

## EVALUATION OF AERATION CAPACITY OF FERMENTORS BY ADAPTIVE IDENTIFICATION METHOD

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A new method of evaluation of the aeration capacity,  $k_L a$ , from data measured with the use of an oxygen electrode was proposed, based on the algorithm of adaptive identification. In this way, even the time dependence of  $k_L a$  in the course of a dynamic experiment can be obtained. The results from mechanically stirred fermentors and apparatuses of the bubbled column type show that the commonly used assumption about the time independence of  $k_L a$  does not hold for intensively aerated apparatuses.

During the aerobic cultivation of microorganisms, the rate of the biosynthesis depends on the transfer of oxygen between the cultivation medium and the air bubbles. A dynamic method was proposed for rapid evaluation of the aeration capacity of fermentors<sup>1</sup>. We studied already the influence of the delay of the oxygen electrode signal caused by diffusion of oxygen through the membrane<sup>2</sup> and the influence of the interaction of bubbles with the electrode surface<sup>3-5</sup> on the value of the obtained aeration capacity,  $k_L a$ . This is usually assumed to be constant during the whole experiment. In reality, this assumption holds only after an equilibrium between the coalescence and dispergation of the air bubbles is attained, as discussed by us qualitatively earlier<sup>3</sup>. It has been recommended<sup>6</sup> to approximate the time of equilibration between the coalescence and dispergation of the bubbles by the mean residence time of the air in the apparatus.

The known methods of evaluation of  $k_L a$  from dynamic experiments use integrated forms of the equations describing the dynamic behaviour of a model apparatus and electrode. These equations are solved under the assumption that the values of  $k_L a$ , equilibrium concentration of oxygen in the interface, the time constant of the electrode, the gas hold up *etc.* are independent of the time. If this is not the case (some parameter changes significantly with the time), the evaluation of the aeration capacity by the linearized or nonlinear regression can lead to a false interpretation of the measured data.

Various methods for the determination of unknown parameters in dynamic systems were proposed<sup>7</sup>. Besides the linearized and nonlinear regression of integrated model equations, or differentiated experimental data, the so-called adaptive identification

methods have been stressed, which were derived from the theory of optimum control. It turned out that the adaptive identification methods can be used for the determination of unknown parameters of the process (identification) so that the controlling quantity is the unknown parameter of the model and the controlled quantity is the minimum difference between the model and the experiment. The adaptive identification method sets the unknown model parameters by means of the optimum control algorithm so that the calculated and experimental data are in the best agreement attainable during the whole experiment. In this way even the time-dependent parameters of the kinetics of the process can be evaluated. In our case, the aeration capacity was evaluated by the continuous gradient method of minimization of the quadratic deviation between the calculated and measured concentrations of the dissolved oxygen.

### THEORETICAL

The balance of the dissolved oxygen in the mixed fermentor is usually described by the equation

$$dc_L/dt = k_L a(c^* - c_L) - rX \quad (1)$$

(see List of Symbols). The concentration of dissolved oxygen,  $c_L$ , is measured by means of an oxygen electrode covered with a semipermeable membrane. Its response is influenced by two factors: a) Diffusion of oxygen through the membrane or liquid film<sup>8,9</sup> causing a delay of the response. This can be described qualitatively as a retarding term of the first order for a shorter time interval (the constant,  $K_P$ , characterizing the delay of the signal is the reciprocal time necessary to attain 63.2% deflection after a step change of the oxygen concentration). b) Interaction with air bubbles. To express this effect, we proposed a model<sup>3,4</sup> based on the relation between the local gas hold up,  $\varepsilon$ , and the mean time of contact of the bubbles with the electrode. The signal of the electrode is then described by the equation

$$dc_P/dt = K_P[c_P - (1 - \varepsilon)c_L - \varepsilon c^*], \quad (2)$$

where  $c_P$  is the current of the electrode recalculated to the concentration of dissolved oxygen.

