Short communication

Analytical Model of Influence of Air Ions on aGrowth of Yeast *Saccharomyces Cerevisiae*

ABSTRACT

Aims: Establish theoretically the influence of the concentration of ions in a nutrient medium both on the surface charge and potential of a yeast cell and diffusion of nutrients through its membrane and on the productivity of baking yeast.

Place and Duration of Study: Department of Electrotechnology Belarusian State Agricultural Technical University and Turbulence Laboratory A.V. Luikov Heat and Mass Transfer Institute of NAS of Belarus, between June 2018 and January 2023.

Results: The article shows that introducing the ionized molecules of air gases and, first of all, of oxygen and nitrogen changes the concentration of ions in the medium, the surface charge and potential of the yeast cell that in turn affect the diffusion of nutrients through membrane into the cell. The growth rate of the yeast cell mass depends on the amount of electricity, transported by air ions into the nutrient medium, and is limited by its certain value.

Conclusion: Depending on the amount of electricity transported by air ions into the nutrient medium, the increase is described by the yeast biomass growth equation. A priori simulation shows that the productivity of the baker’s yeast can increase by 12…17%.

Keywords: yeast cell; electricity; ions; potential; diffusion; growth kinetics.

1. INTRODUCTION

Work [1] is concerned with the influence of negatively charged ions of air oxygen and nitrogen on the nutrient medium of the baker’s yeast Saccharomyces cerevisiae. It is found that hydrogen peroxide is the main active factor. K. Godon [2] showed that this factor changes the concentration of ions in the nutrient medium, activates the formation of new substances and the growth of yeast cells. Y.H. Lin, W.S. Chien, K.J. Duan [3], T.V. Meledina [4] and others claim that changing the surface charge and potential of a living cell affects the diffusion of nutrients through its membrane and, hence, its growth.

The objective of the present research was to establish theoretically the influence of the concentration of ions in a nutrient medium both on the surface charge and potential of a yeast cell and on the diffusion of nutrients through its membrane.

Comment [MPB1]: This text is not an introduction to the work, it does not provide adequate background. It looks like a discussion of results. It must be rewritten

2. ANALYTICAL MODEL OF YEAST BIOMASS GROWTH

Comment [MPB2]: The materials and methods used are also not clearly defined. For example, what were the growth conditions for the yeast?

The change in the molar volume concentration of substance (mol/m3) for an infinitely small time $d\tau$ in a medium volume where there occurs a current generated by the flow of air ions is:

$$\Delta C_{k_i a_j} = \frac{1}{VF}\int_0^{\tau} I n_{k_i a_j} d\tau\,, \quad . \tag{1}$$

here V is the volume of a processed medium, m^3; I is the instantaneous strength of the current flowing through the medium for a time $d\tau$, A; $F = 96485$ C/mol is Faraday's number; $n_{k_i a_j}$ is the instantaneous number of transfer of the *i*th cation k or the *j*th anion a for a time $d\tau$.

Transform (1) using the amount of electricity:

$$\Delta C_{k_i a_j} = \frac{1}{F}\int_0^{Q_V} n_{k_i a_j} dQ_V\,, \quad . \tag{2}$$

here $dQ_V = I d\tau / V$ is the amount of electricity transported by the air ions flowing through the medium, C/m^3.

Allowing for Faraday's law, the molar volume concentration of negative ions C_{i^-} (mol/m^3) is obtained as a result of air ion processing of the medium:

$$C_{i^-} = C_{0i^-} + \frac{Q_V}{F}\eta_{i^-}\,, \quad . \tag{3}$$

here C_{0i^-} is the initial molar volume concentration of negative ions, mol/m^3, and η_{i^-} is the current output of negatively charged particles.

The total yeast cell surface density ρ_S (C/m^2), generated, for example, by the cations of kind i^- [4], is:

$$\rho_S = \frac{\rho_b C_{i^-}^2 + K_a(\rho_b - \rho_a)C_{i^-} - \rho_a \dfrac{K_a K_w}{K_b}}{C_{i^-}^2 + 2K_a C_{i^-} + \dfrac{K_a K_w}{K_b}}\,, \tag{4}$$

where ρ_a, ρ_b is the surface density of the charge of acid and basic groups, respectively, C/m^2; K_a, K_b, K_w are the dissociation constants of acid/basic groups and water, respectively, mol/m^3.

At the same time,

$$K_a = \frac{C_{H^+} C_{i^-}}{C_{H^+ i^-}};\; K_b = \frac{C_{OH^-} C_{i^+}}{C_{OH^- i^+}};\; K_w = \frac{C_{H^+} C_{OH^-}}{C_{H_2O}}, \tag{5}$$

C_{i^+} is the concentration of positively charged ions, mol/m3; C_{H^+}, C_{OH^-} is the concentration of ions of hydrogen and hydroxide, respectively, mol/m3; $C_{H^+ i^-}$, $C_{OH^- i^+}$, C_{H_2O} is the concentration of acid/basic groups and water, respectively, mol/m^3.

