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POWRÓT

# TRIBOLOGY OF BONE TISSUE CULTURE IN BIOREACTOR

## TRIBOLOGIA HODOWLI TKANKI KOSTNEJ W BIOREAKTORZE

**Key words:**

friction forces,perfusion, grow of tissue

**Słowa kluczowe:**

siły tarcia, polewanie, wzrost tkanki

**Summary**

This paper describes the tribological parameters during the perfusion process of tissue in the bioreactor. We perfuse cells of tissue by the nutrition liquids and other biologically tolerable media with oxygen carrying fluorocarbons. There are two different kinds of flows in the bioreactor to be expected: The first one is the Newtonian potential flow in some distance from tissue surface and is caused by horizontal perfusion. The second is the viscous non-Newtonian flow in boundary layer direct near the motionless tissue surface. Liquid velocity components and pressure values will be de-

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termined. Analytical calculations deliver results for flow parameter as flow components and friction forces to the optimisation of tissue culture in bioreactor and to optimise the growth of cells. Present paper shows analytical formulae for velocity components of nutrient fluids in thin boundary layer near to the tissue surface to obtain necessary friction forces. Here are derived analytical formulae of tribological parameters in bioreactor and the necessary volume flow rate of stream of media in horizontal direction for good protection of the perfusion of tissue surface. The friction forces occurring in the thin layer of nutrition liquids resting on the superficial tissue layer are examined by numerical way and are illustrated in the pictures.

## AIM OF THE PAPER AND SKETCH OF COMPUTATIONAL METHOD

The transplantation of cartilage in human hip joint is more profitable than transplantation of total artificial joint. The culture of tissue is performed in bioreactor. A bioreactor was designed and developed with the aim of perfusing the scaffolds with the culture medium through their fibre structure in order to expose the cells located in the entire scaffold thickness both to convective solute transport, to a flow-induced shear stress and friction forces. **Fig. 1** depicts a schematic picture of device.

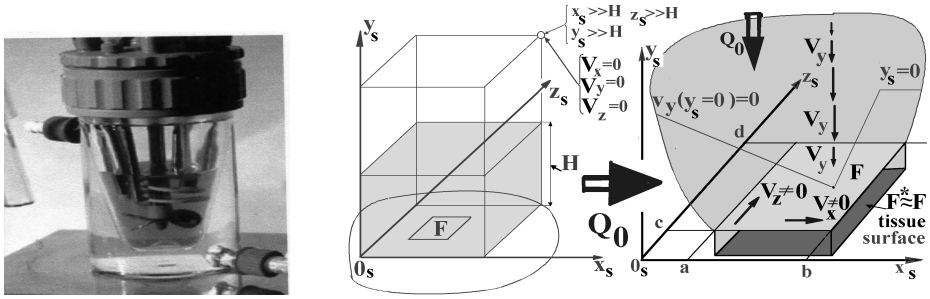


**Fig. 1. Cell culture reactor and boundary conditions of single layer potential flow around motionless tissue body during the perfusion with the biological liquid, $a\leq x_s\leq b$, $c\leq z_s\leq d$, $0\leq y_s\leq\infty$**

Rys. 1. Reaktor hodowli komórki oraz warunki brzegowe dla przepływu potencjalnego warstwy pojedynczej wokół nieruchomego ciała tkanki podczas polewania cieczą biologiczną

The co-ordinate system $x_s,y_s,z_s$ is stiffly fixed with the plane $(x_s0_sz_s)$.It is the lower surface of potential flow. Between the lower surface of potential flow and the tissue surface occurs the thin boundary layer. The distance between these surfaces is $\varepsilon \approx$ 30μm -70μm. The motionless external tissue surface $F^* \approx F$ is continually under horizontal perfusion by the biological liquid, which is supplied by the source with flow rate $Q_o$ distant H from $x_s,z_s$ plane see **Fig. 1**.

The flow of biological nutrient fluid around the tissue surface creates the very small friction forces, which have significant meaning during the growth process i bioreactor. The control of such small friction forces during the growth process is necessary. The measurement of **mentioned small friction forces is very expensive**, moreover introducing of measurement devices into the bioreactor has negative consequences on the growth process of tissue. Therefore in this paper is presented the computational model of simulation and determination of tribological friction forces in bioreactor during the growth process. Presented model enables the control operation and optimization of proper friction forces on the tissue surface. Friction forces in bioreactor are caused by the flow rate of perfusion of nutrient fluid and by the suction and boosted squeezing of the biological fluid into porous structure of the tissue.

A computational model consists of two parts. A first part presents the computational model of potential flow of nutrient fluid in the some distance from the tissue surface.

