FORMING OF CONTROLLED LIVING MICROENVIRONMENTS

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Abstract

The purpose of the present work is to work out an approach for the development of software and the choice of hardware structures when designing subsystems for automatic control of technological processes realized in living objects containing limited space (microenvironment). The subsystems for automatic control of the microenvironment (SACME) under development use the Devices for Air Prophylactic Treatment, Aeroionization, and Purification (DAPTAP) as execution units for increasing the level of safety and quality of agricultural raw material and foodstuffs, for reducing the losses of agricultural produce during storage and cultivation, as well as for intensifying the processes of activation of agricultural produce and industrial microorganisms. A set of interconnected SACMEs works within the framework of a general microenvironmental system (MES). In this research, the population of baker's yeast is chosen as a basic object of control under the industrial fed-batch cultivation in a bubbling bioreactor. This project is an example of a minimum cost automation approach. The microenvironment optimal control problem for baker's yeast cultivation is reduced from a profit maximum to the maximization of overall yield by the reason that the material flow-oriented specific cost correlates closely with the reciprocal value of the overall yield. Implementation of the project partially solves a local sustainability problem and supports a balance of microeconomical, microecological and microsocial systems within a technological subsystem realized in a microenvironment maintaining an optimal value of economical criterion (*e.g.* minimum material, flow-oriented specific cost) and ensuring: *(a)* economical growth (profit increase, raw material saving); *(b)* high security, safety and quality of agricultural raw material during storage process and of food produce during a technological process; elimination of the contact of gaseous harmful substances with a subproduct during various technological stages; *(c)* improvement of labor conditions for industrial personnel from an ecological point of view (positive effect of air aeroionization and purification on human organism promoting strengthened health and an increase in life duration, pulverulent and gaseous chemical and biological impurity removal). An alternative aspect of a controlled living microenvironment forming is considered.

Keywords: Aeroionizer; agricultural raw materials; agriculture; air purifier; baker's yeast; barley; environmental engineering; feed and aeration rates; feedback control system; food processing; material flow-oriented specific cost; mathematical model; microenvironment; overall yield

Introduction

One of the most important tasks of the food and processing branches of the agroindustrial complex is the development and introduction of progressive technological processes, equipment and control systems providing an increase in quality and biological value of the foodstuffs. The significant part of such technological processes is realized in a limited space (microenvironment) containing living objects (for example, cultivation of baker's yeast, storage and transportation of fruits, vegetables, barley and other kinds of agricultural raw material, malting, activation of yeast before fermentation, green sprouting of potatoes before planting, suppression of activity of mould, vermin (insects, acarina), and putrefactive microflora during foodstuff storage, *etc*.). The abovementioned targets could be partially achieved by MES project introduction at food and agricultural enterprises.

Attention must be paid to following an essential feature of this project concerning a sustainable development problem treatment on a local level. By applying SACMEs at food manufacturing enterprises operating with living objects (such as breweries, bakeries, biotechnological productions, *etc*.), for example, a constructive compromise could be achieved in a simultaneous solution of three problems with no contradictions arising: economical growth (productivity increase, raw material saving); ensuring security, safety and quality of agricultural raw material during storage process and of food produce during production technological process; improvement of labor conditions for industrial personnel from an ecological point of view.

In brewing the MES project introduction will result, for instance, in:

- brewer's barley, rice, maize, hops, and malt storage period increase and better preservation (losses decrease, quality increase) during storing;
- putrefactive microflora and mould elimination;
- air purification in storehouse and other industrial departments of dust, pathogenous microorganisms, harmful gaseous impurities;
- brewer's barley germination (box or drum malting) stimulation (But 1977);
- brewer's yeast fermentation intensification;
- elimination of gaseous harmful substance contacts with raw material and beer during various technological stages;
- positive effect of air aeroionization and purifying on industrial personnel promoting strengthened health and life duration increase.

