BOUNDARY CONDITIONS ON THE BIO-CELL SURFACES FOR NANOLUBRICATION OF MICROBEARINGS

Krzysztof Wierzcholski

Gdynia Maritime University
Morska 83, 81-225 Gdynia, Poland
tel.: +48 58 6901348, 3476126, fax: +48 58 6901399
e-mail:wierzch@am.gdynia.pl

Abstract

The aim of the paper is the formulation of boundary conditions for liquid velocity and friction forces in nano scale and presentation of analogies between boundary conditions for super thin liquid layer about 100nm height around cultivated cell of cartilage human joint in bioreactor and boundary conditions for thin lubrication layer in micro bearing with no greater journal diameter than 2mm.

To be considered flow of viscous liquid with non-Newtonian, viscoelastic properties in super thin boundary layer in direct contact with superficial layer of cultivated cells. Such flow is caused by the cell growth, weeping and suction process of the liquid from boundary thin layer into porous cell body. Liquid properties inside super thin layer depend above all from physical properties of bodies and surfaces which are restricted the thin liquid layer. It is specific feature of thin liquid layers which distinguishes such flows from lubrication flows where gap height reaches several dozen micrometers .Apparent viscosity of such liquid depends on shear rate which occur in thin boundary layer. Additional the dynamic viscosity of the liquid depends on Young modulus of cell superficial layer and on geometrical structure of the cell.

Presented model of boundary conditions enables its application to the research connected with the optimal lubrication in slide micro bearings [6], [8].

Keywords*: Boundary conditions, friction forces, nano-scale, bio-cells, slide micro-bearings*

WARUNKI BRZEGOWE NA POWIERZCHNI BIOKOMÓREK DLA NANOSMROWANIA MIKROŁOŻYSK

Streszczenie

Tematem pracy jest sformułowanie warunków brzegowych dla prędkości cieczy i sił tarcia w nanoskali oraz przedstawienie analogii pomiędzy warunkami brzegowymi dla super cienkiej warstewki cieczy o wysokości poniżej 100 nm opływającej hodowane komórki chrząstki stawowej człowieka w bioreaktorze a warunkami brzegowymi dla cienkiej warstwy smarującej w mikro łożyskach o średnicy wału nieprzekraczającej 1mm.

Rozpatrywany jest przepływ cieczy lepkiej o właściwościach nie Newtonowskich, lepko-sprężystych w super cienkiej warstwie granicznej występujący w bezpośrednim otoczeniu warstwy wierzchniej hodowanego chondrocytu. Taki przepływ jest wywołany między innymi wzrostem komórki, a także procesem przesączania się cieczy odżywczej z cienkiej warstwy granicznej do porowatego ciała komórek. Własności cieczy w super cienkiej warstwie zależą przede wszystkim od właściwości fizycznych ciał ścianek lub powierzchni ograniczającej tak cienką warstewkę. Jest to specyfika przepływu w super cienkich warstewkach odróżniająca te przepływy od klasycznych przepływów smarujących gdzie wysokość szczeliny osiąga kilkanaście mikrometrów.

Lepkość pozorna takiej cieczy zależy od prędkości deformacji, a więc od prędkości przepływu tej cieczy w cienkiej warstwie granicznej. Ponadto lepkość takiej cieczy zależy od modułu Younga warstwy wierzchniej oraz od struktury geometrycznej powierzchni hodowanego chondrocytu. Przedstawiony model warunków brzegowych umożliwia jego zastosowania do badań związanych z optymalnym smarowaniem mikro-łożysk ślizgowych.

