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ANALYSIS OF INFLUENCE OF ELECTROLYTE FLOW VOLUME RATE IN INTERELECTRODE GAP ON PHYSICAL AND GEOMETRIC PARAMETERS OF ELECTRO-CHEMICAL MACHINING

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Abstract

In the paper has been presented an analysis of the influence of the electrolyte flow volume stream on the geometry of the work-piece and physical parameters of ECM electrochemical machining. Equations resulting from the principles of momentum, mass and energy conservation describing the physical phenomena which occur during electrochemical machining have been formulated and solved.

Keywords: *electrochemical machining, electrolyte flow, mathematical model*

1. Introduction

Electrochemical machining with the use of a tool-electrode is today one of the basic operations of electrochemical machining technology for machine elements and other mechanical devices [1], [2].

In the constant process the tool-electrode (TE) performs most often a translation motion towards the machined surface. Electrolyte is supplied to the inter electrode gap with high velocity causing carrying away erosion products from the interelectrode gap (IEG). These are mainly particles of hydrogen and ions of the digested metal. Thus, in such conditions we obtain multi-phase, in general, three dimensional flow [3].

Hydrodynamic parameters of the flow and the medium properties determine the processes of mass, momentum and energy exchange within the inter electrode gap. Properly matched they prevent from occurrence of cavitation, critical flow and void fracture [4].

The above mentioned processes have significant influence on the electrochemical machining velocity and application properties of the machined surface [5].

Modelling of ECM involves: determination of the inter electrode gap thickness changes, the machined surface shape evolution in time, and distribution of physics-chemical conditions in the machining area, such as: static pressure distribution, electrolyte flow velocity , temperature and void fracture.

Many authors have dealt with the mathematical description of ECM machining, including:

Tipon [8], Fitzgerald, McGeough and Marsh[9], Alkire[10], Davydov, Kozak[11], Sautebin[12], Jain and Pandey[13], Prentice, Tobias,[14], Białecki[15], Hume [16], Zouh [17], Prentice and Tobias [18] and Dukovic [19] and others.

The purpose of this work is to analyze the influence of the electrolyte flow volume stream inside the interelectrode gap on the machined surface physical parameters and its geometry.

2. Mathematical model of ECM process

Fig. 1 shows the area of electrolyte flow inside the interelectrode gap (IEG), between curvilinear, axially symmetrical surfaces.

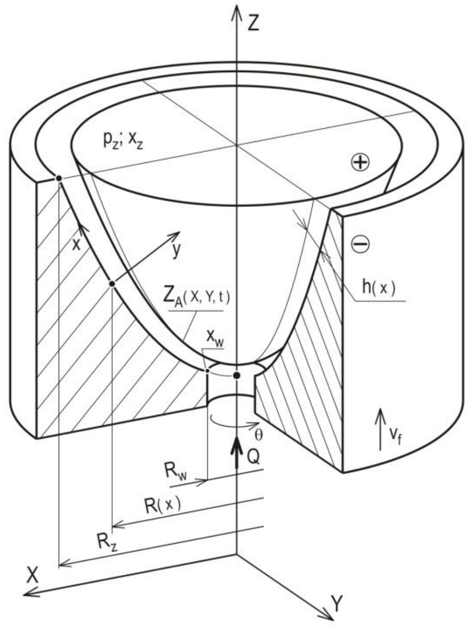

Fig.1. Area flow of electrolyte in interelectrode gap IEG

A general differential equation describing shape evolution of the surface machined by anode dissolution according to ECM dissolution theory, has the form [4,5,6,7]:

$$\frac{\partial F}{\partial t} + k_v \vec{j}_A \, gradF = 0 \tag{1}$$

with initial condition $F(X, Y, 0) = F_0$

where:

$\vec{j}_A = \vec{j}(X_A, Y_A, t)$ - distribution of current density on the machined surface,

k_v - coefficient of electrochemical machinability

$F_0(A,0) = 0$ - an equation describing the initial workpiece (WP),

$F(A, t) = 0$ - an equation describing the anode surface in time t.

