $\delta_c = 55 \dot{A}$, and in the case of an embryo at the maximum possible speed of the micro-flow $\bar{V}_e = 3.3 \frac{\text{м}}{s}$, the thickness of the boundary layer $\delta_e = 0{,}19$ мкм. An analysis of the calculations showed that the maximum possible thickness of the boundary layers are realized at microflow rates, respectively, $\bar{V}_s = 48.8 \frac{\text{м}}{s}$ for sperm and $\bar{V}_e = 0.3 \frac{\text{м}}{s}$ for the embryo.

The maximum speed of micro-flow of both the embryo and sperm is achieved at power $P =$ 5 мкWt and frequency $f = 10$ кHz. With a fixed sound power, the speed of the microflow decreases with increasing frequency. Moreover, the minimum speed of the microflow is achieved at frequency $f = 50$ кHz and power $P = 1$ мкWt and is for sperm $\bar{V}_s = 48.84 \frac{\text{м}}{s}$, and for the embryo $\bar{V}_e = 0{,}3 \frac{\text{м}}{s}$.

Conclusions Calculated formulas are obtained for the time-average micro-flow velocity at the surface of a biological object in a cryo-preservative medium. It has been established that the average speed of a microflow changes only along the normal to the surface of a biological object and takes the maximum value on its surface. These results are the basis for modeling the process of mass transfer of particles of a cryo - preservative medium to the surface of biological objects in the presence of acoustic oscillations.

References

1. Electromagnetic Technologies in the Process of Cryopreservation / Kundenko M. P., Egorova O. Yu., Egorov O. B., Kravchenko P. O., Shinkarenko I. M., Brovko K. Yu., Boroday I. I., Torbievska I. V. *Australian Journal of Education and Science* (the University of Sydney, January-June, 2018). Sydney, 2018. № 1 (21). Vol. XI. P. 253-263.

2. Кунденко М. П., Єгорова О. Ю., Шинкаренко І. М., Бровко К. Ю., Бородай І. І. Акустичні технології в процесі кріоконсервації біологічних об'єктів. II International Scientific and Practical Conference "Modern Methodology of Science And Education" (February 19, 2018). Open Access Peer-reviewed journal. Science Review. RS Global. Warsaw, Poland, 2018. № 2(9). Vol. 2. P. 9-13.

3. Кунденко Н. П. Математическое моделирование процесса воздействия акустического поля на криоконсервующую среду с биологическим объектом. *Вісник ХНТУСГ. Технічні науки.* 2011. Вип. 117. С. 140-142.

4. Кунденко Н. П., Егорова О. Ю., Бровко К. Ю., Шинкаренко И.Н., Бородай И. И. Определение параметров низкоинтенсивных акустических колебаний для воздействия на микрообъекты КРС. *Materialy XIV Miedzynarodowej naukowi-praktycznej konferencji "Naukowa przestrzen Europy-2018",* 7-15 kwietnia 2018 roku po sekcjach: Biologiczne nauki. Weterynaria. Ekologia. Medycyna. Gospodarka rolna. Praha, 2018. Vol. 9. Przemysl: Nauka i studia. P. 29-34.

5. Кунденко Н. П. Теоретический анализ микропотоков при наличии акустических колебаний. *Вісник НТУ "ХПІ"*. Харків, 2011. № 58. С. 158-161.

6. Кунденко Н. П. Математическое моделирование процесса воздействия акустического поля на криоконсервующую среду с биологическим объектом. *Вісник ХНТУСГ "Проблеми енергозабезпечення та енергозбереження в АПК України"*. Вип. 117. Харків, 2011. С. 140-142.

7. Yang Zhonghai, Chongwen Lin, Yingwei Zho. A method for measurement of Q-factor at millimeter wavelength. 10 International Conference "Infrared and Millimeter Waves": inter. conf., 9-13 December 1985: conf. proc. Lake Buena Vista, Fla, 1985. P. 350-351.

Анотація

РОЗРАХУНОК ШВИДКОСТІ МІКРОПОТОКУ У ПОВЕРХНІ КУЛІ, ЩО МОДЕЛЮЮТЬ ЕМБРІОН

Кунденко М. П. Вітковський Ю. П., Kui Jiao

Отримано вирази для середнього значення за часом швидкостей мікропотоків поблизу кордону біологічних об'єктів (ембріон, спермій). Ці результати є основою для моделювання процесу масо переносу частинок кріоконсервуючого середовища до поверхні біологічних об'єктів при наявності акустичних коливань.

Аннотация

РАСЧЕТ СКОРОСТИ МИКРОПОТОКА У ПОВЕРХНОСТИ ШАРА, МОДЕЛИРУЮЩЕГО ЭМБРИОН

Кунденко Н. П., Витковский Ю. П., Kui Jiao

Получены выражения для среднего значения по времени скоростей микропотоков вблизи границы биологических объектов (эмбрион, спермий). Эти результаты являются основой для моделирования процесса массопереноса частиц криоконсервирующей среды к поверхности биологических объектов при наличии акустических колебаний.