The SACME systems could be fulfilled in a stationary performance (for large industrial areas and big volumes of produce to be processed) and in portable or transport modifications for the case of small processing capacities, petty warehouse premises, and also for installation on transport facilities destined for raw material (potatoes, fruit, barley) and ready products (malt, hop, yeast, bread) for long-distance deliveries.

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In this work, the process of industrial baker's yeast cultivation as a basic object for SACME development is chosen with an investigation of possibility of result application for other objects, such as, for instance, the potato storehouse.

The use of DAPTAP through the effects of the various aeroion concentrations on intracellular respiration is offered as an execution device for the purpose of living object control. The mechanisms of aeroionized media influence on living systems are considered in other works (Chizhevsky 1999, Lifshitz 1990, Muzychenko 1991, Temnov et al. 2000).

As the other basic controls in baker's yeast cultivation in a bioreactor, the flow of aerating air can be used as a source of oxygen and the flow of molasses solution as a source of sugars. As the basic measurable and controlled parameters of living systems, the specific metabolic heat generation rate of a living object and the rate of the metabolic by-product formation (ethanol in yeast production and ethylene during agricultural produce storage) can be chosen.

The solution of the control problems was realized with the use of a complex mathematical model, describing a living system on mitochondrial and cellular/population levels and on the level of interaction of the population with the microenvironment.

In the present paper, some results of previous research are used (Amelkin et al. 2003, Amelkin et al. 2001a-2001c, Amelkin et al. 2000a-2000b, Amelkin and Amelkin 1997, Amelkin and Amelkin 1996).

1 Process Modelling

The mathematical model of a bioreactor as an example of a controlled microenvironment containing a living system (a population of yeast), consists of *three subsystems* - a model of intracellular respiration (a model of mitochondrial respiratory chain), intermediate model describing intercoupling of celluar and population levels, and a model of a bioreactor (microenvironment). Hereafter, these three modelling levels will be indicated as Model 1, Model 2, and Model 3, correspondingly.

Below, these three levels of microenvironment modelling are considered in detail.

2.1 A model of intracellular respiration (Model 1)

Two types of respiration exist for a living, aerobic organism - external respiration and cellular respiration. Cellular (mitochondrial) respiration is the process of oxidizing food molecules (like carbohydrates) to carbon dioxide and water. Biochemical oxidation is catalyzed by intracellular (intermitochondrial) enzymes and is the mechanism for obtaining energy from fuels (food molecules). The energy released is stored in the form of ATP for use by all the energy-consuming processes of the cell. Actually 95% of the ATP is produced in the mitochondria. That is why mitochondria are often called 'the cell's power station'. The main and the most complicated part of the total mitochondrial respiration process is the respiratory chain or respiration system, which is based on the inner mitochondrial membrane. Here, most of the ATP is generated due to the proton gradient that is developed across this inner membrane.

The respiratory chain of the mitochondrion (**Fig.1**) consists of three large enzyme complexes built into the inner membrane, which serve as electron carriers (Alberts et al. 1989, Skulachev 1994, Skulachev 1989):

I. *NADH dehydrogenase complex* includes Fe-S centers as well as FMN bound with NADH dehydrogenase, and CoQ.

II. *Electron transport complex*, which is presented by cytochromes b-c_1-c, i.e. iron containing proteins transferring electrons from NADH dehydrogenase complex to cytochrome oxidase complex.

III. *Cytochrome oxidase complex* contains two cytochromes a-a_3 and two copper atoms. It is the site at the end of the mitochondrial respiratory chain. This site is the terminal accumulator of electrons carrying them directly to oxygen.

Beside electron carriers, the respiratory chain also contains several ATP synthase complexes.

The respiration system of mitochondria can be regarded as a biochemical generator with hydrogen electrode (enzyme complex I with potential φ_1) and oxygen electrode 2 (enzyme complex III with potential φ_3) assuming that intermediate redox pairs of respiratory chain play a regulatory role for redox processes in the mitochondrion. A similar assumption is already known (Volkenshtein 1988).