Current density results from Ohm's law [4,5,6,7]:

$$\vec{j} = -\kappa \, grad \, u \big|_A \tag{2}$$

where: u - potential of the electrical field between the electrodes,
κ - conductivity.

In rectangular axis X,Y,Z connected with the immovable anode, the anode surface equation has the form:

$$Z = Z_a(X,Y,t) \tag{3}$$

Introducing equation(3) into dependence (1), one obtains:

$$\frac{\partial Z_A}{\partial t} = k_V j_A \sqrt{1 + \left(\frac{\partial Z_A}{\partial X}\right)^2 + \left(\frac{\partial Z_A}{\partial Y}\right)^2} \tag{4}$$

where: k_v - coefficient of electrochemical machinability
for $t=0$ $Z_A=Z_o(X,Y)$.

Assuming linear distribution of the electrical field potential along IEG the current density in the anode, in a locally orthogonal coordinate system x,y (Fig.1) is expressed in the following way [6,7,20,21].

$$j_A = \kappa_0 \Phi_{TG}^{-1} \frac{U-E}{h} \tag{5}$$

Function Φ_{TG} describes the influence of conductivity changes within the interelectrode gap (IEG) and is determined in the following way:

$$\Phi_{TG} = \frac{1}{h}\left[\int_0^h \frac{dy}{(1+\alpha(T-T_0))(1-\beta)^{3/2}}\right] \tag{6}$$

In order to close equation system (4),(5) and (6) it is necessary to determine temperature rises $\Delta T=T-To$ and the distribution of void fracture β. This requires definition of pressure, speed and temperature distributions within the curvilinear interelectrode gap.

Mathematical modeling of the electrolyte flow through the interelectrode gap has been performed in a curvilinear, locally orthogonal coordinate system connected with immobile surface [4].

Having accepted for consideration a model of two phase, anti-slide flow, the mixture movement equations resulting from laws of mass, momentum and energy preservation in curvilinear locally rectangular axis, are in the form [20]:

$$\frac{1}{R}\frac{\partial(\rho_e R v_x)}{\partial x} + \frac{\partial(\rho_e v_y)}{\partial y} = 0 \tag{7}$$

$$\frac{1}{R}\frac{\partial(\rho_H R v_x)}{\partial x} + \frac{\partial(\rho_H v_y)}{\partial y} = j\eta_H k_H h^{-1} \tag{8}$$

$$0 = -\frac{\partial p_e}{\partial x} + \mu_e \frac{\partial^2 v_x}{\partial y^2} \tag{9}$$

$$0 = -\frac{\partial p_e}{\partial y} \tag{10}$$

$$\rho_e = \rho_{eo}(1-\beta), \qquad \rho_H = \rho_{Ho}\beta \tag{11}$$

where: v_x, v_y - components of velocity vector,

p_e - electrolyte pressure,
ρ_{eo} - electrolyte density,
ρ_{Ho} - hydrogen density,
μ_e - dynamic coefficient of electrolyte viscosity,
μ_H - dynamic coefficient of hydrogen viscosity,
β - void fraction,
j, η_H, k_H - are, respectively, current density, current efficiency of hydrogen emission, hydrogen electrochemical equivalent,
R - tool electrode surface radius.

Energy equation for the considered flow, taking into consideration Joul's heat, emitted during the current flow, forced heat convection caused by the electrolyte flow, heat exchange by electrodes and negligence of the dispersed energy, has now the form [22]:

$$v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} = \frac{1}{R} \frac{\partial}{\partial x}\left(a R \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(a \frac{\partial T}{\partial y} \right) + \frac{j^2}{\rho_e c_p \kappa} \tag{12}$$

where:
a - coefficient of electrolyte thermal diffusivity,
κ - electrolyte conductivity,
T - electrolyte temperature,
c_p - specific heat with constant pressure,

Formulated equation system (7)-(12) is the principal system of equations for the analysis of an axially-symmetrical flow of the electrolyte and hydrogen mixture flow through the interelectrode gap.

The solution of equation system (7)-(12) will enable to define distributions of velocities, pressures and temperature in the interelectrode gap. The obtained formulas defining the temperature distribution in the gap will be utilized for determination of the workpiece (WP) shape evolution (anode) on the basis of equation (4).