Assume that the yeast cell is shaped as a sphere covered with negative-sign ions with a surface density ρ_S. The potential of the sphere surface is governed by the known equation:

$$\varphi_S = \frac{1}{4\pi\varepsilon_0\varepsilon}\int_S \frac{\rho_S}{R_C} dS . \qquad . \tag{6}$$

where $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m is the electric constant; ε is the relative dielectric constant of the nutrient medium; S is the cell surface area, m^2; $R_C = 5 \cdot 10^{-6}$ m is the cell radius [5].

Thus, the current flowing in the form of air ions changes the concentration of charged particles in the nutrient medium (3), cell surface charge (4) and potential (6) that in turn determine the diffusion rate and direction of substances through the cell membrane.

The concentration of ions within a living cell can be ten times different from their concentration in the ambient medium, the concentration gradients of different-sign ions being observed. This is attributed to transport dynamics of ions through the membrane and depends on the properties of a specific cell. The concentration difference of ions outside and inside the cell under normal conditions gives rise to voltage between citoplasma and ambient nutrient medium. It ranges from 50 to 70 mV [6, 7]. When air ions are applied, this potential difference can be larger than the membrane voltage breakdown (100…200 mV) [8].

Calculate the concentration gradient of ions at the cell edge, during the creation of which there arises a potential difference enough for membrane breakdown.

The diffusion equation for ions inside the cell pore is of the form [9]

$$\frac{d^2C}{dr^2} + \frac{2dC}{rdr} = 0 \tag{7}$$

at the boundary conditions: $r = R_C$, m; $C = C_1$ is the concentration of ions at the cell surface, mol/m^3; $r = \infty$, $C = C_0$ is the concentration of ions in a region far from the cell surface, mol/m^3; here $C(r)$ is the concentration of ions at a distance r from the center of the cell, mol/m^3.

The solution to (7) assumes the form:

$$C(r) = C_0 + \frac{(C_1 - C_0)R_C}{r} . \tag{8}$$

The diffusion flow of ions Φ (mol/s) through the surface of the cell with allowance for its spherical symmetry is:

$$d\Phi = -D_0 C(r) dS , \tag{9}$$

or

$$\Phi_0 = -D_0 \int C dS = -4\pi R_C^2 D_0 \frac{dC}{dr} , \tag{10}$$

where $D_0 \approx 10^{-9}$ m^2/s is the diffusion coefficient of substance in the medium [4]; dS is the surface element of the cell, m^2.

From (10), one obtains

$$\frac{dC}{dr} = -\frac{(C_1 - C_0)R_C}{r^2} , \tag{11}$$

at $r = R_C$

$$\frac{dC}{dr} = -\frac{C_1 - C_0}{R_C}, \tag{12}$$

i.e.

$$\Phi = 4\pi R_C D_0 \left(C_1 - C_0 \right). \tag{13}$$

On the other hand-side, by definition

$$\Phi = C_1 \vartheta S = 4\pi R_C^2 C_1 \vartheta, \tag{14}$$

where ϑ is the average ion velocity, m/s.

Taking into account (6) and (12) yields the average ion velocity in a pore:

$$\vartheta = \frac{C_1 - C_0}{C_1} \frac{D_0}{R_C}, \tag{15}$$

or

$$\bar{\vartheta} = \frac{C}{C_1} \frac{D_0}{R_C}, \tag{16}$$

where C/C_1 is the concentration gradient of ions on the cell membrane.

In turn, the drift velocity of an ion is associated with the potential difference φ (V):

$$\vartheta_d \approx \lambda \frac{\varphi}{l}, \tag{17}$$

where λ is the ion mobility in the medium, m2/(s·V); l is the distance between different-potential regions, m.

Assume that $l = 1.5\delta$, where δ is the membrane thickness, m.

From (16) and (17), one obtains

$$\frac{C}{C_1} \frac{D_0}{R_C} = \lambda \frac{\varphi}{l}, \tag{18}$$

$$\varphi = \frac{C}{C_1} \frac{D_0 l}{R_C \lambda}. \tag{19}$$

Relation (19) permits calculating the concentration gradient of ions outside and inside the cell. It provides a required potential difference φ.

Bearing in mind the known gradient C/C_1, relation (19) may be used to calculate a resulting potential difference. In this case, the concentration gradient can be directed to both sides, i.e., varying the ion composition of the medium makes it possible to change electric charge and cell behavior.