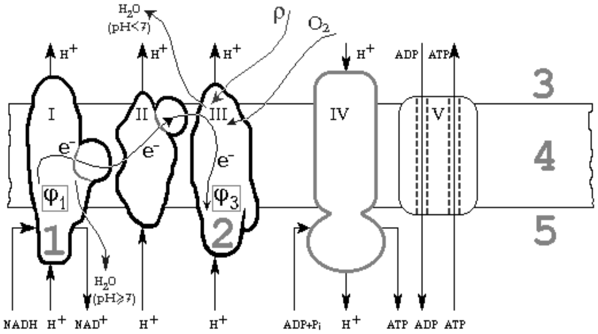

Fig.1: Respiration system of mitochondria as a biochemical generator with hydrogen electrode 1 and oxygen electrode 2 (enzyme complexes: I - *NADH dehydrogenase complex*; II - *Electron transport complex*; III - *Electron transport complex*; IV - ATP synthase complex; V - Adenine nucleotide transporter). Enzyme complexes I-V are built into the the inner membrane 4, separating matrix 5 from intermembrane space 3.

The mathematical description (Model 1) of the respiratory chain is a system of dynamic equations and kinetic expressions describing the electrochemical and biological processes of respiration occurring in a living organism on a cellular (mitochondrial) level. The Model 1 describes mechanisms of pH oscillation, proton and electron transport, oxidative phosphorylation, dismutation of superoxide radicals, and superoxide dismutase (SOD) activation.

The pH oscillations phenomenon takes place in matrix and, in case of pH oscillation, center shift into extremely alkaline or acid zone metabolism is retarded (this can occur under definite environmental parameter variation conditions). The above mentioned oscillation processes during respiration and a level of SOD activity can be controlled by the rate of income of superoxide radicals from the execution device DAPTAP to mitochondrial matrix.

2.2 An Intermediate Model (Model 2) Describing Intercoupling of Cellular and Population Levels

With the aim of the cellular and population mathematical models coupling it is necessary to build the intermediate Model 2 describing relationships between the main parameters for different levels (Amelkin et al. 2000b, Wolf et al. 2000).

Such intermediate model linking population and cellular levels is destined to describe links between concentrations of the key components in cultural liquid (or in ambient medium) and flows to mitochondrion and its respiratory chain:

- flows of protons and of NADH to the respiratory chain of mitochondrion are determined by the Krebs cycle action and is linked with sugar concentration in the cultural liquid value;
- flow of molecular oxygen to the respiratory chain of mitochondrion is linked with dissolved oxygen concentration in the cultural liquid;
- flow of superoxide radicals is determined by superoxide radical concentration in cultural liquid, which in its turn is linked with negative aeroions concentration in aeration air;
- flows of ADP, of inorganic phosphate and of Ca^{2+} and Na^{+} cations are controlled by pumping processes and other factors.

Model 2 will describe such parts of cell metabolism as Glycolysis, Acetyl-CoA Pathway, Krebs Cycle, as well as transport, dynamic and quantitative links of these parts with population level, on the one hand, and mitochondria inner membrane level (electron and ion transport, and oxidative phosphorylation systems) on the other hand.

2.3 Population Model (Model 3)

The population model is a combination of mass, volumetric, gaseous, and heat balances of a bioreactor. In this investigation a concrete example of the population model published in work is used (Amelkin et al. 1995). Model 3 is a system of differential material, gaseous and heat balances equations. The structural and parametric identification of Model 3 was fulfilled by the authors of this work on the basis of the industrial and experimental data obtained during cultivation of various strains of baker's yeast (Amelkin 1991, Amelkin et al. 1995, Castrillo and Ugalde 1994, Gaponov 1984, Okada et al. 1981, Peringer et al. 1974, Shkidchenko et al. 1983, Sonnleitner and Käppeli 1986, Wöhrer and Röhr 1981).