Solutions of equations (7)-(12) should satisfy boundary conditions with regard to :

- pressure and velocity components:

$$\begin{gathered} v_x = v_y = 0 \quad dla \quad y = 0, \\ v_x = v_y = 0 \quad dla \quad y = h, \\ p = p_z \quad dla \quad x = x_z \end{gathered} \tag{13}$$

- for temperature:

$$\begin{gathered} \text{- on the walls: } T = T_s \quad dla \quad x \geq x_w \quad \text{i} \quad y = 0 \quad \text{oraz } y = h \\ \text{- on the inlet: } T = T_w \end{gathered} \tag{14}$$

where: p_z – pressure on the interelectrode gap outlet,
x_z – coordinate of the interelectrode end
x_w - coordinate of the interelectrode beginning
T_s - temperature of electrodes, T_w – temperature on the inlet,

When integrating motion equations (7) – (10), one can obtain formulas defining velocities and pressures within the interelectrode gap.

$$v_x = \frac{3Q}{\pi R h^3}(hy - y^2) \tag{15}$$

$$p(x) = -\frac{6\mu_e Q}{\pi h^3}(A_x - A_z) + p_a, \quad A_x = \int \frac{dx}{R}, \; A_z = A(x_z) \tag{16}$$

Dependencies (15)-(18) describe velocity and pressure distributions in the mixture laminar flow through the gap, with a random profile of surfaces limiting the flow. The assumption of specific geometry of the axially-symmetrical surface leads to accurate definition of velocity and pressure distributions.

Distribution of void fracture β was determined from the mass balance of hydrogen, given off on the cathode.

When integrating equation (8) across the gap

$$\frac{1}{R}\frac{\partial}{\partial x}\left(\rho_H R \int_0^h v_x dy\right) + \rho_H v_y\Big|_0^h = j\eta_H k_H \tag{17}$$

and, next, accepting the assumption that $\beta = \beta(x)$ one can obtain, after transformations:

$$\frac{\partial}{\partial x}\left(\frac{p}{T}\beta\right) = \frac{2\pi\,\eta_H k_H}{\mu_H Q} jR \tag{18}$$

whereas: β - void fracture, $\rho_{Ho} = \frac{\mu_H p}{R_H T}$ - hydrogen density, η_H - current efficiency of gas emission, k_H - hydrogen electrochemical equivalent, R_H - hydrogen gas constant, μ_H - hydrogen molar mass.

Solution to equation of the machined surface shape evolution (4) was based on the method of successive approximations in combination with the time step method [6,7,20,21,22].

3. Numerical model of ECM process

This problem is accounted for according to a successive approximation method for all used numerical schemes using at the same time the time steps method [6,7,20,21].

Energy equation (12) has been solved numerically with the use of finite difference method replacing the temperature derivatives with algebraic expressions.

Simplified algorithm of a mathematical model solution is presented in Fig. 2.

