The 13th IEEE International Conference on Dependable Systems, Services and Technologies, DESSERT'2023
13-15 October, 2023, Athens, Greece

Optimization of Ethanol Production Using State-Space Modeling and Optimal Control Technology

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***Abstract* — in this paper we develop the automatic optimal control of the production process of dough mixture preparation, that can be used in the production of alcohol and fuel ethanol from grain raw materials. Known methods of automatic control of the dough preparation process were based on measuring the consumption of raw materials and the concentration of the dough and regulating the water supply. We offer an improved method based on robust stabilization nonlinear process control that will ensure more stable operation of the system, smooth transitions of regimes and economy of used energy, improvement of the quality of the mixture dough, as well as final ethanol product. The optimal operating modes of the installation were investigated using state-space dynamical modelling technic and ethanol production process simulation.**

Keywords* — *automatic optimal control, dynamical modelling, ethanol production, state-space system, dynamical modeling

I. INTRODUCTION

Due to large global demand for outgoings and supplies, the industry actualy is looking for fuel and energy solutions that give result in economy, savings and sustainability. That is why the energy consumption is one of the largest source of expenditure in the industrial plants on the planet. In the same time there is no suitable energy integration, leading to more outgoings and expenditure and more pollution from the burning of fuels. This can lead to making the industry and privat sector acting unfavorable to modern competitive markets. In the same time under large global demand for supplies, the industry market in general has been increasingly looking for energy solutions that result in savings and sustainability. Nowadays the industry has a large energy demand due to the high energy consumption that is necessary in different industry processes. In this context ethanol is a product that has been used as an alternative fuel and energy production raw in many countries, including USA, Brazil, Ukraine as a solution to reduce atmospheric pollution.

This is due to its using as an alternative fuel in many countries as a solution to reduce atmospheric pollution, ethanol is necessary in the fight against global warming, making clear the importance and actuality of reducing expenses for ethanol production. It is making the process more competitive in the global scenario.

Therefore one renewable solution concerning the depletion of fossil fuels and the atmospheric pollution derived from their combustion is the use of ethanol and bioethanol production, use the ethanol as a fuel. The conversion of the functioning of industrial plants into ethanol fuel and biofuels represents an important option for both the exploitation of an alternative source of energy and the reduction of polluting gases, mainly carbon dioxide. The most important biofuel is the fuel ethanol, which can be utilized as an oxygenate of gasoline elevating its oxygen content, allowing a best oxidation of hydrocarbons and reducing the amounts of polluting gases released into the atmosphere. Fuel ethanol is obtained from sugarcane in some tropical countries like Brazil and India. Beet molasses are used in some European countries like France. The main feedstock in the US is starch from corn. In Ukraine the most common technology is based on the use of grain as feedstock. In order to design a well integrated useful energy plant, it is necessary to use effective theoretical tools, one of them is the mathematical modeling, control system theory, state-space modeling technic that is done in this paper.

Therefore, in this paper we develop an optimal technology that can be applied in a cheap, simple and effective way in the development and elaboration, besause it allows to simulate the production system and its optimal modes of operation already at the design stage, and the production technology is based on the use of grain as feedstock used in Ukraine. In this context the aim of this work is to investigate control strategy in different modes for the technological production of fuel ethanol analyzing them from the energy viewpoint and from their integration possibilities through process simulation. The objective function used for the analysis was the energy consumption defined as the thermal and electric energy demanded during the production of ethanol from grain and other similar biomass. The effectiveness and assessment of the major stages is an important tool for the identification of the most energy-consuming steps and for the proposal of improved technological configurations of the process allowing the reduction of final ethanol costs. In addition, this work is aimed to the preliminary estimation of the optimal control strategy for the ethanol production process from biomass based on the results obtained during the simulation of the best flowsheet configuration. In this work, we consider dynamical process configurations for ethanol, especially fuel ethanol production that is considered as one of the most vide perspective used and important renewable fuels due to their the economic and environmental benefits of its use. It is the most prospective and promising feedstock for producing ethanol including bioethanol due to its global availability and to the energy gain that can be obtained that can be used for cogeneration of fuel, heat and power.

In the literature, different plants and flowsheets for the production of ethanol and fuel ethanol from plants have been reported [1-5,8,11]. They are based on experimental studies which are executed and carried out. In the same time only information about reached yields and material balances is done without detail further effectiveness, energy or costs analysis [2], [3]. In the works [4,5] the authors describe a generic ethanol production process from wood, which has been analyzed from the viewpoint of production costs for the specific case of ethanolic fermentation and separate cellulose hydrolysis. In the same time the presented models take into account the the evaporation of stillage and dehydration of ethanol. In the paper [6] the evaluation of production costs is done for some flowsheet variants corresponding to the process from pine, they develop a simulation of ethanol production processes from woody biomass with increased utilization of pentoses [7]. In this paper [7] performed energy analysis showed that using internal recycles can allow the increase of ethanol concentration before distillation, that can leads to reducing the related energy requirements.