Słowa kluczowe: *Warunki brzegowe, siły tarcia, nano-skala biologiczne komórki, mikro-łożyska ślizgowe*

1. Introduction

The most excellent slide bearings are the biological bearings which are shaped through the nature over the many thousand years of evolution. Human joint cartilage creates slide surfaces of such bearings which have properties similarly to good bearing alloy namely *hard crystals on the soft basis.* Cartilage joint is simultaneously soft and deformable and has properties of the hard bed. Such properties of bearing alloy are desired in slide micro-bearings where the diameter of bearing shaft is smaller than 2mm.To know the secrets of nature concerning the construction of the such ideal bearing material we can see on the Fig.1 where the cell structure of human joint cartilage in nano-level is shaped by the chondrocytes [7],[9].

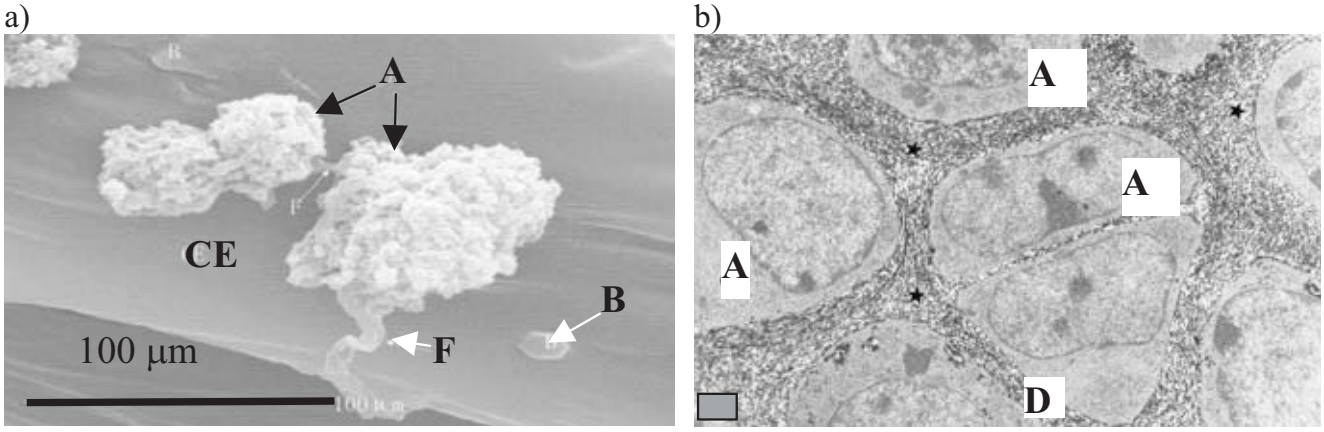

Fig.1. Pictures of chondrocytes: a) 7 days after cultivation obtained by virtue scanning microscope (enlargement about 5000×)[9], b) 7 days after cultivation obtained by virtue AFM microscope (enlargement about 8000×)[7] where we denote (A) chondrocyte; (B) bladder; (C) matrix; (D) joint capsule (E) cell layer; (F) duckweed
Rys. 1. Obrazy chondrocytów: ***a)*** *po 7 dniach hodowli uzyskany z mikroskopu skaningowego (powiększenie 5000×)[9],* ***b)*** *po tygodniu hodowli uzyskany z mikroskopu elektronowego (8000×)[7] gdzie:(A) chondrocyt; (B) pęcherzyk; (C) macierz; (D) jamka (E) warstwa komórkowa; (F) rzęsa*

The main component of the joint cartilage is water about from 65 to 80 percent, collagen from 10 to 30 percent and proteoglycans from 5 to 10%. Remainder components are non-collagen proteins and a few lipids. Chondrocytes i.e. cells of cartilage constitute about 2-10% of tissue volume. During to grow old of human joint is observed the decreasing of the number of cells in cartilage. In this time average surface section of chondrocytes attain value 90 [μm^2] in new born child (see Fig.1a) and increases to 370 [μm^2] in the third decade of human life (see Fig.1b).