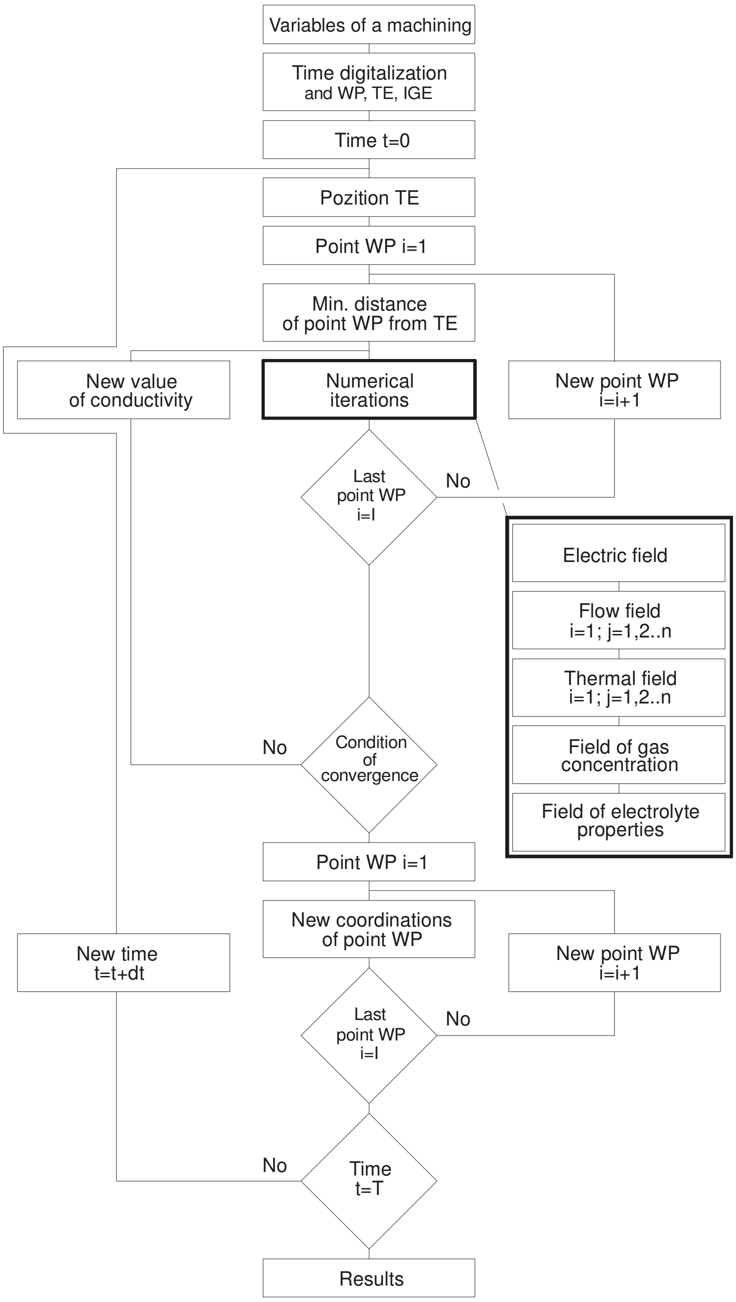

Fig.2. ECM computer simulation algorithm

4. Exemplary calculations

Calculations were performed for shaping rotary electrodes with spherical surface profiles. The supply system ensures the electrolyte fixed flow rate in the interelectrode gap. Passivating electrolyte was accepted for calculations. Calculations had been performed until a quasi – stationary state was reached.

For calculations the following, machining parameters were accepted:

initial gap	$h_o = 0.2$ mm
speed of move forward of TE	$V_f = 0.01$ mm/s
interelectrode voltage	$U = 15$ V
volume rate	$Q = 3, 4, 5$ dm^3/min
pressure	$p_z = 0{,}1$MPa

The obtained results have been illustrated in charts (Fig.3-8) which demonstrate distributions of: interelectrode gap height h, current density j, temperature T, void fraction β, velocity V_m, and pressure p along the interelectrode gap (IEG).