This task of reducing the related energy requirements can be realized with use of model-based control strategy that we do in this paper, computer simulation and technological process dynamic reconstruction. It can make possible to simulate the capabilities and effectivness the optimal control strategy. In this context the study of existing dynamic models can be used for determining the parameters of technological proceses and systems at the early stage of their designing, as well as for the studies of the control systems and stability of such devices.

Therefore in our paper we use the methodology presented in [9,10], and based on this methodology we design the controller and make it simulation on the real data. The choice of the state-space model is justified by the fact that this model includes linearized equations, it is suitable for the study of state variables in response of small disturbances. The goal is also to adapt the control systems analysis techniques to provide an explanation for the selection of control variables strategies in applying to description of system functioning. Therfore we develop the automatic optimal control of the production process of dough preparation, that can be used in the production of alcohol and fuel ethanol from grain raw materials. Known methods of automatic control of the dough preparation process were based on measuring the consumption of raw materials and the concentration of the dough and regulating the water supply. We offer an improved method based on robust stabilization nonlinear process control that will ensure more stable operation of the system, smooth transitions of regimes and economy of used energy, improvement of the quality of the dough miztures, as well as final ethanol product. The optimal operating modes of the installation were investigated using state-space dynamical modelling technic and production process simulation. So, we propose an improved control that can be incorporated in the objective function that includes following the target values obtained from the experiments, minimization of "energy effort," along with stabilization of the system. In our methodology we propose approach of imitation of fuel ethanol production testbed using observation data stored into the specified look-up tables.

This paper is organized as follows. In Section II the world trends and actuality of the considered research problem area are described, in Section III the model specifications has been done. After having introduced the control design problem and methodology in Section IV, construction of control law, its calculation and simulation are presented in Section V. Conclusion and recommendation for a future work are finally presented in the last Section.

II. WORLD TRENDS AND ACTUALITY

Ethanol fuel is fuel containing ethyl alcohol, it is most often used as a motor fuel, mainly as a biofuel additive for gasoline, in the world the several common ethanol fuel mixtures are in use. Among them using of pure hydrous or anhydrous ethanol in internal combustion engines (ICEs) is only possible if the engines are designed or modified for that purpose. Anhydrous ethanol can be blended with gasoline (petrol) for use in gasoline engines, but with high ethanol content only after engine modifications to meter increased fuel volume since pure ethanol contains only 2/3 the energy of an equivalent volume of pure gasoline. High percentage ethanol mixtures are used in some racing engine applications as the very high octane rating of ethanol is compatible with very high compression ratios. Bioethanol is a form of renewable energy that can be produced from agricultural feedstocks. It can be made from very common crops such as hemp, sugarcane, potato, cassava and corn, grain.

The first production car running entirely on ethanol was the Fiat 147, introduced in 1978 in Brazil by Fiat. According to publicly available sources, world ethanol production for transport fuel tripled between 2000 and 2007 from 17×109 liters (4.5×109 U.S. gal; 3.7×109 imp gal) to more than 52×109 liters (14×109 U.S. gal; 11×109 imp gal). From 2007 to 2008, the share of ethanol in global gasoline type fuel use increased from 3.7% to 5.4%. In 2011 worldwide ethanol fuel production reached 8.46×109 liters (2.23×109 U.S. gal; 1.86×109 imp gal) with the United States of America and Brazil being the top producers, accounting for 62.2% and 25% of global production, respectively. US ethanol production reached 57.54×109 liters (15.20×109 U.S. gal; 12.66×109 imp gal) in May 2017. Ethanol fuel has a "gasoline gallon equivalency" (GGE) value of 1.5, i.e. to replace the energy of 1 volume of gasoline, 1.5 times the volume of ethanol is needed. Ethanol-blended fuel is widely used in Brazil, the United States, and Europe (see also Ethanol fuel by country). Most cars on the road today in the U.S. can run on blends of up to 15% ethanol, and ethanol represented 10% of the U.S. gasoline fuel supply derived from domestic sources in 2011. Some flexible-fuel vehicles are able to use up to 100% ethanol. Since 1976 the Brazilian government has made it mandatory to blend ethanol with gasoline, and since 2007 the legal blend is around 25%

ethanol and 75% gasoline (E25). By December 2011 Brazil had a fleet of 14.8 million flex-fuel automobiles and light trucks and 1.5 million flex-fuel motorcycles that regularly use neat ethanol fuel (known as E100).