In the sufficient large distance from the lower surface, all fluid velocity components are equal_zero **[L. 1–4]**. The fluid velocity component $V_x,V_z$ tangential to the lower surface of potential flow, in horizontal directions are different from zero. The vertical component of fluid velocity $V_y$ on the level $y_s = 0$ is equal zero**.**

here a in *m*, b in *m*, c in *m*, d in *m* are the limits of region F. Simple potential function $\phi$ in $m^2/s$ determines fluid velocity components in the form **[L. 7]**:

$$V_x(x_s,y_s,z_s)=\frac{\partial\phi}{\partial x_s},\ V_y(x_s,y_s,z_s)=\frac{\partial\phi}{\partial y_s},\ V_z(x_s,y_s,z_s)=\frac{\partial\phi}{\partial z_s},\quad \phi\equiv\frac{Q}{\sqrt{x_s^2+y_s^2+z_s^2}},\quad \nabla^2\phi=0 \qquad (1)$$

whereas: Q – integration constant in $m^3/s$ .

We perfuse the total surface of tissue. Therefore absolute value of the resultant vector of velocity on the tissue surface multiplied by the value of surface equals flow rate $Q_o$ in $m^3/s$ of supplied fluid. Hence we have condition:

$$\iint_F \sqrt{V_x^2(x_S, y_S=0, z_S)+V_y^2(x_S, y_S=0, z_S)+V_z^2(x_S, y_S=0, z_S)}\,dx_S dz_S = Q_O \qquad (2)$$

where: $F(x_s,z_s)$: $\{a\le x_s\le b,\ c\le z_s\le d\}$ is the perfuse region of tissue surface in $m^2$.

## STUDY OF COMPUTATIONAL MODEL OF FRICTION FORCES

For a new coordinate system (x,y,z) following relations are valid: $y_s=y-\varepsilon$, $x_s=x$, $z_s=z$. Axis x is parallel to the axis $x_s$ and axis z to the axis $z_s$. Axis y coincides with $y_s$. Continuity, conservation of momentum equations and stress-strain relations have the form **[L.** 4**]**, **[L.** 5**]**, **[L.** 6**]**, **[L.** 7**]**:

$$\mathrm{div}(\rho\mathbf{v})=0,\ \mathrm{Div}\mathbf{S}=0,\ \mathbf{S}=-p\mathbf{I}+\eta\mathbf{A_1}+\alpha\mathbf{A_1}\mathbf{A_1}+\beta\mathbf{A_2}, \qquad (3)$$

where:**v** $(v_x,v_y,v_z)$ – velocity vector of the fluid in boundary layer, **I**-unit tensor**,** **S**-stress tensor in the biological fluid in *Pa*, $\mathbf{A_1}$**,** $\mathbf{A_2}$ strain tensors, $\eta$-dynamic, viscosity in Pas, $\alpha$, $\beta$-empirical coefficient, which describes viscoelastic properties in $Pas^2$.

Gap is limited by the inequalities: $a\le x\le b$, $0\le y\le\varepsilon$, $c\le z\le d$. For Newtonian fluid ($\alpha=0,\beta=0$). Boundary conditions are graphically presented in Fig.2 for fluid flow near the tissue body caused by horizontal perfusion, vertical grow and suction effect of porous tissue. Lower thin layer surface coincides with upper tissue surface. We have following boundary conditions:

$$v_x(x=0, y=0, z=0)=0,\ v_y(x=0, y=0, z=0)=\partial\varepsilon^*/\partial t + (-\rho g+\partial p_p/\partial y)c_k/\eta,\ v_z(x=0, y=0, z=0)=0 \qquad (4)$$

where: $p_p$ – pressure in porous, $c_k$ – coefficient in $m^2$ of penetration of biological fluid to the porous external surface of tissue, g – acceleration of gravity in $m/s^2$, t – time in *s*, $\varepsilon^*$ – height of superficial layer of tissue in *m*,$\varepsilon$ - height of boundary layer in *m* (see **Fig. 2**). Upper surface of bounda-

ry layer coincides with the lower surface of region of potential flow. In this place fluid particles move in x and z directions and values of these velocities we can determine from solutions (1). The horizontal velocity component in potential flow on the lower surface of potential region must have the same values as horizontal velocity component of viscous flow in upper surface of boundary layer. Hence:

$$v_x(x,y=\varepsilon,z)=V_x(x_s=x,y_s=0,z_s=z), \qquad v_z(x,y=\varepsilon,z)=V_z(x_s=x,y_s=0,z_s=z). \tag{5}$$