In cytoplasm occur the strongly developed net of the inter-plasma and a lot of bubbles. Cell membrane of chondrocytes has many insertions and small protuberances. Directly around the cells occurs the cell matrix which is separated by the border from the territorial matrix. This border is known joint capsule or cavity. In the each cavity we can find some chondrocytes to come into being by the fission of the one cell. Chondrocytes lying in the one cavity create the chondron as a new structural unit. Fine net of fibres on the chondron surface secures the cells against the action of mechanical forces and give the elastic and hyper-elastic properties for the tissue.

The Massachusetts Institute of Technology micro-engine robots are supported by journal and thrust micro-bearings [4], [6], [8]. The performance of such bearings can be influenced by geometric non-uniformities which arise in the process of micro-fabrication. To enable height speed operation of the micro-devices it is important to quantify these effects. Moreover the bearing clearances, orifice diameter and profiles occurring in micro-bearing must be adopted in each case to the work conditions of the micro-devices. Author hopes that the experiences gained during the study of cell lubrication enable to give good applications in micro-bearing- constructions [6], [8].

2. The weeping flow velocity boundary conditions of the viscous liquid in the super thin layer with growth effect

Fig. 2 presents the boundary conditions in super thin liquid boundary layer about 100 nm tricks for the flow caused by the weeping of the liquid into molecular micro-porous surface of the cell body. Additional the flow is caused by the growth and reproduction of the cells.

Lower surface of the liquid boundary layer coincides with the upper surface of the cell superficial layer. This surface is motionless in horizontal direction. Hence velocity component in horizontal direction is equal zero.

Nonzero value of the velocity vector component directed vertical to the lower liquid surface on the cell is caused by the growth of the cell superficial layer and by the simultaneously weeping of the liquid into the cell pores.

The upper cell surface grows in the time period i.e. the height ε of the liquid boundary layer changes in the time t. The changes of the liquid boundary layer generate the arising of the vertical component of the velocity vector inside the thin liquid layer. Hence we have:

$$v_y(x, y = 0, z) = \frac{\partial \varepsilon^*}{\partial t}, \tag{1}$$

where:

ε^* – the height of the cell superficial layer in the length unit.

Upper surface of the liquid boundary layer moves in horizontal and vertical plane accordingly to the extortions caused by delivering of external liquid.