Fig.1. The Saab 9-3 SportCombi BioPower which uses bioethanol fuel (Sweden)

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Fig.2. The Brazilian 2008 Honda Civic

On Fig.1 is shown the Saab 9-3 SportCombi BioPower which uses bioethanol fuel (Sweden), it was the second E85 flexifuel model introduced by Saab in the Swedish market. The Saab 9-3 (pronounced nine-three) is a compact executive car initially developed and manufactured by the Swedish automaker Saab. The first generation 9-3 (1998-2003) is based on the GM2900 platform, changing to the GM Epsilon platform with the introduction of the second-generation car (2003-2012). Other vehicles using this platform include the Opel Vectra, Chevrolet Malibu, and Cadillac BLS. Saab's parent company during 2013 and 2014, National Electric Vehicle Sweden (NEVS), briefly assembled a few 9-3 sedans. The Brazilian 2008 Honda Civic which also uses bioethanol fuel, it is flex-fuel has outside direct access to the secondary reservoir gasoline tank in the front right side; the corresponding fuel filler door is shown by the arrow. Energy consumption analysis of integrated flowsheets for production of fuel ethanol gives the following results.

In Ukraine, for security purposes legislative initiatives are also being introduced regarding the use of liquid biofuel (biocomponents) in the field of transport. Today, in the conditions of the military aggression and war against Ukraine and in view of the issues of energy security and stable functioning of the fuel market, these initiatives are gaining special relevance. The main goal is to establish a mandatory rate of addition of bioethanol to alternative fuels for gasoline engines at a level of at least 5% (by volume). The ethanol has other advantages — a high octane number, which can make the engine more efficient by increasing the compression ratio. Only the degree of compression on ethanol engines can make the engine more powerful and more economical in terms of fuel consumption. In cars with a flexible choice of fuel, the engines can get the same power output when using gasoline or ethanol. Fuel consumption for high compression vehicle engines running on pure ethanol is currently 20-30% higher than gasoline consumption compared to the gasoline version. Adding a variable compression ratio turbocharger can be optimal and fuel economy will be consistent with any ethanol blend. Nowadays of most Ukrainian plant distilleries, the cost of bioethanol from grain is low, and the total cost depends on conditions of its production. Consumption of ethanol in engine power is 51% higher than consumption of gasoline, because the energy per unit volume of ethanol is 34% lower than that of gasoline. But ethanol has other advantages — a high octane number, which can make the engine more efficient by increasing the compression ratio. Only the degree of compression on ethanol engines can make the engine more powerful and more economical in terms of fuel consumption. In cars with a flexible choice of fuel, the engines can get the same power output when using gasoline or ethanol. Fuel consumption for high compression vehicle engines running on pure ethanol is currently 20-30% higher than gasoline consumption compared to the gasoline version. Adding a variable compression ratio turbocharger can be optimal and fuel economy will be consistent with any ethanol blend.

Therefore, fuel ethanol is considered one of the most important renewable fuels due to the economic and environmental benefits of its use, it is the most promising feedstock for producing bioethanol due to its global availability and to the energy gain that can be obtained from biomass are used for cogeneration of heat and power.

III. RESEARCH PROBLEM FORMULATION

In this work, we develop the automatic optimal control of the production process of dough mixture preparation, that can be used in the production of ethanol from grain raw materials. Known methods of automatic control of the dough preparation process were based on measuring the consumption of raw materials and the concentration of the dough and regulating the water supply. We offer an improved method based on robust stabilization nonlinear process control that will ensure more stable operation of the system, smooth transitions of regimes and economy of used energy, improvement of the quality of the dough, as well as final ethanol product.

According to the proposed method, the concentration of raw materials is determined, and the regulation of water supply is carried out according to a non-linear law. Input data - consumption of raw materials, concentration of raw materials, current value of the concentration of the mixture, target value of the concentration of the mixture.

It is developed several process configurations for fuel ethanol production from were studied using state-space dynamical modelling technic and process simulation .

The production device (Fig. 3) consists of a pre-boiler mixer 1 into which grain of a given rate and concentration and water of a known rate are supplied. It has a regulating effect. The device consists of a multiplication block 2, which receives the measured current values of flow rates; adder to which the resulting signal is applied and the signal corresponding to the target value of the mixture concentration is subtracted; division block 4, where the output signal from block 3 is divided into a signal corresponding to the current value of the mixture concentration; adder 5 into which the resulting signal from the division block is input; control valve 6, which changes the water supply to the mixer, the position of which is controlled by the resulting adder signal.

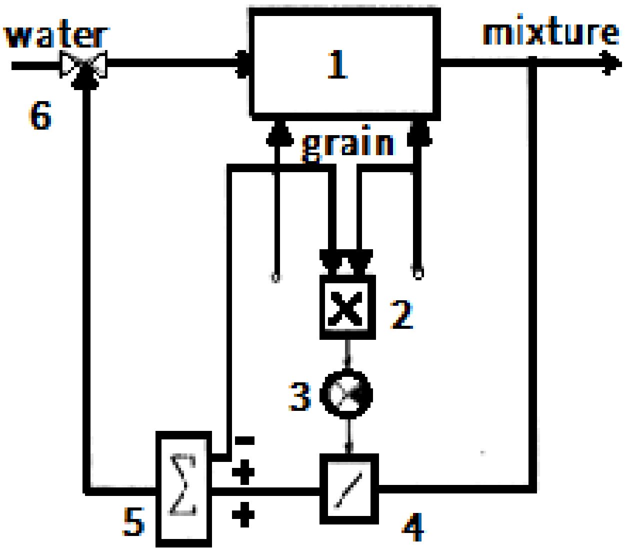

Fig.3 The ethanol production device

Grain or potatoes are used as starch-containing raw materials that are processed into alcohol. This raw material is mixed with water and served for boiling, and the concentration of such mixture is determined by the content of starch in it.