3 Optimal Control Problem Solution for the Cellular Level

The optimal control problem is reduced to maximization of energy evolution function of mitochondrion expressed in ATP synthesis by influence on respiratory chain of aeroion flow determined by the input voltage of the DAPTAP aeroion generator.

The optimal control problem treatment was fulfilled within a class of stepwise constant functions on a qualitative level with the use of OptiMod software (Amelkin 1992, Amelkin et al. 2000a) on the basis of Model 1. The results for the potatoes storage/ greensprouting case is depicted on **Figs. 2-5**.

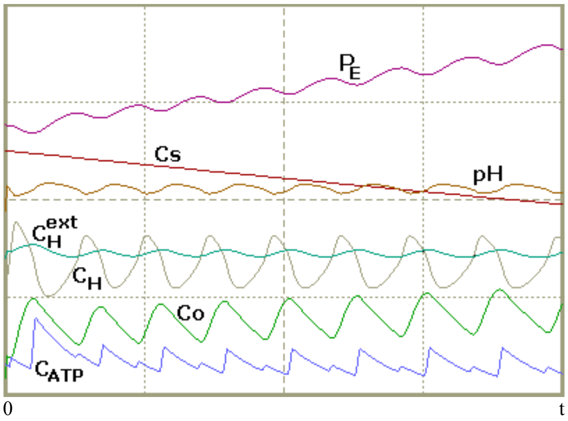

Fig.2: A case of no control.

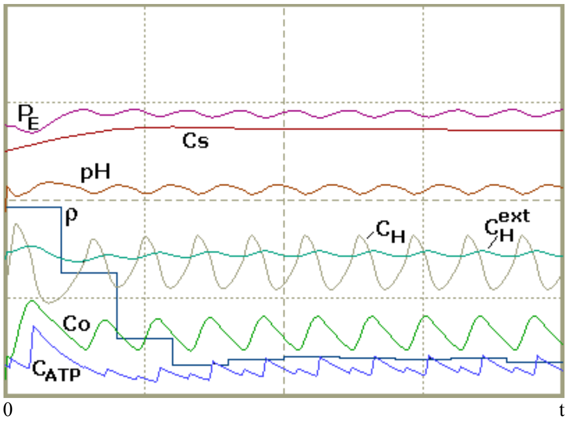

Fig.3: Potatoes greensprouting.

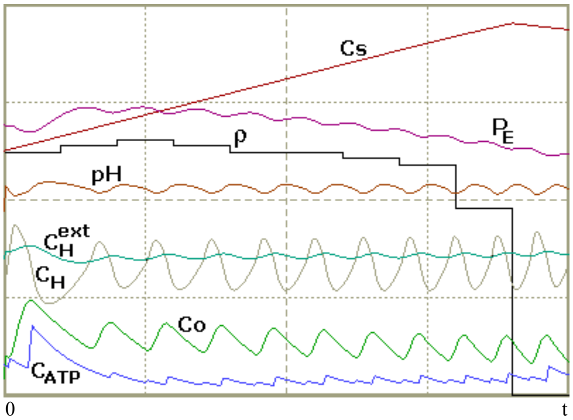

Fig.4: Potatoes storage control by ethylene parameter.

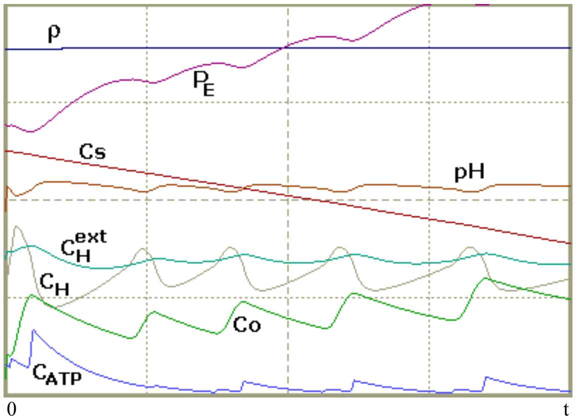

Fig.5: Overshoot case.