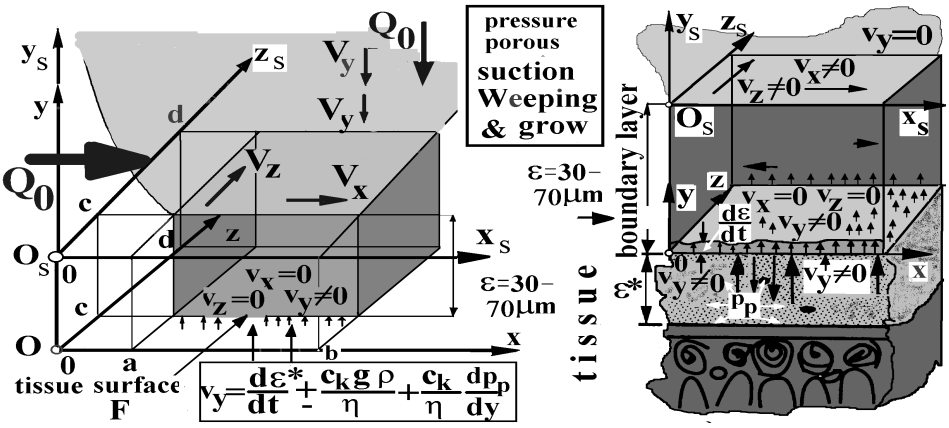


**Fig. 2. Boundary conditions for horizontal perfusion with suction, grow, weeping**
Rys. 2. Warunki brzegowe dla poziomego polewania ze ssaniem, wzrostem i przesączaniem

Now we assume dimensionless values:$x_1,y_1,z_1$, $\psi_1,\psi,a_1,b_1,c_1,d_1$ and dependencies between dimensional and dimensionless values respectively:

$$x\equiv Lx_1,\ y\equiv\varepsilon y_1,\ z\equiv Dz_1,\ \kappa_1\equiv D/L,\ \psi_1\equiv\varepsilon/L,\ \psi\equiv\varepsilon/D,\ a\equiv La_1,\ b\equiv Lb_1,\ c\equiv Dc_1,\ d\equiv Dd_1 \tag{6}$$

We assume following notations: L = b – a length of tissue surface under perfusion, D = d – c wide of tissue surface under perfusion, F = LD area of tissue surface under perfusion, whereas L in *m* and D in *m* and $F_1\{[a_1\le x_1\le b_1]\times[c_1\le z_1\le d_1]\}$, $0\le y_1\le 1$.We denote: $x_1$ – dimensionless coordinate in length direction, $y_1$ – dimensionless coordinate in gap height direction, $z_1$ – dimensionless coordinate in wide direction, $a_1$ – first value in length direction, $b_1$ – second value in length direction, $c_1$ – first value in wide direction,$d_1$ – second value in wide direction. We integrate equ-

ations (3) with respect to the variable y for $\alpha=0,\beta=0,\psi\equiv\varepsilon/(d-c)\approx 0{,}0001$, after boundary layer simplifications,. Continuity equation we integrate once with respect to the variable y. Afterwards we impose boundary conditions (7),(5) on the fluid velocity components. Hence velocity component in boundary layer near to the tissue surface have the following form:

$$v_x(x_1,y_1,z_1)=\frac{\rho\varepsilon^2}{2\eta}\frac{Q^2}{L^5}X_1(x_1,z_1)\times\left(y_1^2-y_1\right)-\frac{Q}{L^2}X_2(x_1,z_1)\times y_1, \quad (7)$$

$$v_z(x_1,y_1,z_1)=\frac{\rho\varepsilon^2}{2\eta}\frac{Q^2}{L^5}X_3(x_1,z_1)\times\left(y_1^2-y_1\right)-\frac{Q}{L^2}X_4(x_1,z_1)\times y_1, \quad (8)$$

$$v_y(x_1,y_1,z_1)=\frac{\rho\varepsilon^3}{12\eta}\frac{Q^2}{L^6}X_5(x_1,z_1)\times\left(2y_1^3-3y_1^2\right)-\frac{\varepsilon Q}{2L^3}X_6(x_1,z_1)\times y_1^2-$$
$$-\frac{c_k}{\eta}\left(\rho g-\frac{\partial p_p}{\partial y}\Big|_{y=0}\right)+\frac{\partial\varepsilon^*(t)}{\partial t} \quad (9)$$

$$X_1(x_1,z_1)\equiv 2x_1Y_1^3,\quad X_2(x_1,z_1)\equiv x_1Y_1^{1,5}, X_3\equiv 2\kappa_1 z_1Y_1^3,$$
$$X_2(x_1,z_1)\equiv\kappa_1 z_1Y_1^{1,5} \quad (10)$$

$$X_5(x_1,z_1)\equiv 8Y_1^3,\quad X_6(x_1,z_1)\equiv Y_1^{1,5}, Y_1\equiv\left(x_1^2+\kappa_1^2z_1^2\right)^{-1} \quad (11)$$

where: $0\le y_1\le 1$, $a_1\le x_1\le b_1$, $c_1\le z_1\le d_1$, $\kappa_1$ = D/L, Q – constant flow ratio in $m^3/s$.