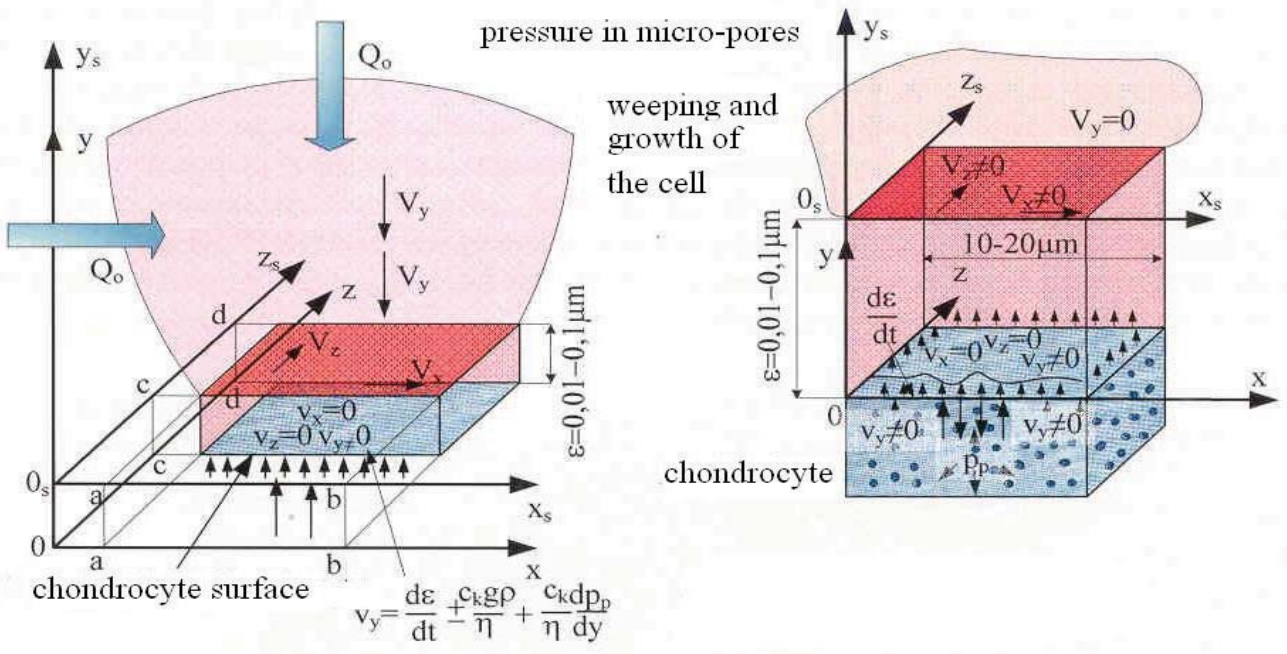

Fig.2. Illustration of the boundary conditions for weeping of the liquid and growth of the cell
Rys. 2. Ilustracja warunków brzegowych dla przesączania cieczy oraz wzrostu komórki. Oznaczenia: powierzchnia chondrocyte (surface of chondrocyte), przesączanie i wzrost komórki (weeping and growth of the cell), ciśnienie w mikrosporach (pressure in micropores)

3. The viscous liquid velocity conditions in the boundary layer between microporous cell and potential flow

We take into account the case, where boundary layer of viscous, nutrient liquid is limited from the lower side by the permeable superficial layer of the chondrocytes and from the upper side by the movable non viscous potential flow or motionless non loaded free liquid surface [4], [5].After Beavers investigations [1], [2] for both above cases the boundary conditions for liquid velocity are presented in Fig.3. In both cases liquid velocity distribution depends on the gradient of the pressure in pores p_p.

In the case presented in Fig.3b the liquid velocity additional depends on the potential flow which drifts motion in boundary layer and depends on pressure p which occurs in potential flow. In the case presented in Fig.3c not occurs the influence of the pressure p from potential flow on the liquid velocity.

The origin of the Cartesian coordinate system is assumed on the level of the external surface of chondrocytes see Fig.3. In the case if boundary layer of nutrient liquid is limited from the bottom by the permeable superficial layer of chondrocytes body and from the top by the movable liquid layer of potential flow in bioreactor (see Fig.3a) then the boundary Beavers conditions for velocity liquid components are as follows:

$$v_x = \Xi_x \text{ dla } y = \varepsilon, \tag{2}$$

$$v_x = v_{xb} \text{ dla } y = 0, \tag{3}$$

$$\frac{dv_x}{dy} = \frac{c_\alpha}{\sqrt{c_k}}\left(v_{xb} - V_b\right), \text{ dla } y = 0, \tag{4}$$

$$V_b = -\frac{c_k}{\eta}\frac{\partial p_p}{\partial x}. \tag{5}$$

The function Ξ_x in [m/s] describes the known horizontal component of velocity vector in potential flow. Symbol v_{xb} unknown velocity value in [m/s], which attain velocity vector component tangential to the porous cell surface. This value will be determined from the additional conditions (4), (5). Symbol V_b denotes liquid flow velocity in horizontal direction x on the porous cell surface caused by the gradient of pressure in pores p_p. Dimensionless value c_α depends from the surface porosity degree. The flow presented in Fig.3b is caused as well by the pressure and liquid motion in potential flow as by the pressure in pores and liquid flow in pores.

In the case if boundary layer of nutrient viscous liquid is limited from the bottom by the permeable cell superficial layer and from top by the motionless and non loaded free liquid surface (see Fig.3c),then in this case we put $\Xi_x = 0$, and the flow in boundary layer is caused only by the flow and pressure in pores.