4 Microenvironment Optimal Control Problem Solution for the Yeast Cultivation Process

The lion's share of expenditures in baker's yeast production falls on the technological process of fermentation. That is why the fermentation process is usually given principal consideration in systems of automatic and automatized control of production as a whole. On the other hand, this process is the most complicated from the point of view of control.

Material costs make up the largest cost component in most production companies, at an average of up to 60% of total costs. In baker's yeast production the greatest portion of material costs is formed by molasses, salts and other feed component costs.

Taking into account the relatively high price of the main raw material (sugar beet molasses) and its high share in the process profit the microenvironment optimal control problem for baker's yeast industrial fed-batch cultivation in a bubbling bioreactor is reduced from a profit maximum to a maximization of the overall yield by the reason that the reciprocal value of overall yield correlates closely with the material flow-oriented specific cost.

The microenvironment optimal control problem for baker's yeast industrial fed-batch cultivation treatment was fulfilled with the use of OptiMod software as well (Amelkin et al. 2000a) on the basis of Model 3 within a class of stepwise constant functions.

5 Development of Algorithm of Microenvironment Automatic Control

The analysis of optimal control problem solution results has shown that the optimal controls can be approximated for a significant length of time by exponential dependences.

The maximum of the biomass instantaneous yield corresponds to the maximum specific metabolic heat generation rate which allows one to use this parameter as a main parameter of feedback control during development of algorithms of automatic control. The rate of ethanol formation could be chosen as an additional feedback parameter which could be used in a control algorithm. The combination of these two parameters gives an opportunity of unambiguous recognition of the type and degree of technological process unfavorable variation.

At the present moment, the computer simulation of the elaborated algorithm of automatic control is being accomplished including measuring errors and parameters of drift simulating, and applying methods of exponential filtering of measured parameters and information validity monitoring.

6 Functional and Parametric Scheme of SACME

The functional and parametric scheme of subsystems for automatic control of the microenvironment (SACME) is developed. The SACME must function in close intercoupling with other MES control subsystems. In a potato storehouse, for example, SACME should interact with the subsystem of air conditioning (Brook 1999, Muzychenko 1991), in brewing - with air treatment and temperature control subsystems (Lobanov et al. 2000), and in yeast production - with control subsystems of cultural liquid temperature, pH, heat exchanger, *etc*. The SACME under design for baker's yeast cultivation includes sensors of state and perturbation parameters (temperature of liquid flows to and out of heat exchanger, cultural liquid temperature, flow of cooling water, temperature of feed flow, ethanol concentration), execution devices (the control valves in lines of aeration air and feed, aeroionizing device - DAPTAP), as well as control algorithm, realized by software means of a central computer or microprocessor controller. In the case of a potato storehouse, the periphery content is to be changed accordingly: for example, the concentration of ethylene but not ethanol is to be used as a measurable metabolic by-product of living objects. For the purpose of SACME simulation it is planned to use the complex mathematical model (Model 1 + Model 2 + Model 3) with a further demand of special experiments series setting to finish the structural and parametric identification of models.

7 Execution Device for Air Aeroionizing

The in-flow aeroionizing of aeration air in baker's yeast production could be realized at early stages of the process only during seed and intermediate culture production when air flow values are relatively small. Air aeroionizing is to be realized with the help of stationary or portable modifications of DAPTAP.

Stationary modifications of DAPTAP can be installed in the input air flow entering the bioreactor or malt-house, and portable modifications (**Fig.6**) are to be used for microenvironment control in boxes for seed culture growing as well as in storehouses, transport, hothouses, *etc*.