If we assume that the aeration capacity  $k_L a$  changes significantly during the response of the apparatus to the change of the aeration regime, and that the same applies for the constant  $K_P$  and local hold up  $\varepsilon$ , then we must solve besides (1) and (2) the following differential equations for the determination of these three parameters by the adaptive identification method:

$$\frac{dk_L a}{dt} = -\alpha(c_P - c_M) \frac{\partial c_P}{\partial k_L a}, \quad (3)$$

$$\frac{d\varepsilon}{dt} = -\alpha(c_p - c_M) \frac{\partial c_p}{\partial \varepsilon}, \quad (4)$$

$$\frac{dK_p}{dt} = -\alpha(c_p - c_M) \frac{\partial c_p}{\partial K_p}, \quad (5)$$

where  $\alpha$  is the damping coefficient of the method, usually 0.2–0.8. The initial conditions for the system of ordinary differential equations (1)–(5) must be chosen according to the experimental conditions. In contrast to the original dynamic method<sup>1</sup>, it is possible to evaluate  $k_L a$  from the dynamics of transition between two aeration regimes without surpassing the critical oxygen concentration in the fermentation medium.

The system of equations (1)–(5) was integrated numerically by means of the Runge–Kutta method of the fourth order. The experimental value of  $c_p$  was interpolated with the aid of the spline function<sup>10</sup>. The partial derivatives in Eqs (3)–(5) were calculated numerically.

#### EXPERIMENTAL

Measurements were carried out in fermentors of 25 and 150 l working volume and on a bubbled column of 0.2 m diameter described earlier<sup>5</sup>. The composition of the mineral medium was (in g/l):  $(\text{NH}_4)_2\text{SO}_4$  1.0,  $\text{KH}_2\text{SO}_4$  1.6,  $\text{MgSO}_4 \cdot 7 \text{H}_2\text{O}$  0.5, and  $\text{ZnSO}_4 \cdot 6 \text{H}_2\text{O}$  0.01 dissolved in tap water. The temperature of measurement was 30°C. The fermentors were equipped with

TABLE I

Comparison of Methods for Evaluation of  $k_L a$  ( $\text{h}^{-1}$ )

1  $\dot{Q} = 3.5$  l/min,  $n = 400$   $\text{min}^{-1}$ ,  $V = 25$  l; 2  $\dot{Q} = 6.2$ ,  $n = 400$ ,  $V = 25$ ; 3  $\dot{Q} = 3.5$ ,  $n = 600$ ,  $V = 25$ ; 4  $\dot{Q} = 15$ ,  $n = 200$ ,  $V = 150$ ; 5  $\dot{Q} = 15$ ,  $n = 400$ ,  $V = 150$ .

Method	Experimental conditions				
	1	2	3	4	5
Bandyopadhyay <sup>1</sup>	52	62	106	25	92
Fuchs <sup>11</sup>	53	64	111	25	94
Linek <sup>2</sup>	52	63	108	26	93
Heineken <sup>12</sup>	54	66	114	26	97
Benedek <sup>13</sup>	56	66	114	26	100
Votruba <sup>3</sup>	56	66	116	27	100
Present work	56	67	114	27	97

a 6-blade open turbine. The concentration of dissolved oxygen was measured with a polarographic Pt-Ag electrode covered with a polypropylene membrane of a thickness of 10–15  $\mu\text{m}$ . The signal of the electrode was recorded by a TZ-21 S type recorder (Laboratorní přístroje, Prague) with a response time of 0.5 s.

FIG. 1  
Evaluated Dependence of  $k_L a$  on Time  
for a 25 l Fermentor

1  $\dot{Q} = 6.2 \text{ l/min}$ ,  $n = 400 \text{ min}^{-1}$ ; 2  $\dot{Q} = 12.5 \text{ l/min}$ ,  $n = 400 \text{ min}^{-1}$ .

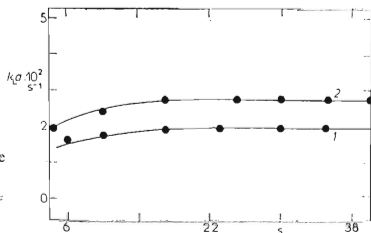


FIG. 2  
Evaluated Dependence of  $k_L a$  on Time  
for a 25 l Fermentor

1  $\dot{Q} = 18.7 \text{ l/min}$ ,  $n = 600 \text{ min}^{-1}$ ; 2  $\dot{Q} = 12.5 \text{ l/min}$ ,  $n = 800 \text{ min}^{-1}$ ; 3  $\dot{Q} = 12.5 \text{ l/min}$ ,  $n = 1000 \text{ min}^{-1}$ .