The thin boundary layer of the lubricant in micro-bearings has the height non greater than 100 nm. This layer swims round the shaft porous surfaces where the journal diameter is smaller than 1mm in micro-bearings. In such micro-bearings the boundary conditions for the lubricant flow are similar to the conditions which occur above in bio-bearings and in bioreactors.

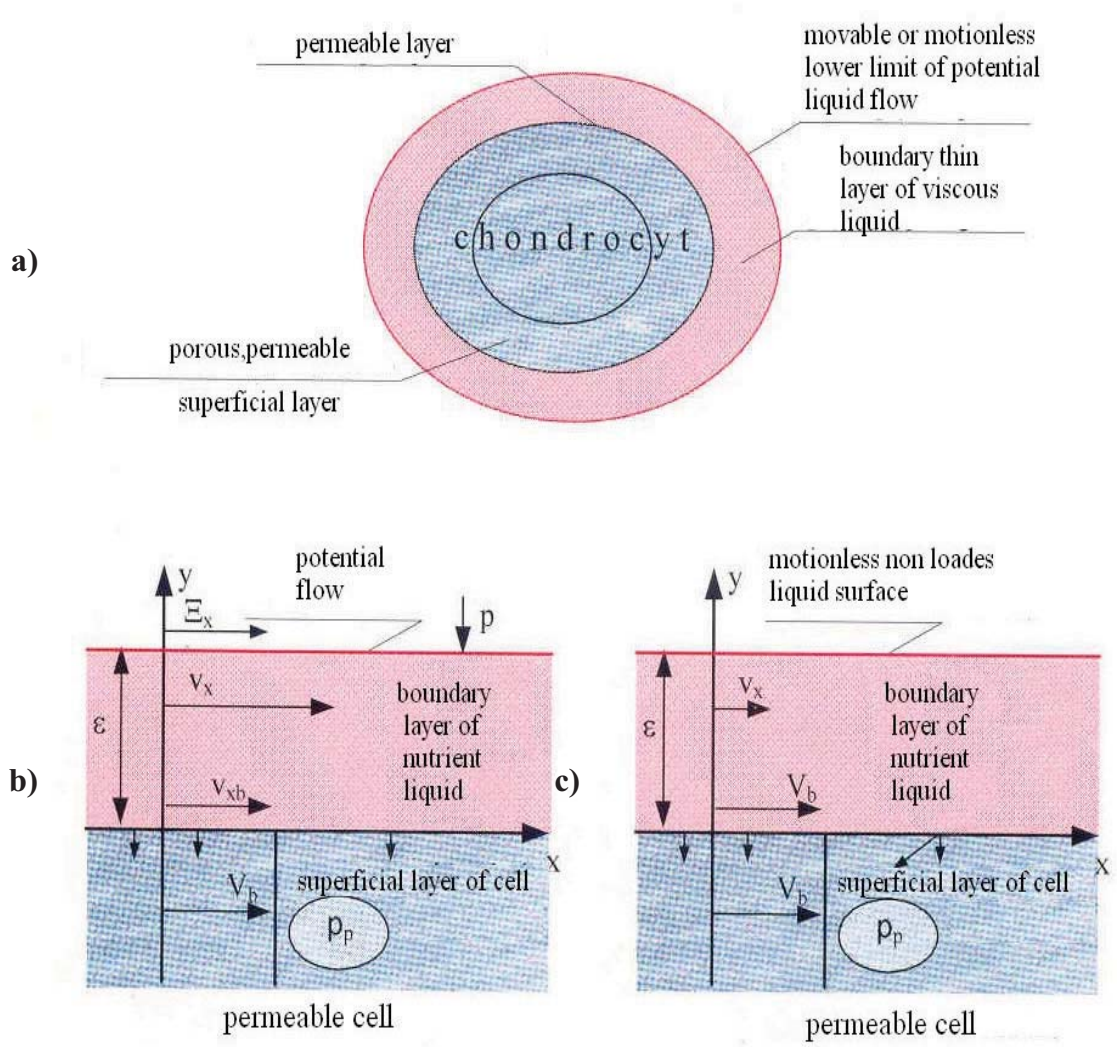

Fig.3. Illustration of the boundary conditions in thin liquid layers: a) thin liquid layer flow around a chondrocytes, b) liquid layer restricted with the permeable wall of porous cell body and with the zone of movable potential flow, c) liquid layer restricted with the permeable wall of porous cell body and with the non movable and non loaded free liquid surface