Relation (19) has been obtained while assuming the transport of one-kind ions only through the membrane. In the general case, relation (19) takes the form:

$$\varphi = \frac{D_0 l}{R_C} \left[\frac{C_{(1)}}{\lambda_1 C_1} + \frac{C_{(2)}}{\lambda_2 C_1} + \ldots + \frac{C_{(i)}}{\lambda_{(i)} C_1} \right], \tag{20}$$

where $C_{(i)}/C_1$ is the gradient of ith kind-ions that participate in transport through the membrane.

Assume that the potential breakdown difference for the membrane $\varphi_{bd} = 150$ mV. Then based on (20), the concentration gradient of corresponding ions is obtained:
$H^+ : C/C_1 = 150$; $NH_4^+ : C/C_1 = 200$; $K^+ : C/C_1 = 250$; $Na^+ : C/C_1 = 130$; $OH^- : C/C_1 = 810$; $NO_3^- : C/C_1 = 250$; $O_2^- : C/C_1 = 3700$.

Using Nernst's equation

$$\varphi = \frac{D_0 l}{R_C}\left[\frac{C_{(1)}}{\lambda_1 C_1} + \frac{C_{(2)}}{\lambda_2 C_1} + ... + \frac{C_{(i)}}{\lambda_{(i)} C_1}\right], \qquad (21)$$

$\varphi = 144.6$ mV, i.e., the results are practically identical. Here R is the universal gas constant, J/(mol·K); T is the absolute temperature, K, at a total concentration gradient with regard to the ion mobility $C/C_1 = 250$.

It can then be assumed that the diffusion of ions, providing a normal function of a cell, depends on the electric field generated by the charge of ions around the cell and in the cell itself.

According to Fick's law, the diffusion rate of substance inside the cell is:

$$\frac{dM_C}{d\tau} = \frac{D_\phi}{h}\pi R_C^2 \frac{3M}{4\pi R_C^3}\left(M_S - M_C\right) = \\ = \frac{3}{4}\frac{D_\phi M}{hR_C}\left(M_S - M_C\right), \qquad (22)$$

where τ is the diffusion time, s; D_ϕ is the coefficient of diffusion of ions into the cell through the membrane pore, m^2/s; M is the specific volume of cells in the medium, m^3/m^3; h is the diffusion layer thickness, m; M_C is the substance concentration in the cell, kg/m^3; M_S is the substance concentration in the medium, kg/m^3; πR_C^2 is the cell surface area, m^2; $\frac{4}{3}\pi R_C^3$ is the volume of one cell, m^3.

Diffusion of ions into the cell through the membrane pore in the presence of the cell surface potential, m^2/s, [9] is:

$$D_\phi = D_O \exp\left(-\frac{nF\left|\varphi_S\right|}{RT}\right), \qquad (23)$$

where n is the empirical coefficient and φ_S is the cell surface potential, V.

Assume that the cell membrane pore represents a tube with a radius RP and a length h (Fig. 1). Upon transformations, with the consideration of pore sizes formula (6) takes the form:

$$\varphi_S = \frac{\rho_S R_P}{2\varepsilon_0 \varepsilon}\int_0^h \frac{dx}{\sqrt{R_P^2 + x^2}}, \qquad (24)$$

where x is the distance along the tube axis from the pore entrance to the section plane passing through the middle of a strip dS, m, pictured in Fig. 1 and $R_P = 2.5 \cdot 10^{-9}$ m is the cell pore radius [5].

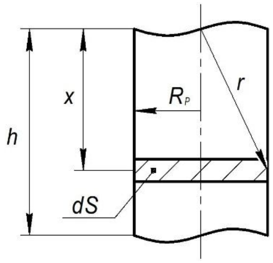

Fig.1.Potential calculation inside the membrane pore

Solution to (24) can be written as:

$$\varphi_S = \frac{\rho_S R_P}{2\varepsilon_0\varepsilon}\ln\left(\frac{x+\sqrt{R_P^2+x^2}}{R_P}\right)\Bigg|_0^h, \tag{25}$$

From (25), the potential at the pore entrance is:

$$\varphi_S = \frac{\rho_S R_P}{2\varepsilon_0\varepsilon}\ln\left(\frac{h+\sqrt{R_P^2+h^2}}{R_P}\right), \tag{26}$$

With (22) taken into account, according to Michaelis–Menten's equation, biosynthesis can be described by the system of differential equations [10, 11]:

$$\begin{cases} \dfrac{dM}{d\tau} = \mu\dfrac{M\cdot M_C}{M_C+K_S}, \\ \dfrac{dM_C}{d\tau} = \dfrac{3}{4}\dfrac{D_\phi M}{hR_C}\left(M_S-M_C\right)-\alpha\mu\cdot\dfrac{M\cdot M_C}{M_C+K_S}, \end{cases} \tag{27}$$

where K_S is the substrate constant, kg/m^3; α is the chemical activity the medium and μ is the yeast specific growth rate, s^{-1}.