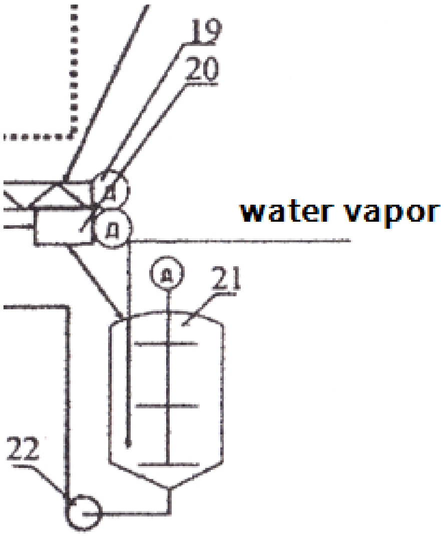

Fig.4 Water vapor.

To ensure the homogeneity of the mixture, it is mixed with a propeller stirrer. The purpose of boiling raw materials is to release starch from plant cells and convert starch into a soluble state. In the boiling process, the batches are also sterilized, which is important in the further technological processes of saccharification and fermentation, therefore the task of timely control and regulation of the parameters of this technological process is set. In order to achieve effective automated regulation, it is first necessary to conduct simulation (Fig. 4). The modeling method allows you to avoid big mistakes during the implementation of production and accelerates its development. Many processes cannot be studied in industrial devices due to the impossibility of arbitrarily changing their mode of operation, the difficulty of separately studying jointly acting factors, and the possible spoilage of a large number of products.

Mixing processes are widely used in the food industry for the formation of homogeneous products with defined properties, as well as for the intensification of technological processes. Mixing is carried out in different ways in different devices with stirrers, as well as in gas and liquid flows.

IV. DESCRIPTION OF THE MODEL AND CONTROL METHODOLOGY

A. *Dynamic Model in the Space of States*

Consider the control system for the process of mixing liquids. The scheme of the process is shown in fig. 1. The capacity is filled with the help of two streams having variable instantaneous flows $F_1(t)$, $F_2(t)$. Both incoming streams contain soluble liquid with constant concentrations c_1, c_1. The exit stream has a mass outflow velocity *F(t).* It is assumed that the contents of the tank are mixed so that the concentration of the output stream is equal to the concentration *c(t)* in the tank.

We develop robust control strategy under minimization of the energy efforts of ethanol production plant, and in the presence of small state perturbations of the states from the position of equilibrium. To solve this problem, we consider the space-state model technic, proposed by [9,10]. This model includes linearized equations and full feedback, taking into account nonlinearities. We have

$$\frac{dV(t)}{dt} = F_1(t) + F_2(t) - F(t),$$
$$\frac{d}{dt}[c(t)V(t)] = c_1F_2(t) + c_2F_2(t) - c(t)F(t),$$

where *V(t)* is the volume of liquid in the tank. The instantaneous output flow F(t) depends on the height *h(t)* as follows:

$$F(t) = k\sqrt{h(t)},$$

where *k* – is experimental constant; $F(t) = k\sqrt{\frac{V(t)}{S}}$;

$$\frac{dV(t)}{dt} = F_1(t) + F_2(t) - k\sqrt{\frac{V(t)}{S}},$$

$$\frac{d}{dt}[c(t)V(t)] = c_1F_1(t) + c_2F_2(t) - c(t)k\sqrt{\frac{V(t)}{S}}.$$

In the case of a steady state, all quantities are constant:

F_{10}, F_{20}, and F_0 – relative flow rates,

V_0 – volume, and c_0 – concentration in the tank.

Under small deviations from the equilibrium state, we obtain

$$F_1(t) = F_{10} + \mu_1(t),$$
$$F_2(t) = F_{20} + \mu_2(t),$$
$$V(t) = V_0 + \xi_1(t),$$
$$c(t) = c_0 + \xi_2(t),$$

where μ_1 i μ_2 are system inputs, a $\boldsymbol{\xi}_1$ i $\boldsymbol{\xi}_2$ – are state variables which are current value of volume of liquid in the tank and the mixture concentration respectively.

We define: $\frac{V_0}{F_0} = \theta$ as a paprameter, obtained from the experimental data.

Linearized state space equations sysytem has a form

$$\dot{x}(t) = \begin{pmatrix} -\frac{1}{2\theta} & 0 \\ 0 & -\frac{1}{2\theta} \end{pmatrix} x(t) + \begin{pmatrix} 1 & 1 \\ \frac{c_1 - c_0}{V_0} & \frac{c_2 - c_0}{V_0} \end{pmatrix} u(t),$$

where stare space vector is $x(t) = col[\xi_1(t),\ \xi_2(t)]$ and control inputs vector is $u(t) = col[\ \mu_1(t),\ \mu_2(t)\ ]$.