By virtue of solutions (7), (8), (9) follows, that if flow ratio Q tends to zero i.e. if we have not external perfusion, then flow in boundary layer in horizontal plane not exists i.e. $v_x = 0$, $v_z = 0$ except the vertical velocity component which is different from zero $v_y \neq 0$ because this component depends on suction and vertical grow of porous tissue. For the fluid flow around the tissue surface in boundary thin layer we have that vertical component $v_y$ of fluid velocity vector different from zero in lower surface

of the thin layer and equals zero in the upper surface of boundary thin layer i.e. in plane $y = \varepsilon \Leftrightarrow y_1 = 1$, hence we write:

$$\frac{1}{F_1}\iint_{F_1} v_y(x_1, y_1 = 1, z_1)dx_1 dz_1 = 0 \tag{12}$$

Imposing condition (12) on the solution (9) we obtain following equation:

$$-\frac{\rho\varepsilon^3}{12\eta}\frac{Q^2}{L^6}X_{5c} - \frac{\varepsilon Q}{2L^3}X_{6c} - \frac{c_k}{\eta}\left(\rho g - \left.\frac{\partial p_p}{\partial y}\right|_{y=0}\right) + \frac{\partial \varepsilon^*(t)}{\partial t} = 0 \tag{13}$$

$$X_{ic} \equiv \iint_{F_1} X_i(x_1, z_1)dx_1 dz_1 \text{; for i = 1, 2, 3, 4, 5, 6,}$$

where: $F_1\{a_1 \le x_1 \le b_1, c_1 \le z_1 \le d_1\}$ (14)

From (13) follows, that unknown constant flow ratio Q in $m^3/s$ has the following form:

$$Q = -\frac{UL^2}{2}\Gamma_c S_{\eta k}, \quad \Gamma_c \equiv \frac{X_{6c}}{X_{5c}}, \; U \equiv \frac{6\eta L}{\rho\varepsilon^2},$$
$$S_{\eta k} \equiv 1 + \sqrt{1 + 8(Str)\frac{X_{5c}}{X_{6c}^2}\left[\frac{\varepsilon_o}{\varepsilon}se^{st_1} + \frac{Ga}{6Str}\left(\left.\frac{\partial p_p}{\rho g \partial y}\right|_{y=0} - 1\right)\right]} \tag{15}$$

where we assume following assumptions for dimensionless time $t_1$, dimensionless superficial layer $\varepsilon_1$, dimensionless grow coefficient s, Strouhal Number, Galileus Number:

$$t_1 = t/t_o \; \varepsilon_1(t_1) \equiv \exp(st_1), \; \varepsilon^* = \varepsilon_o\varepsilon_1, \; 0 < s < 1, \; Str \equiv L(Ut_o)^{-1},$$
$$Ga \equiv c_k \varepsilon g \rho^2/(\eta^2) \tag{16}$$

If we put constant (15),(16) in solutions (7), (8), (9), hence we obtain velocity components of nutrient fluid in bioreactor in following final form:

$$v_x(x_1,y_1,z_1)=Uv_{x1}=U\left\{0{,}75\times\Gamma_c^2\times S_{\eta k}^2\times X_1(x_1,z_1)\times\left(y_1^2-y_1\right)+\right.$$
$$\left.+0{,}50\times\Gamma_c\times S_{\eta k}\times X_2(x_1,z_1)\times y_1\right\} \tag{17}$$

$$v_z(x_1,y_1,z_1)=Uv_{z1}=U\left\{0{,}75\times\Gamma_c^2\times S_{\eta k}^2 X_3(x_1,z_1)\times\left(y_1^2-y_1\right)+\right.$$
$$\left.+0{,}50\times\Gamma_c\times S_{\eta k}X_4(x_1,z_1)\times y_1\right\} \tag{18}$$

$$v_y(x_1,y_1,z_1)=\frac{1}{2}U\psi v_{y1}=\frac{1}{2}U\psi_1\left[0{,}25\times\Gamma_c^2\times S_{\eta k}^2 X_5(x_1,z_1)\times\left(2y_1^3-3y_1^2\right)+\right.$$
$$+0{,}50\times\Gamma_c\times X_6(x_1,z_1)S_{\eta k}\times y_1^2+ \tag{19}$$
$$\left.-\frac{1}{3}(Ga)\left(1-\frac{1}{\rho g}\frac{\partial p_p}{\partial y}\bigg|_{y=0}\right)+2(Str)\frac{\varepsilon_o}{\varepsilon}s\,e^{st_1}\right],$$

where: $0\le y_1\le 1$ $a_1\le x_1\le b_1$, $c_1\le z_1\le d_1$, $\psi_1\equiv\varepsilon/L$ and U denotes dimension velocity.