Based on the time-independent solution to (27), one has:

$$\left(M_S-M_C\right)\left(M_C+K_S\right)-\frac{4\alpha\mu hR_C M_C}{3D_\phi}=0\,,$$

$$K_S M_S+\left(M_S-K_S-\frac{4\alpha\mu hR_C}{3D_\phi}\right)M_C-M_C^2=0\,.$$

Upon solution, the substance mass in the cell is

$$M_C = \frac{A}{2}+\sqrt{\frac{A^2}{4}+K_S M_S}\,, \tag{28}$$

where the factor

$$A = M_S-K_S-\frac{4\alpha\mu hR_C}{3D_\phi} = M_S-K_S-\frac{\mu}{K_0\cdot\exp\left(-\dfrac{nF\left|\varphi_S\right|}{RT}\right)} \tag{29}$$

where $K_0 = \frac{3D_0}{4\alpha h R_C}$.

Substituting (29) into the first equation of system (28) yields the yeast growth rate equation:

$$\frac{dM}{d\tau} = \mu \frac{M_C\left(\frac{A}{2} + \sqrt{\frac{A^2}{4} + K_S M_S}\right)}{K_S + \frac{A}{2} + \sqrt{\frac{A^2}{4} + K_S M_S}}, \tag{30}$$

or

$$\Delta M = \int_0^\tau \mu \frac{M_{C0}\left(\frac{A}{2} + \sqrt{\frac{A^2}{4} + K_S M_S}\right)}{K_S + \frac{A}{2} + \sqrt{\frac{A^2}{4} + K_S M_S}} d\tau, \tag{31}$$

Integrating (31) within given ranges provides the equation for the biomass specific growth under the influence of air ion processing:

$$\begin{aligned} \Delta M = \mu M_{C0}\tau \Bigg[& \frac{A}{2} + \sqrt{\frac{A^2}{4} + K_S M_S} - \\ & - K_S \ln\left(K_S + \frac{A}{2} + \sqrt{\frac{A^2}{4} + K_S M_S}\right)\Bigg]. \end{aligned} \tag{32}$$

Equation (32) confirms that the yeast biomass growth depends on the cell surface potential φ_S that determines the diffusion of ions into the cell (29). Mathematically, it describes the change in the productivity of the baker's yeast and the medium when acted upon by air ions.

3. YEAST BIOMASS GROWTH RESULTS

The proposed analytical model allows computing: the concentration of negative ions with the consideration of the amount of electricity flowing through the medium when (3) undergoes transformation; the total density of the surface charge of the yeast cell (4); the potential at the cell pore entrance (26); the simplification factor A (29); the yeast biomass growth (32) per m^3 of the nutrient medium. The results are depicted in Fig. 2.

Fig. 2 illustrates that the yeast biomass can increase per 15.5 kg/m3 of the nutrient medium when processed by the amount of electricity ranging from 375 to 425 C/m3 (m3 of the nutrient medium contains 90…110 kg yeast).

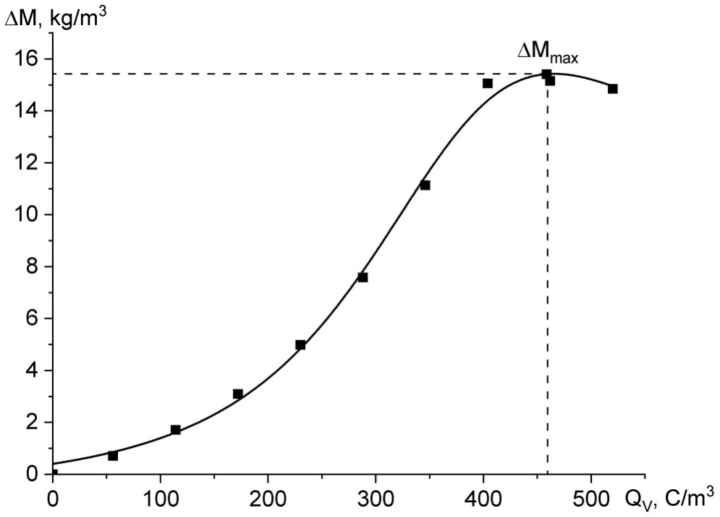

Fig.2.Change in the yeast biomass growth when acted upon by air ions according to (31)

4. CONCLUSION

Thus, introducing the ionized molecules of air gases and, first of all, of oxygen and nitrogen changes the concentration of ions in the medium, the surface charge and potential of the yeast cell that in turn affect the diffusion of nutrients through membrane into the cell.

The growth rate of the yeast cell mass depends on the amount of electricity, transported by air ions into the nutrient medium, and is limited by its certain value.

Depending on the amount of electricity transported by air ions into the nutrient medium, the increase is described by the yeast biomass growth equation. A priori simulation shows that the productivity of the baker’s yeast can increase by 12…17%.

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