And output vector

$$y(t) = \begin{pmatrix} \frac{1}{2\theta} & 0 \\ 0 & 1 \end{pmatrix} x(t),$$

where $y(t) = col\ [\ \eta_1(t), \eta_2(t)\ ]$.

B. Control Design

In order to choose the correct response, a control selection center uses the mechanical states to select the amount of response necessary to counter the disturbances. This center evaluates the difference between an estimated state and the desired state, and chooses the appropriate trajectory, and feedback gains. Control selection center effectively chooses the appropriate gain matrix. The motor control system (4) is presumed to receive a desired state vector $\bar{x}$ from experiments, compare it with the measured state, and generate the control command u .

The design objectives are the following. Regulation of the states $x(t)$ to their respective set points $\bar{x}(t)$ determined from the experimental data were obtained from the biomechanical tests conducted with aid of motion tracking software OptiTrack with dedicated software, as it will be described below. We use LQR regulator [2] in order to selects trajectories that minimize an objective function which weights the deviations of the controls and states from nominal. Therefore, to render the system (4) into the reference values $x(t) = \bar{x}$, we introduce new independent variables y and make the changing $x(t) = \bar{x} + y$, $u = \bar{u} + v$, where $\bar{u}$ is selected from the condition

$$A\bar{x} + B\bar{u} = 0.$$

Obtain

$$\bar{u} = -B^{-1}A\bar{x},$$

and the system:

$$\dot{y} = Ay + Bv$$

will have zero position of equilibrium.

Find an appropriate feedback gain matrix K such that the system (4) under state variable feedback of the form

$$u = \bar{u} - K(x - \bar{x}) \tag{5}$$

has the following properties:

(i) $u(x)$ achieves asymptotic stability of the equilibrium.

(ii) $u(x)$ minimizes the cost functional

$$J = \int_0^\infty [(x - \bar{x})^T Q(x - \bar{x}) + (u - \bar{u})^T R(u - \bar{u})]dt, \tag{6}$$

where Q and R are weighting matrices for deviations of states x and controls u, from nominal $\bar{x}$ and $\bar{u}$ respectively.

The optimal state trajectory $x(t) = x_{opt}(t)$ produced by LQR control minimizes a set of objectives collected in functional (6). The control law $u(x)$ drives the system asymptotically to the target $\bar{x}$. Both Q and R are free to be chosen as long as they are constant, symmetric, positive definite matrices. The matrices Q and R determine the balance between the cost of not being at the origin and the cost of control to move the system to the origin.

We use known theory and solve the Riccati equation

$$PA + A^T P - PBR^{-1}B^T P = -Q, \tag{7}$$

obtaining the gain matrix $K = R^{-1}B^T P$. This controller produces a close-loop system with any desired eigenvalues.

Our goal is choosing the appropriate Q and R matrices. For given Q and R, the matrix P can be obtained from (7), and K is then will be determined for use in the feedback control law (5). We use numerical methods of MatLab for solving (7). To apply the control law we center the controls at their set points values. The designed controller defined in (5) provides a globally asymptotically stable origin. The robustness of optimal control follows from the Hamilton-Jacobi-Bellman equation, which leads to optimality and asymptotic stability of the error system.

V. EXPERIMENTAL RESULTS

A. Experimental Tests

The model experimental data were taken from the ethanol production installation used at most plant in Ukraine. Necessary experimental tests were conducted in real-time in order to provide the further analysis in MATLAB environment. The plant of ethanol production is shown on Fig.5 and the reletive technological scheme is presented on Fig.6.

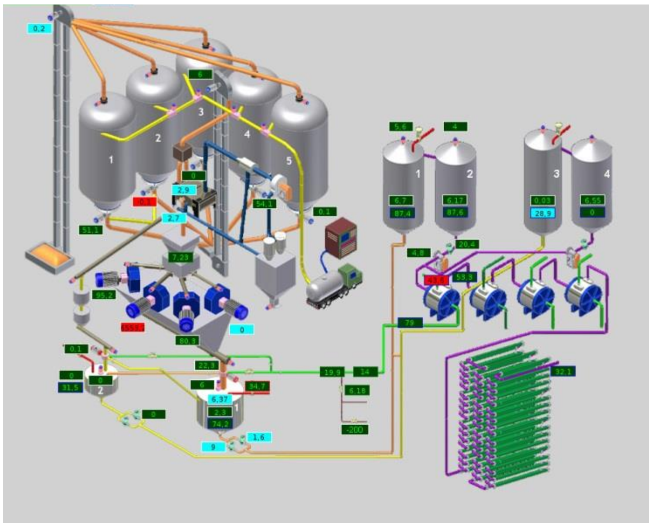

Figure 5: The plant of ethanol production.