Friction forces in x and z directions occurring in the upper surface of boundary layer we obtain from the following formulae:

$$F_{Rx}=\iint_F\left(\eta\frac{\partial v_x}{\partial y}\right)_{y=\varepsilon}dxdz,\quad F_{Rz}=\iint_F\left(\eta\frac{\partial v_z}{\partial y}\right)_{y=\varepsilon}dxdz, \tag{20}$$

Putting solutions (17), (18) in formulae (20), thus for $F_1\{a_1\le x_1\le b_1$, $c_1\le z_1\le d_1\}$.we obtain:

$$F_{Rx}=F_{Ro}\left[0{,}75\times\Gamma_c^2\times\iint_{F_1}S_{\eta k}^2X_1(x_1,z_1)dx_1dz_1+\right.$$
$$\left.+0{,}50\times\Gamma_c\times\iint_{F_1}S_{\eta k}X_2(x_1,z_1)dx_1dz_1\right] \tag{21}$$

$$F_{Rz} = F_{Ro}\left[0{,}75\times\Gamma_c^2\times\iint_{F_1} S_{\eta k}^2 X_3(x_1,z_1)dx_1dz_1 + \right.$$
$$\left. + 0{,}50\times\Gamma_c\times\iint_{F_1} S_{\eta k} X_4(x_1,z_1)dx_1dz_1\right] \qquad (22)$$

If pressure in porous $p_p$ is neglected and Ga=O($10^{-2}$), then from equation (15) follows:

$$S_{\eta k}\equiv 1+\sqrt{1+8(Str)\frac{X_{5c}}{X_{6c}^2}\frac{\varepsilon_o}{\varepsilon}se^{st_1}} \qquad (23)$$

and friction forces (21),(22) have the following form:

$$F_{Rx} = F_{Ro}F_{Rx1},\ F_{Rz} = F_{Ro}F_{Rz1},$$

$$F_{R\Sigma} \equiv F_{Ro}\sqrt{F_{Rx1}^2+F_{Rz1}^2},\quad F_{Ro}\equiv\frac{6\eta^2L^2D}{\rho\varepsilon^3} \qquad (24)$$

$$F_{Rx1}\equiv 0{,}75\times\Gamma_c^2\times X_{1c}S_{\eta k}^2+0{,}50\times\Gamma_c\times X_{2c}\times S_{\eta k},$$
$$F_{Rz1}\equiv 0{,}75\times\Gamma_c^2\times X_{3c}\times S_{\eta k}^2+0{,}50\times\Gamma_c\times X_{4c}\times S_{\eta k} \qquad (25)$$

## FRICTION FORCES CALCULATIONS

Now we examine numerically time depended friction forces during the time of growth of tissue. In this example we are neglecting pressure in porous. In calculations we take following data: height of fluid boundary layer flowing around a tissue: $\varepsilon=30\times10^{-5}$m, height value of superficial layer of tissue:$\varepsilon_o=10^{-3}$m.Nutrient dynamic viscosity has value: $\eta=10^{-3}$*Pas*. Fluid density magnitude equals $\rho=1000$*kg/m*$^3$.We assume following dimensionless growth coefficients s=0,08;0,10;0,12;Average time value of tissue growth $t_o$=1000s for dimensionless time interval of tissue growth:$0<t_1\leq40$. Length of tissue equals L = 0,10*m*, wide of perfuse tissue is D = 0,10*m*,hence $\kappa_1$=D/L=1,0. We assume that the region of tissue

surface determine following inequalities: $a_1 \le x_1 \le b_1$, $c_1 \le z_1 \le d_1$ for $a_1=1, b_1=2$, $c_1=1, d_1=2$. Hence from (14) we obtain: $X_{1c}=0{,}0422$, $X_{2c}=0{,}1621$, $X_{3c}=0{,}0422$ $X_{4c}=0{,}1621$, $X_{5c}=0{,}1274$, $X_{6c}=0{,}1147$. From equations (15),(16),(23),(24),(25) we obtain following formulae and values:

$$U = \frac{6\eta L}{\rho\varepsilon^2} = \frac{6\times10^{-3}\,\mathrm{Pas}\times10^{-1}\,\mathrm{m}}{1000\,\mathrm{kg/m^3}\times(30\times10^{-5}\,\mathrm{m})^2} = \frac{2}{3}\times10\,\mathrm{m/s};$$
$$\mathrm{Str} = \frac{L}{Ut_o} = \frac{0{,}10\,\mathrm{m}}{(2/3)\times10\,\mathrm{m/s}\times1000\,\mathrm{s}} - 1{,}500\times10^{-5}, \tag{26}$$

$$F_{Ro} = \frac{6\eta^2L^2D}{\rho\varepsilon^3} = \frac{6\times(10^{-3}\,\mathrm{m})^2\times(10^{-1}\,\mathrm{m})^3}{1000\,\mathrm{kg/m^3}\times(30\times10^{-5}\,\mathrm{m})^3} = 0{,}22\,\mathrm{N} \tag{27}$$

$$F_{Rx1} = F_{Rz1} = \frac{3}{4}\left(\frac{0{,}1147}{0{,}1274}\right)^2\times0{,}0422\times\left(S_{\eta k}\right)^2 + \frac{0{,}1147}{2\times0{,}1274}\times0{,}16212\times S_{\eta k} \tag{28}$$

thus
$$F_{Rx1} = F_{Rz1} = 0{,}0255\,S_{\eta k}^2 + 0{,}0729\,S_{\eta k}, \tag{29}$$

$$S_{\eta k} = 1 + \sqrt{1 + 8\times\frac{3}{2}\times10^{-5}\times\frac{0{,}1274}{(0{,}1147)^2}\times\frac{10^{-3}\,\mathrm{m}}{30\times10^{-5}\,\mathrm{m}}\times\frac{1}{10}\times e^{s\times t_1}} \tag{30}$$
$$= 1 + \sqrt{1 + 0{,}00391\times e^{s\times t_1}}.$$

Dimensionless velocity distribution in dimensionless height $y_1=0{,}50$ of thin layer has by virtue of solution (17) the following form:

$$v_{x1}(x_1, z_1, t_1) = v_x / U = -0{,}3039\times S_{\eta k}^2\times\frac{x_1}{\left(x_1^2 + z_1^2\right)^3} + 0{,}225\times S_{\eta k}\times\frac{x_1}{\left(x_1^2 + z_1^2\right)^{1{,}5}} \tag{31}$$

$1 \le x_1 \le 2$, $1 \le z_1 \le 2$. **Fig. 3** and **Fig. 4** shows dimensionless velocity distributions for s = 0,10 and s = 0,08 for dimensionless times: $t_1 = 10$; $t_1 = 20$; $t_1 = 30$; $t_1 = 40$ respectively.

To obtain dimensional velocity values we must multiply values obtained from the formula (31) or values presented in **Fig. 3**, by the dimensional velocity factor U=6,67 m/s.