Rys. 3. Ilustracja warunku brzegowego przepływu w cienkiej warstwie cieczy; a) opływ chondrocytu cienką warstwą cieczy, b) warstwa cieczy ograniczona ścianką przepuszczalnego porowatego ciała komórki oraz strefą ruchomego przepływu potencjalnego, c) warstwa cieczy ograniczona ścianką przepuszczalnej porowatej powierzchni oraz nieruchomą, nieobciążoną powierzchnią swobodną cieczy. Oznaczenia: przenikalna komórka (permeable cell), warstwa wierzchnia komórki (superficial layer of the cell), warstwa graniczna cieczy odżywczej (boundary layer of the nutrient liquid), przepływ potencjalny (potential flow), nieruchoma nieobciążona powierzchnia cieczy (motionless non loaded liquid surface), porowata przepuszczalna warstwa wierzchnia (porous permeable superficial layer), warstwa graniczna płynu lepkiego (boundary layer of viscous fluid), ruchoma lub nieruchoma dolna warstwa przepływu potencjalnego (motion or motionless lower layer of potential flow)

4. Boundary conditions for the viscous flow in the micro channels in cells between permeable and not permeable surfaces

After Beavers investigations [1], [2] and accordingly to the Darcy law, the vector velocity component v_x of the viscous liquid in the thin boundary layer is described by the following equation [3]:

$$\frac{\partial^2 v_x}{\partial y^2} = \frac{1}{\eta}\frac{\partial p_p}{\partial x}. \tag{6}$$

In this case the liquid flow in boundary layer depends only from the pressure p_p in micro-pores and depends from the adhesive and cohesion forces which occur between biological liquid particles in micro-canals with mean diameter about 0,01 do 0,1 micrometer. The origin of the coordinate system was assumed on the permeable surface. Axis y is situated in the height direction of the liquid layer (see Fig.4).