Technological process of ethanol production is the following. Dry grain is delivered by road transport to the hopper (1). Next, the grain is fed to the silage farm with a noria (2). From the silos (3), the raw material is fed by a noria (4) through a magnetic separator (5), where metal impurities are removed. Then the grain enters the grain cleaning machine (6), where light garbage, mineral, organic and grain impurities are removed, which are taken to the waste hopper (9) with the help of an aspiration system (fan (7) and cyclone (8). After the grain cleaning machine (6) the grain enters the pre-weighing hopper (10), from there to the automatic scale of continuous action (11). The weighed grain enters the hopper (12), which ensures uniform distribution of grain with the help of screws (13) on screen crushers (14). Crushed grain (grinding) from the crushers enters the hopper

(15). The crushers work with an aspiration system (fan (17) and cyclone (16). From the hopper (15) grinding is carried out by an auger (18), which works with the help of a motor-reducer (19), is fed to the dismembrator (20). Grinding grain is an important stage of its preparation for boiling, since the quality and uniformity of grinding determine the temperature regime of water-heat treatment and the degree of carbohydrate loss at this stage of the technological process. Grinding must be uniform: passage through a sieve with a diameter of 1.0 mm must be at least 95%. Grind is mixed with water in the dismembrator (20). Then the mass enters the mixing bowl (21). Bard filtrate is added to the mixture to adjust the pH of the medium for optimal action of enzyme preparations and yeast growth. The pH of the mixture is maintained within 5.0-6.5. Maintenance of the necessary concentration with a constant supply of grinding is regulated by automatic water supply (hydromodule) depending on the starchiness and moisture content of the grain, the mixture is continuously mixed with a stirrer. The wort concentration is maintained at the level of 15-20 degrees B (according to the hydrometer-sugar meter). The temperature of the mixture is maintained within 30-90 °C by automatic supply of cold water, hot water, bard filtrate and steam to the bubbler. Diluting enzyme preparations (α-amylase and cellulase (when processing rye)) are added to the water fed into the mixing tank (21) by dosing pumps, respectively, in the following amounts: cellulase 0.1-0.4 l/t of conventional starch, a- amylase 0.5-1.4 l/t conventional starch. Next, the mixture is fed by the pump (22) to the department of hydro-enzymatic processing of raw materials.

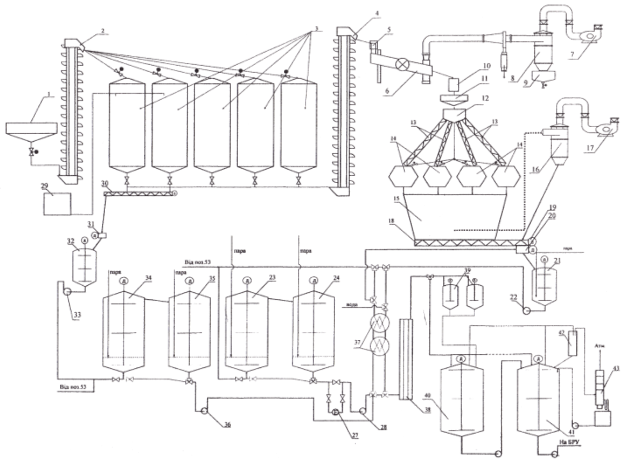

Figure 6. Technological scheme of alcohol production

A flour processing scheme is also provided. Flour is supplied to the silo (3) by a flour truck with the help of a blower (29). Then, the flour enters the auger (30) on the dismembrator (31), where it is mixed with water. Then the mass enters the mixing bowl (32). Bard filtrate is added to the mixture to adjust the pH of the medium for optimal action of enzyme preparations and yeast growth. The pH of the mixture is maintained in the range of 5.0-6.5. Maintenance of the necessary concentration with a constant supply of grinding is regulated by automatic water supply (hydromodule) depending on the starchiness and moisture content of the grain, the mixture is continuously mixed with a stirrer. The wort concentration is maintained at the level of 15-20 degrees B (according to the hydrometer-sugar meter). The temperature of the mixture is maintained within 30-90 °C by automatic supply of cold water, hot water, bard filtrate and steam to the bubbler. Diluting enzyme preparations (α-amylase and cellulase (when processing rye)) are added to the water fed into the mixing tank (32) by dosing pumps, respectively, in the amount: cellulase 0.1-0.4 l/t of conventional starch, a- amylase 0.5-1.4 l/t conventional starch. Next, the mixture is fed by the pump (33) to the department of hydroenzymatic processing of raw materials.

In order to perform an analysis and obtain the real data for the control law simulation as reference values, the experimental testing was conducted and the data analysis was spent (Fig.7,8), from which the reference values of consumption of grain and water were taken, collected transformed, analyzed, converted into appropriate units and then are used for the controller simulation. Using the available MATLAB tools CFTool Data Analyzing we calculate the reference values of the system states according to the given experiments. To do this we use Matlab Curve Fitting Toolbox (CFTool). In order to built the appropriate look-up table for the controller evaluation, series of experiments were conducted. The controller takes the initial and reference values from the preliminary experimental data collected in appropriate look-up table and from this we select the referene values.