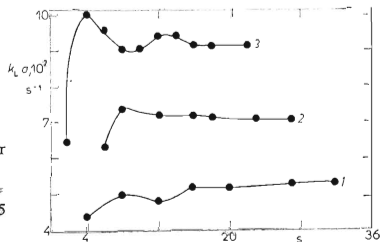
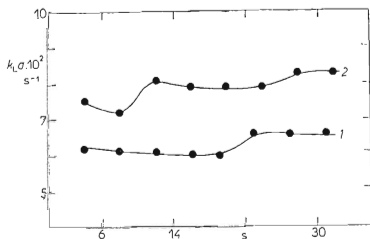


FIG. 3  
Evaluated Dependence of  $k_L a$  on Time  
for a Bubbled Column Type Fermentor

Column diameter 20 cm. 1  $\dot{Q} = 31.5 \text{ l/min}$ ,  $V = 9 \text{ l}$ ; 2  $\dot{Q} = 120 \text{ l/min}$ ,  $V = 57 \text{ l}$ .



## RESULTS AND DISCUSSION

The constant  $k_L a$  was evaluated under different aeration regimes; its time course for a pilot scale fermentor of 25 l volume is shown in Fig. 1. In this case, the aeration was relatively low. The dependence of  $k_L a$  on time suggests that the aeration capacity attains relatively rapidly a constant value. The values of  $k_L a$  calculated by various methods for fermentors with a volume of 25 and 150 l working with a low aeration intensity are given in Table I. It is seen that under these conditions all methods lead to the same values. Hence, up to the value of aeration capacity of about  $100 \text{ h}^{-1}$  the adaptive identification method brings no advantage and any of the methods given in Table I can be used as well.

In the case of intensively aerated fermentors, the situation is different (Fig. 2). A constant value of  $k_L a$  is attained after a long time, often comparable with the duration of the experiment. This is due to the fact that the time of equilibration between the coalescence and dispergation of the bubbles is comparable with the dynamics of transition from one aeration regime to the other. With small laboratory fermentors with a working volume of 1 l, which are intensively stirred (the time of homogenization is about 1 s), the aeration capacity does not attain a steady value owing to the small volume, so the commonly used assumption about constancy of  $k_L a$  is not adequate.

The adaptive identification method was used in the analysis of data obtained on a bubbled column<sup>5</sup>. It is seen from Fig. 3 that at strong aerations the assumption of constant  $k_L a$  is not justified either.

The method of evaluating the aeration capacity involves in its original form a possible time dependence of the delay of the electrode signal due to a low rate of the oxygen transfer between the streaming liquid and the electrode surface. However, this effect is not observed even in viscous media (0.5M carboxymethylcellulose), hence the constant of the electrode,  $K_p$ , can be considered independent of the time.

The evaluation of  $k_L a$  in intensively aerated fermentors shows unequivocally that the time necessary to attain a dynamic equilibrium between coalescence and dispergation of the gas phase is a controlling factor from the point of view of the kinetics of the oxygen transfer. The commonly used assumption that this time is very short against the time of the transient process is not fulfilled in intensively aerated fermentors.

## LIST OF SYMBOLS

- $a$  specific interfacial area
- $c^*$  equilibrium concentration of oxygen on the interface
- $c_M$  measured concentration of oxygen
- $c_L$  concentration of dissolved oxygen calculated from Eqs (1) and (2)
- $e_p$  electrode signal calculated from Eqs (1) and (2)
- $k_L$  oxygen transfer coefficient

- $K_p$  constant of electrode  
 $n$  number of revolutions per minute  
 $Q$  rate of air flow  
 $r$  rate of respiration of microorganisms  
 $V$  working volume of fermentor  
 $X$  concentration of biomass  
 $t$  time  
 $\alpha$  damping coefficient, Eqs (3)–(5)  
 $c$  local gas hold up

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