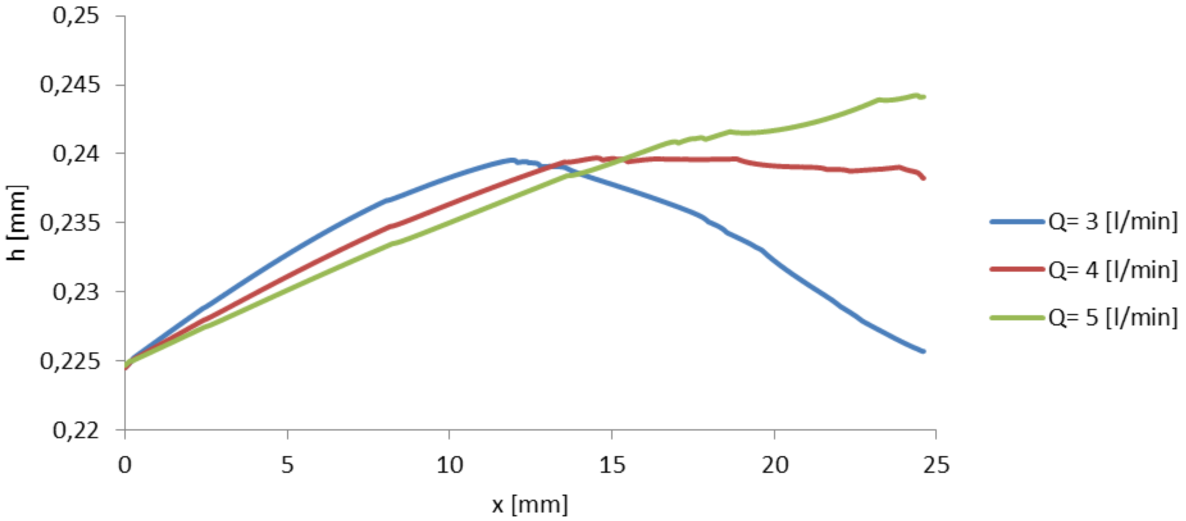

Fig. 3. Distribution of gap height h along IEG

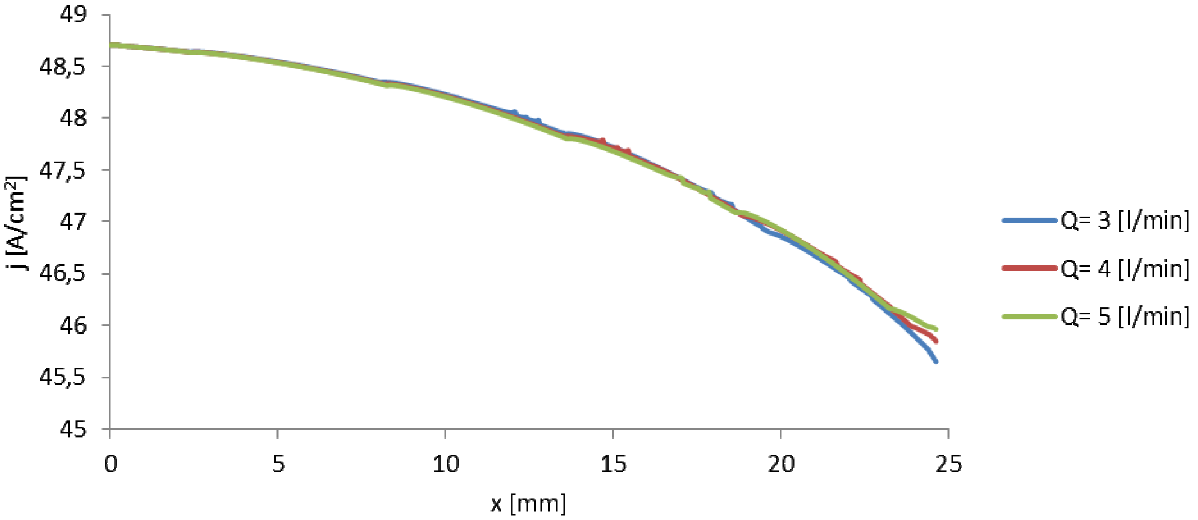

Fig. 4. Distribution of current density j along IEG

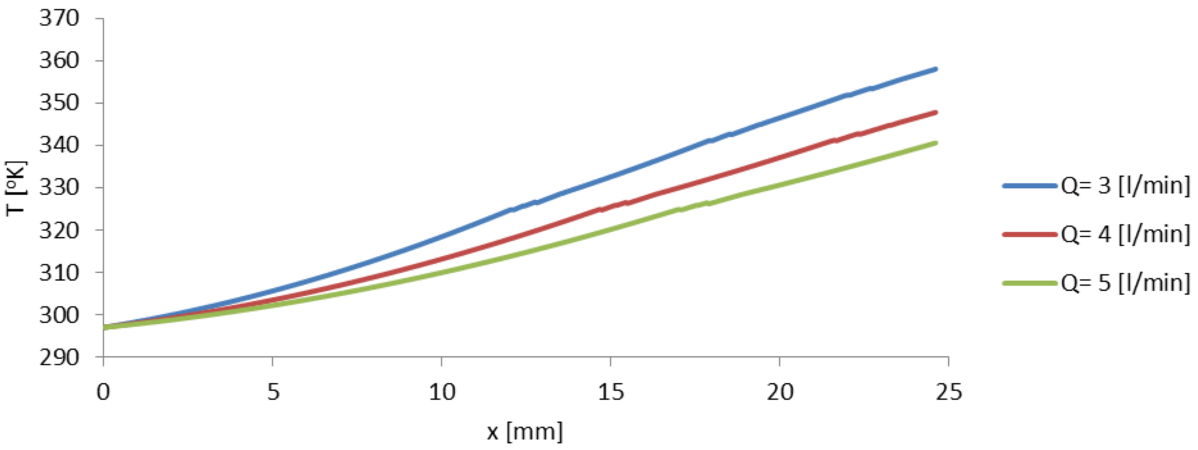

Fig. 5. Distribution of average temperature T along IEG

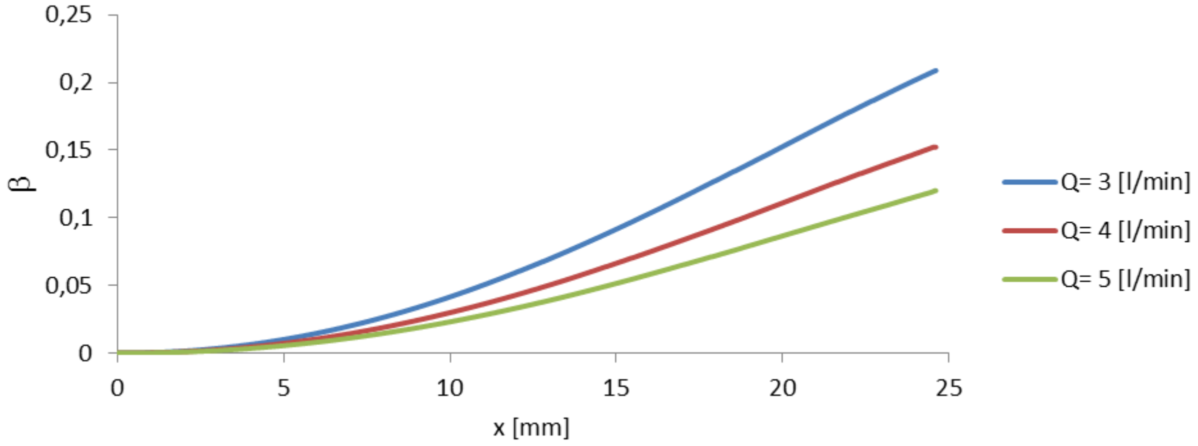

Fig. 6. Distribution of void fraction β along IEG

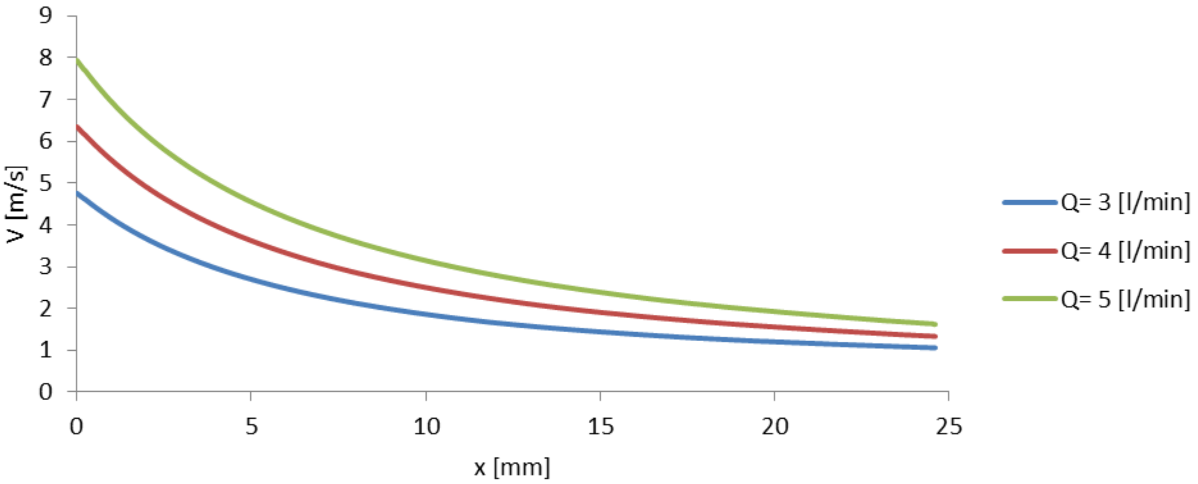

Fig. 7. Distribution of average velocity V along IEG

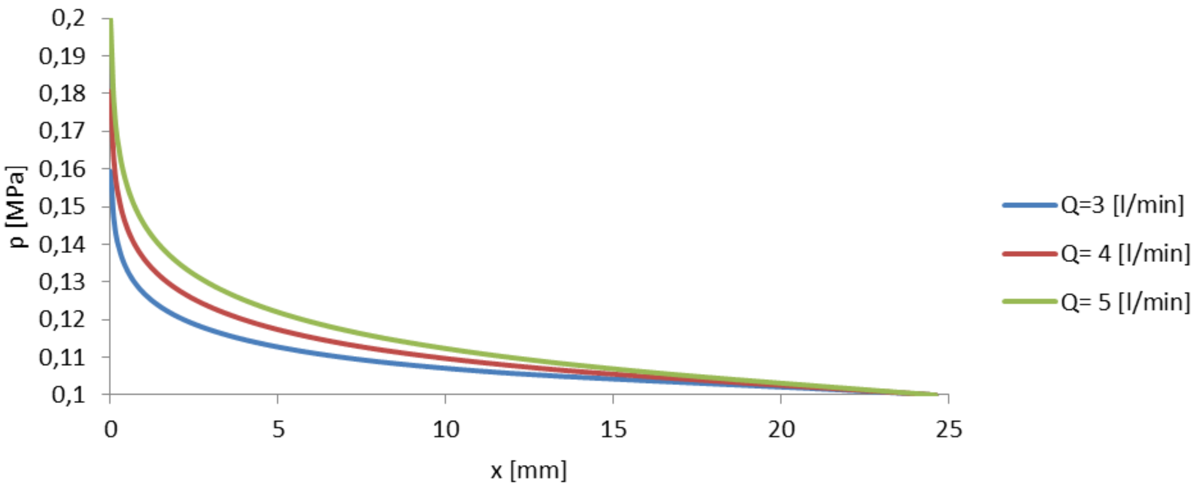

Fig. 8. Distribution of pressure p along IEG

5. Conclusions

The above presented charts allow for formulation of the following conclusions:

- Changes of the inter-electrode gap are caused by dynamically changing physical conditions inside the gap (variable viscosity, density, electrolyte conductivity and also significantly changing velocity of the flow and pressure) Increase in the volume stream has a considerable influence on the interelectrode gap thickness.
- Distribution of the volume fracture (of hydrogen) along the interelectrode gap increases nonlinearly. Value of β on the gap outlet decreases along with an increase in the volume stream and is significantly smaller than the boundary value, above which there occurs a transition from a bubble into the so called corks flow. According to Gryfith and Snyder the critical value is β_{gr}=0.5,
- Distributions of mean velocity, pressure and temperature along the inter-electrode gap definitely depend on the volume stream value. They result from the gap cross-section field change and rapidly changing physical parameters of the flow caused by electrochemical dissolution. The maximum velocity inside the gap, right behind the inlet, does not exceed the speed of sound in a two-phase medium. The minimal value of pressure in the area of inter-electrode gap (beyond the gap inlet) is considerably higher than pressure of saturated vapor. The temperature distribution indicates a distinct increase in temperature on the inter-electrode gap outlet. It is caused by an increase of the volume fracture at the end of the gap and rapid drop of pressure along the gap.
- Distribution of current density along the inter-electrode gap depends on its local thickness. Increase in the stream volume slightly raises the current density values, especially on the gap outlet.

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