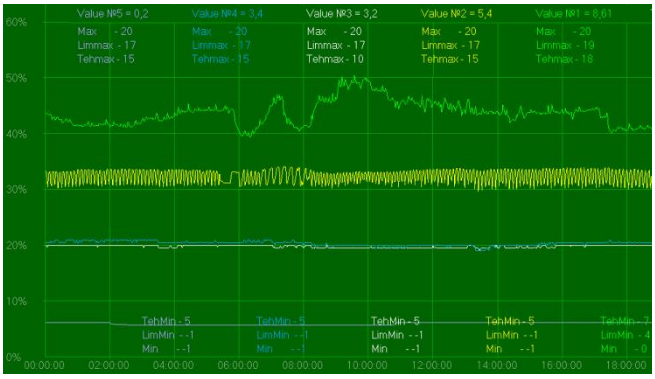

Figure 7. Test experiments: consumption of grain (green color); noria current (toque) 1 (yellow color); grain cleaning machine current (toque) (white color); the current (toque) of the auger of the grain cleaning machine (blue color); noria current (toque) 2 (grey color).

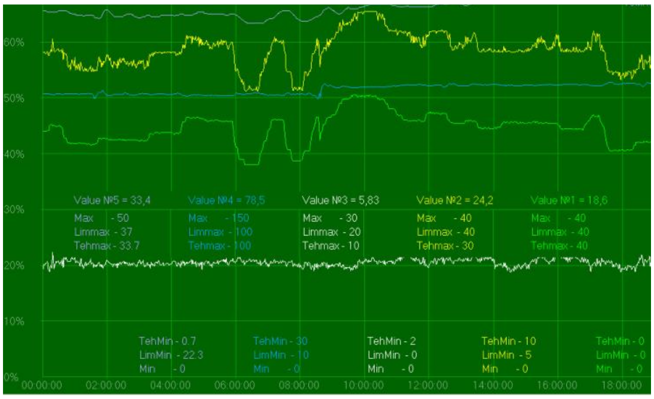

Figure 8: Test experiments: water consumption (green color); hydraulic module (yellow color); consumption of bard filtrate (white color); water temperature (blue color).

We use MATLAB function *ode45* for the system simulation and Control System Toolbox to solve the Riccati equation. With aid of function *care* of MATLAB we compute the solution X of the Riccati equation. Rendering the states and controls to their reference (target) values, we manipulate the weighting matrices R and Q and they can be chosen so as to penalize excessive exertion of control inputs and desire the reference state variables - desired values of volume of liquid in the tank and the mixture concentration respectively.

In order to calculate the estimated values we make fit in curve of the loaded data using the appropriate Curve Fitting Toolbox. We use the polynomials for interpolation and characterize data using a global fit in order to obtain a simple empirical models of each experiments. The main advantages of selected polynomial fit is reasonable flexibility for data that is not too complicated. Analyzing the data-sets of experiments we obtain resulting non-linear models which are polynomials of the degrees 4-6 respectively. The coefficients are calculated with 95 percents of confidence bounds. The goodness of the fits are defined by SSE, R-square, Adjusted R-square, RMSE. Therefore the calculated reference and initial values of the states used in this simulation are following: $\xi_1(t)_{ref} = 1.6$, $\xi_2(t)_{ref} = 1.04$, $\xi_1(t)_{init} = 1$, $\xi_2(t)_{init} = 1$.

Control center evaluates the state after a perturbation and then set the gain matrix parameters. For the set-point $\bar{x} = (1.6; 1.04)$ we compute the several variants of the control gain dependent of the choice of weighting matrices R and Q as shown below. The stabilized trajectories for dynamical system are shown on Fig.9, Fig.10.

Experiment (1). For the weighting matrices

$$Q = \begin{pmatrix} 1 & -0.1 \\ -0.1 & 1 \end{pmatrix}, \ R = \begin{pmatrix} 0{,}001 & 0 \\ 0 & 0{,}001 \end{pmatrix}$$

we obtain the control gain

$$K = \begin{pmatrix} 20.7291 & 18.9720 \\ 23.6260 & -20.3500 \end{pmatrix}$$

The control gain for set-point $\bar{x}_1 = (0; 0; 0.04; 0.18)$ be

$$\bar{u} = \begin{pmatrix} 69{,}9510 \\ 8{,}7245 \end{pmatrix}.$$

The resulting controlled trajectory is shown on the Fig.9, Fig 10 (Solution 1) for current values of volume of liquid in the tank and for the current mixture concentration value.