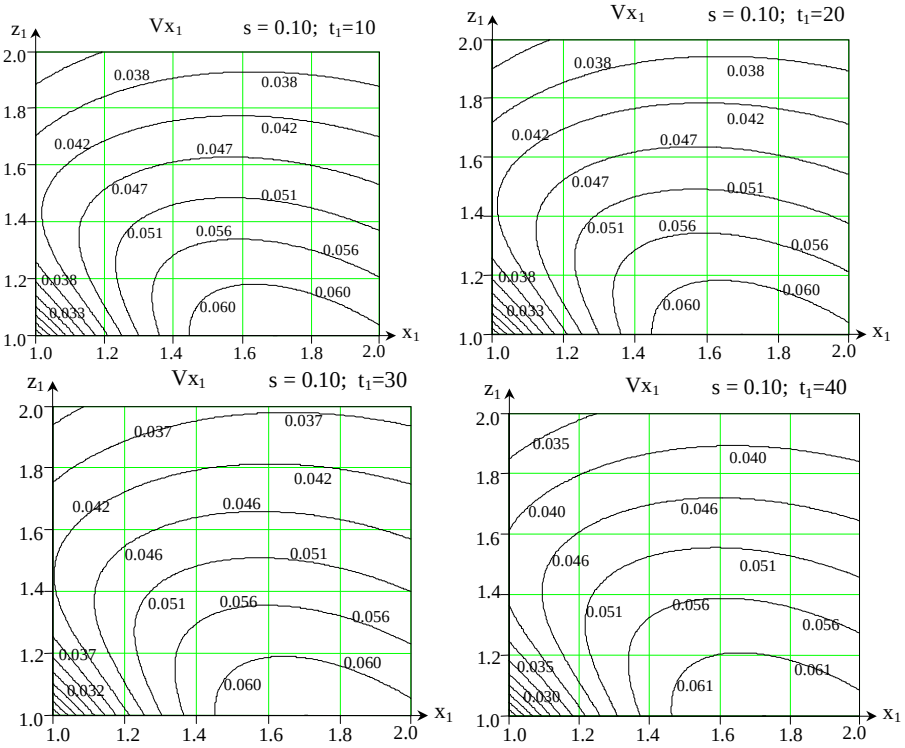


**Fig. 3. Dimensionless velocity distribution in the dimensionless distance $y_1$ = 0,50 from the external tissue surface for grows coefficient s = 0,10 in dimensionless times $t_1$ = 10; 20; 30; 40**

Rys. 3. Bezwymiarowe rozkłady prędkości w bezwymiarowej odległości $y_1$ = 0,50 od zewnętrznej powierzchni tkanki dla współczynnika wzrostu s = 0,10 w bezwymiarowych ostępach czasu $t_1$ = 10; 20; 30; 40

For dimensionless time: $t_1 = 0$, $t_1 = 10$, $t_1 = 20$, $t_1 = 30$, $t_1 = 40$ and s = 0,10, we obtain: from the formula (30) following dimensionless values $S_{\eta k}$ = 2,000; 2,005: 2,014; 2,038; 2,100 respectively, from the formulas (24), (25) we obtain dimensionless values of friction forces:

$F_{R\Sigma}/F_{Ro}$= 0,3509; 0,3518; 0,3540; 0,3600; 0,3759, from the formula (16) we have following dimensionless values of the height of superficial layer:$\varepsilon_1$ = 1,000; 2,7183; 7,3891; 20,0855; 54,5982 respectively. To obtain realistic values of friction forces we must multiply dimensionless values of friction forces by the factor $F_{Ro}$ = 0,22 N. To obtain realistic time we must multiply dimensionless time values $t_1$ by the factor $t_o$=1000s.To obtain realistic values of the height of superficial layer we must multiply dimensionless values $\varepsilon_1$ by the factor $\varepsilon_o$ = 0,001 m. Hence for times: t=0s, 10 000s, 20 000s, 30 000s, 40 000s we have values of friction forces: 0,0770 N, 0,0772 N, 0,778 N, 0,789 N, 0,0825 N respectively. In above mentioned times the superficial layer has following realistic heights $\varepsilon^*$: 0,00100m; 0,00271m; 0,00739m; 0,02008m;0,05459m.

## CONCLUSIONS

In this paper are derived analytical formulae for friction force components caused by the nutrient fluid flow in boundary thin layer resting on the tissue surface in bioreactor during the perfusion, growth and suction of porous occurring in superficial layer. Typical nutrient fluid has density value $\rho = O(1000 kg/m^3)$. Height of fluid boundary layer in bioreactor has values from $\varepsilon = 3\times10^{-5} m$ to $\varepsilon = 30\times10^{-5} m$. Characteristic height value of superficial layer of human cartilage has value $\varepsilon_o = 10^{-3}$ m. Ambient growth coefficient of joint cartilage has dimensionless value $s = O(10^{-1})$ for dimensionless time interval $0<t_1\leq40$,where characteristic time value of growth of tissue in bioreactor equals $t_o = O(1000\ s)$.Dynamic viscosity of typical nutrient fluid equals $\eta = O(10^{-3}\ Pas)$. Typical length of tissue in bioreactor has values L from $10^{-2}\ m$, to $10^{-1} m$. The coefficient of penetration of nutrient fluid to the porous superficial layer of normal cartilage of human hip joint has value $c_k = O(10^{-12}\ m^2)$. For above data the Strouhal Number has values from $Str = 0(10^{-5})$ to $Str = 0(10^{-4})$, Galileus Number has value $Ga = 0(10^{-2})$.Typical volume flow rate of perfusion of nutrient fluid in bioreactor has value $Q_o = 0(10^{-8} m^3/s)$.By virtue of presented computational model we obtain following quantities of velocity components: $v_x = 0(10^{-2}\ m/s)$, $v_z = O(10^{-2}\ m/s)$, $v_y = O(10^{-4}\ m/s)$, and following quantities of components of friction forces $F_{Rx}$, $F_{Rz}$ in interval from $O(10^{-2}\ N)$ to $O(10^{-1}\ N)$ .