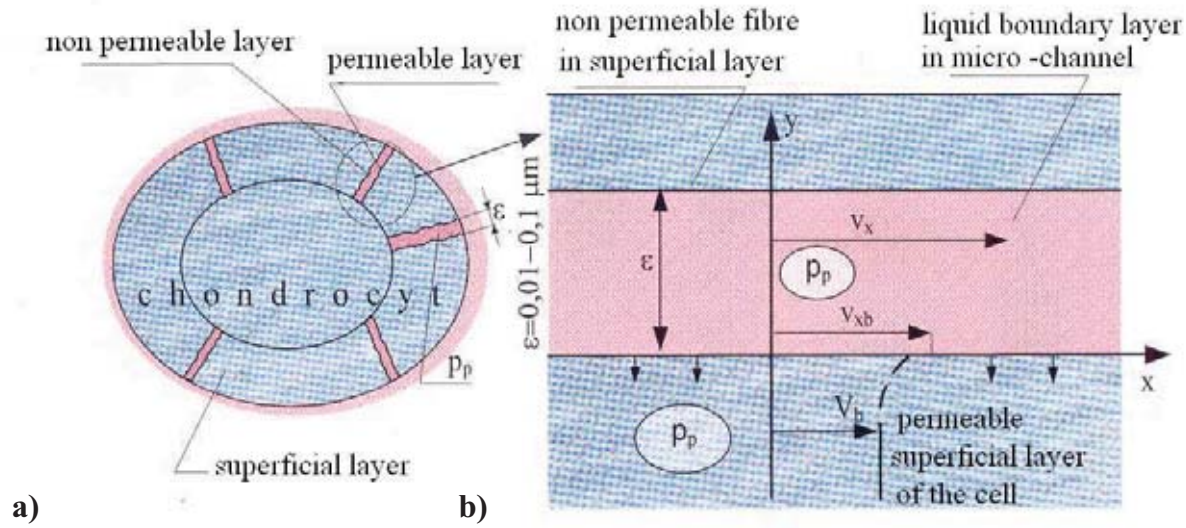

Fig.4. Illustration of the boundary conditions in thin liquid layers inside pore micro-canals which are restricted with the surface of body cells and not permeable layer of collagen fibres: a) structures of micro-canals in micro-porous superficial layer of the chondrocytes, b) model of micro-canal
Rys. 4. Ilustracja warunku brzegowego przepływu cieczy w mikro-kanałach porów ograniczonych przepuszczalną powierzchnią ciała komórki oraz nieprzepuszczalną warstwą włókna kolagenowego;
a) struktury mikro-kanalików w mikroporowatej warstwie wierzchniej chondrocytu, b) model mikro kanału. Oznaczenia: warstwa wierzchnia (superficial layer), nieprzenikalne włókno we warstwie wierzchniej (non permeable fiber in superficial layer),warstwa graniczna cieczy w mikro-kanaliku (liquid boundary layer in micro-canal), warstwa przenikalna (permeable layer)

In the case if boundary layer of nutrient liquid is limited from the bottom by the permeable superficial layer of chondrocytes body and from the top by the non permeable cell surface then the boundary conditions for velocity liquid components are formulated as follows:

$$v_x = 0 \text{ dla } y = \varepsilon, \tag{7}$$

$$v_x = v_{xb} \text{ dla } y = 0, \tag{8}$$

$$\frac{dv_x}{dy} = \frac{c_\alpha}{\sqrt{c_k}}\left(v_{xb} + \frac{c_k}{\eta}\frac{\partial p_p}{\partial x} \right), \text{ for } y = 0. \tag{9}$$

To determine unknown horizontal component of the liquid velocity v_{xb} on the permeable surface of chondrocytes in the place y = 0, then we use Beavers condition (9) which determines the angle pitch value of velocity profile on the permeable surface.

The boundary conditions presented in Fig.4 for the liquid velocity depend only from the pressure and liquid velocity in micro-pores. Dimensionless value c_α depends from the degree of micro-porosity of surface structure. Symbol v_{xb} denotes the unknown velocity value in [m/s] which attain the component of liquid velocity vector tangential to the micro-porous cell surface.

5. Conclusions and Applications

Scientific effort contained in this elaboration presents an impact to the domain by deliver of some comparisons data between boundary conditions for lubrication flow in super thin boundary layer lying on the external surface of biological cells of joint cartilage and boundary conditions for micro-bearing lubrication, where the shaft has the diameter smaller than 2 mm.

Numerical calculations are performed by the Computational Fluid Dynamics Methods, Neural Network Analysis and Molecular Dynamic Calculation Methods.

Presented description of comparisons between biological cells and micro-bearings was adapted to the optimization of tribological effects using computer analysis. Obtained results can be applied to solve tribological problems in micromanipulators [10], [11] (see Fig. 5).