The essential feature of the constructed devices is that they ionize preliminarily ozonated and purified air during three-stage filtration, evolve almost no ozone into the environment and permit one to get air free of dust and gaseous chemicals, and of biological impurities, with an efficiency close to 100% and low power consumption. The modular construction of DAPTAP permits one to create stationary and portable devices of various modifications, capacities and configurations. The device is inexpensive and simple to operate. The microprocessor control unit will allow one to realize various optimal control modes depending upon aim of treatment and type of object. The working model of DAPTAP was tested at a potato-storehouse: the losses of potatoes were reduced by 30% (Amelkin et al. 2000a). Similar results were obtained during the fruits and vegetables storage process with the use of a device for aeroionization treatment of agricultural raw materials (Muzychenko 1991). The manner of air treatment and devices for its realization are protected by a valid patent (Amelkin et al. 1998).

Fig.6: A pilot model of DAPTAP portable modification.

8 Sensors

In SACME there are various sensors are to be used for ethanol, ethylene, ozone, and biomass concentration detection by various methods: selective UV absortion, electrochemical fuel cell method, conductance-measuring method, *etc.*

9 The Domestic and Medical Application

An alternative application of the execution device for air purification and aeroionizing DAPTAP is its use in domestic conditions and for medical purposes. A group of pediatricians of Kazakhstan (Skuchalina et al. 2001) recently reported about a constant percentage growth of children sick with allergic bronchial asthma and atopic dermatitis throughout the world. The authors pointed to the responsibility of the microenvironment for the development of allergic diseases at child age. The main microecological factor is multicomponent composition of a domestic dust containing up to 900 ticks, 520000 fungus cells and 26770000 microflora cells per 1 gram of dust. Taking this into account, a controlled living microenvironment forming with DAPTAP use will be health-giving in regard to domestic and medical application.

10 Conclusions

1. The approach to SACME designing is developed: *(a)* the three-level mathematical model of microenvironment development; *(b)* the control problem's formulation and solution; *(c)* the optimal solution analysis and construction of algorithms of automatic control; *(d)* the functional and parametric scheme of SACME construction; and *(e)* choice of software/hardware means for SACME realization.
2. The use of DAPTAP device as an execution device for microenvironment aeroionizing is offered. The effect of DAPTAP on a living organism (human, mammal, gallinaceae, vegetable, fruit, cereal, plant, fungus, bacterial, vegetable, insect, *etc.*) can be indirectly monitored by measuring the different integral feedback parameters (the maximum specific metabolic heat generation rate, the rate of ethanol formation, *etc.*).
3. During further development of the present work it is proposed: *(a)* to set the series of special experiments; *(b)* to finish structural and parametric identification of complex mathematical model; *(c)* to accomplish SACME simulation with the use of the complex mathematical model; and *(d)* to choose the software/hardware means for SACME realization for various control objects.
4. The SACMEs under development can be applied within the MES framework in any areas where the living objects placed into a limited microenvironment are used.
5. The SACMEs serial production organization, including scientific laboratory establishment and the conductance of experimental investigations will need 500,000 USD of the total investments with 30 months repayment and 20% interest.

Nomenclature

Variables:

C_{ATP} - concentration of ATP, M;
C_S - concentration of active superoxide dismutase, M;
C_O - concentration of superoxide radicals, M;
C_H - protons concentration in matrix, M;

C_H^{ext} - protons concentration in intermembrane space, M;

φ_1, φ_3 - electrochemical potentials of I and III complexes as hydrogen and oxygen electrodes of biochemical generator of electric current, respectively, V;

$\Delta\varphi$ - potentials difference (= $\varphi_3 - \varphi_1$), V;

P_E - by-product (ethanol for yeast case or ethylene for vegetables storage case) concentration in cell, M;

Pi - inorganic phosphate concentration, M;

pH - value of pH of matrix;

pH^{ext} - value of pH of intermembrane space between the inner and outer membranes;

ρ(t) - income of superoxide radicals from the device to mitochondrial matrix (control function), M/h;

t - time, h;

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