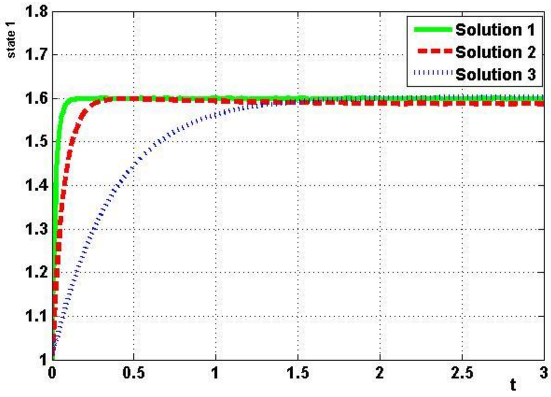

Figure 9. Controlled trajectory (volume of liquid)

Experiment (2). For the weighting matrices

$$Q = \begin{pmatrix} 1 & -0.1 \\ -0.1 & 1 \end{pmatrix}, \ R = \begin{pmatrix} 0{,}01 & 0 \\ 0 & 0{,}01 \end{pmatrix}$$

we obtain the control gain

$$K = \begin{pmatrix} 6{,}5699 & 4{,}5022 \\ 7{,}2862 & -5{,}0084 \end{pmatrix}$$

The control gain for set-point $\bar{x}_1 = (0; 0; 0.04; 0.18)$ be

$$\bar{u} = \begin{pmatrix} 22{,}0593 \\ 2{,}8581 \end{pmatrix}$$

The resulting controlled trajectory is shown on the Fig.9, Fig 10 for current values of volume of liquid in the tank and for the current mixture concentration value.

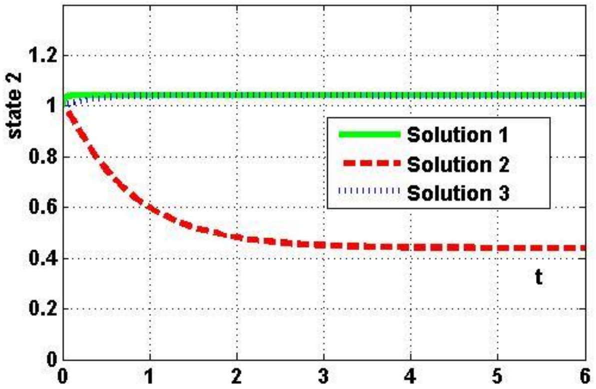

Figure 10. Controlled trajectory: current mixture concentration value

Experiment (3). For the weighting matrices

$$Q = \begin{pmatrix} 1.1 & -0.1 \\ -0{,}1 & 1{,}1 \end{pmatrix}, \ R = \begin{pmatrix} 0{,}3 & 0 \\ 0 & 0{,}3 \end{pmatrix}$$

we obtain the control gain

$$K = \begin{pmatrix} 1{,}2030 & 0{,}2614 \\ 1{,}2532 & -0{,}3443 \end{pmatrix}$$

The control gain for set-point $\bar{x}_1 = (0; 0; 0.04; 0.18)$ be

$$\bar{u} = \begin{pmatrix} 4{,}2598 \\ 0{,}8615 \end{pmatrix}$$

The resulting controlled trajectory simulation result is shown on the Fig.9, Fig 10 (Solution 3) for current values of volume of liquid in the tank and for the current mixture concentration value.

The resulting controlled state variable value volume of liquid in the tank is shown on the Fig.9 (Solution 1-3); state variable mixture concentration on Fig.10 (Solution 1-3). On Fig. 9, Fig. 10 are shown these controlled trajectories rendering to set-point comparing to other experimental tracks. The control gains obtained in simulation experiment (1) are quite well approximates the state behavior, demonstrate fast achievement of desired value, as shown on Fig.9-Fig.10 (Solution 1). The control gain obtained in experiment 3 (Solution 3) provides a well-damped robust control, smooth trajectory degradation. The control gain obtained in experiment (Solution 2) does not satisfy the requirement because there is no precision in achieving the desired value for the second state variable mixture concentration. So, we use it to make other simulations using the set-points obtained from experiments (2)-(3).

Developed control law guarantee that the states of system are finally stabilized and follow to defined above reference values and the estimation error converges to zero as have been shown on Fig.9-Fig.10. Control center evaluates the state after a perturbation and then set the control gain matrix parameters. Inherent properties of the developed LQR-controller are assumed to provide a well-damped and smooth control trajectory that adequately approximates both the desired and actual state behavior. We can see the desired (experimental) states and their good model realization based on LQR-control technic. The control gains obtained in the presented simulation experiments demonstrate graceful trajectory degradation and minimal energy and control efforts.

VI. CONCLUSION

In this paper we have developed the automatic optimal control of the production process of dough mixture preparation, that can be used in the production of alcohol and fuel ethanol from grain raw materials. The developed improved method based on robust stabilization nonlinear process control that will ensure more stable operation of the system, smooth transitions of regimes and economy of used energy, improvement of the quality of the mixture dough, as well as final ethanol product. We can see the desired (experimental) states and their good model realization based on LQR-control technic. The control gains obtained in the presented simulation experiments demonstrate graceful trajectory degradation and minimal energy and control efforts. The optimal operating modes of the installation were investigated using state-space dynamical modelling technic and ethanol production process simulation.

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