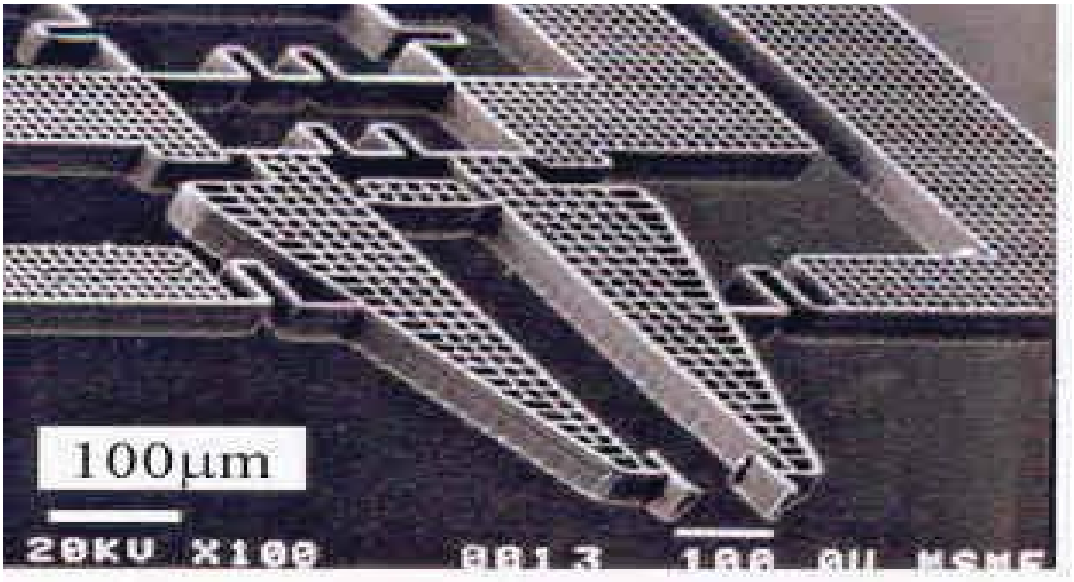

Fig. 5 Micro-manipulator
Rys. 5. Mikromanipulator

Acknowledgement

The present research is financially supported within the frame of the TOK–FP6, MTKD-CT-2004-517226

References

[1] Beavers, G. S., Joseph, D. D., *Boundary conditions at a naturally permeable walls*, Journal of Fluid Mechanic, Vol.30, part 1, pp.197-207, 1967.

[2] Beavers, G. S., Sparrow, E. M., Magnuson, R. A., *Experiments on Coupled Parallel Flows in a Channel and Bounding Porous Medium*, Journal of Basic Engineering, pp.843- 848, 1970.

[3] Cieszko, M., Kubik, J., *Derivation of Matching Conditions at the Contact Surface Between Fluid-Saturated Porous Solid and Bulk Fluid*, Transport in Porous Media, 34, pp.319-336, 1999.

[4] Errol, B., Arkilic, Schmidt, Martin A. & Kenneth, Breuer S., *Gaseous slip flow in long micro-channels*, submitted to J.Micro-electromechanical Systems, pp.1-16, 1995.

[5] Johnson, G.A., Rajagopal, K.R., Woo, S. L-Y., *A Single Integral Finite Strain (sifc) Model of Ligaments and Tendons*, Advances in Bioengineering, 22, pp.245-248, 1992.

[6] Liu, L.X., Spakovszky, Z. S., *Effects of Bearing Stiffness Anisotropy on Hydrostatic Micro gas Journal Bearing Dynamic Behavior*, J. of Engineering for Gas Turbines and Power, ASME, vol.129,pp.177-184, Jan.2007.
[7] Shakibaei, M., De Souza, P., *Differentiation of mesenchymal limb bud cells to chondrocytes in alginate beads*, Cell Biology International, Vol.21, No.2, pp.75-86, 1997.
[8] Teo, C. J., Spakovszky, Z. S., *Analysis of the Tilting Effects and Geometric Non-uniformities in Micro-hydrostatic Gas Thrust Bearing*, Transaction of ASME, Vol.128, pp.606-615, Oct. 2006.
[9] Ying, Deng, Kai, Zhao, Xiong-Fei, Zhang, Ping, Hu, Guo-Qiang, Chen, *Study on the three-dimensional proliferation of rabbit articular cartilage-derived chondrocytes on poly-hydroxyalkanoate scaffolds*, Elsevier, Biomaterials, 23, pp.4049-4056, 2002.
[10] www.nanonet.pl.
[11] www.almaden.ibm.com.