## Acknowledgement

Author thanks for cooperation with Central Institute Department of Biomedical Engineering in University Ulm in Germany and cooperation with Clinic of Georg August University Göttingen, Department of Jaw Orthopedics This paper was financed by KBN Founds in years 2003-2006 as Scientific Project KBN 411E-030-25

## APPENDIX

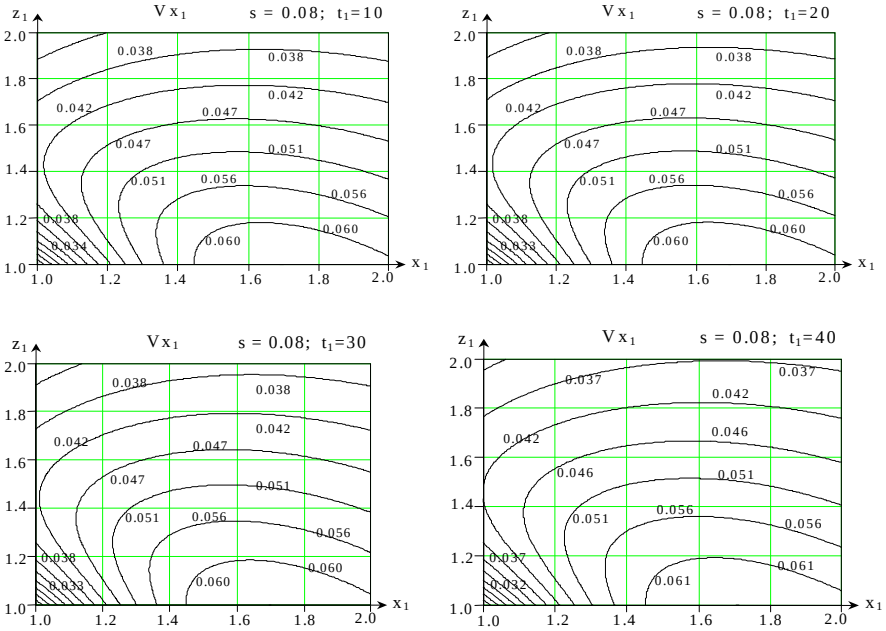


**Fig. 4. Dimensionless velocity distribution in the dimensionless distance $y_1$ = 0,50 from the external tissue surface for grows coefficient s = 0,08 in dimensionless times $t_1$ = 10; 20; 30; 40**

**Rys. 4. Bezwymiarowe rozkłady prędkości w bezwymiarowej odległości $y_1$ = 0,50 od zewnętrznej powierzchni tkanki dla współczynnika wzrostu s = 0,08 w bezwymiarowych ostępach czasu $t_1$ = 10; 20; 30; 40**

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**Streszczenie**

**Najnowsze trendy naukowe w Unii Europejskiej i w USA w zakresie biotribologii idą w kierunku hodowli w bioreaktorze gotowych części chrząstki stawowej na bazie tkanek rodzimych pacjenta. Przeszczepów można dokonać wiele razy w życiu pacjenta, natomiast endoprotezę zakłada się conajwyżej dwa, razy. Tkanka kostna umiejscowiona w szkieletowym łóżku bioreaktora jest permanentnie zraszana i polewana mediami o właściwościach nie newtonowskich. Są to ciecze odżywcze z odpowiednimi dodatkami lepkosprężystymi wywołującymi pożądany wzrost tkanki. Opływ takiej tkanki w pewnej od niej odległości stanowi przepływ nie lepki, bezwirowy, potencjalny. W bezpośredniej bliskości tkanki w warstewce granicznej, przyściennej o grubości od 70 do 100 mikronów mamy do czynienia z przepływem lepkim. Składowe mikro prędkości tego przepływu nie newtonowskiej cieczy zależą nie tylko od wydatku objętościowego pompy zraszającej łóżeczko bioreaktora lecz również od sił ssących ciecz poprzez porowatą warstewkę wierzchnią tkanki a także przez permanentny mikro wzrost tkanki. Pole małych prędkości płynu na powierzchni tkanki, wywołuje siły tarcia o małych wartościach poniżej 1N,które mają jednak bardzo istotne znaczenie w trakcie hodowli tkanki. Pomiar tak małych sił tarcia w warunkach ciągłego wzrostu tkanki przy obecnych warunkach technicznych jest bardzo utrudniony, kosztowny i niepożądany ze względu na zaburzenia procesu wzrost tkanki. Dlatego prace analityczno numeryczne mają duże znaczenie poznawcze. Niniejsza praca przedstawia model obliczeniowy sił tarcia w bioreaktorze. Model ten pozwala wyznaczać, symulować siły tarcia i sterować siłami tarcia a przez to również optymalizować siłami tarcia do pożądanych wartości.**