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Control model of bread-baking oven under uncertainty

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Abstract
In this research, the control task of thermal processes under uncertainty was discussed by the example of technological process of baked goods. In this paper the complex objects are observed, particularly, the bread-baking oven. The thermal processes apply to the class of the systems with non-linear distributed parameters. The flow chart of bread-baking oven is given and its controlled parameters, control actions external disturbances are enumerated. Also the bread-baking oven description work is represented. The difference between the designed method and the traditional method of control theory is proved. The usage of fuzzy inference methods for the temperature control in the bread-baking oven is well-founded. The problem of temperature control in the bread-baking chamber under uncertainty is given. The parameters of control object are determined by the usage of the fuzzy set theory. The fuzzy model is offered to control the processes in the bread-baking oven. This model is distinguished by the taking into account of quantitative and qualitative information, expert knowledge and a prior uncertainty of bread-baking process. The fuel consumption is the main parameter in the work of bread-baking process. Application of expert knowledge and description of qualitative information can lead to appearance of subjectivity and ambiguity of setting values and also to false work of fuzzy control system. The methods of probability theory are offered to use in order to remove the consequences of inaccurate setting of fuzzy model parameters.

Keywords: thermal processes, bread-baking oven, control, uncertainty, fuzzy set, expert knowledge, updating of knowledge.

Introduction

In the process of solving of the control problem of any object it is necessary to conduct its informal description at the beginning. The work of bread-baking processes is connected with many difficulties. The problem of effective thermal processes control is actual for many production facilities [1-4]. The thermal processes exist in many industrial spheres, for example, in chemical, metallurgical, oil-refining, power, and food industries. In the thermal production the main control objects are ovens, furnaces, kilns, boilers and other facilities.

The thermal processes control is a complex task because there are no adequate mathematical models of combustion action. Also the data of static and dynamic behaviors can be incomplete or insufficient. The thermal processes are characterized by sizable delays and thermal inertia, complexity of object's current state identification, impossibility of smooth changing of fuel consumption and transition to other temperature condition.

The bread-baking process refers to the discussed class of thermal processes [5]. Also the thermal processes refer to the class of the systems with non-linear distributed parameters and represent the complex production facilities. The application of the traditional methods of control theory becomes inefficient for control of the thermal processes, particularly, for bread-baking process.

Control problem

The bread-baking processes are connected with some problems. The main problem is temperature control in the oven. The successful solution of this problem influences on quality and readiness of baked goods. This problem is actual for Russian and foreign researchers [6–10]. The flow chart of bread-baking oven is shown in Figure 1 [11, 12]. The bread-baking process continues permanently after ignition of the oven.

The flues and baking chamber are divided along the oven's length into I - IV zones that are corresponded to the different temperature conditions of baking. The oven has two separate gas contours. The first furnace plant operates zone I, the second furnace plant operates other zones.

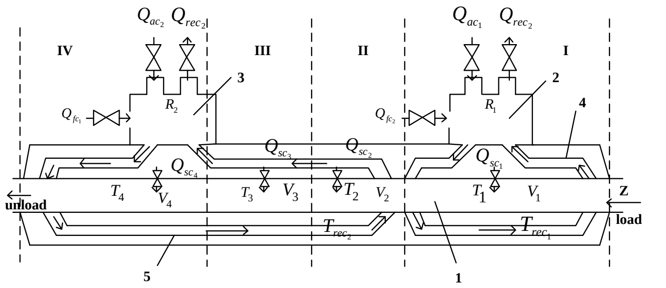
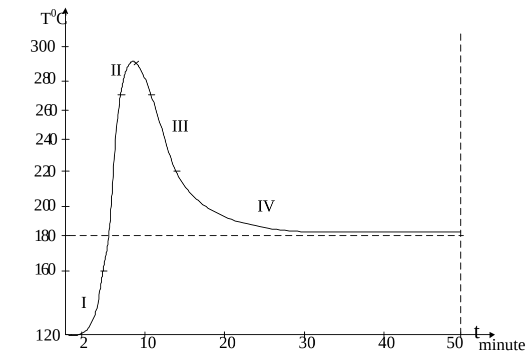


Fig. 1. Flow chart of bread-baking oven. 1 – baking chamber, 2, 3 – furnace plants, 4, 5 – upper and lower flues

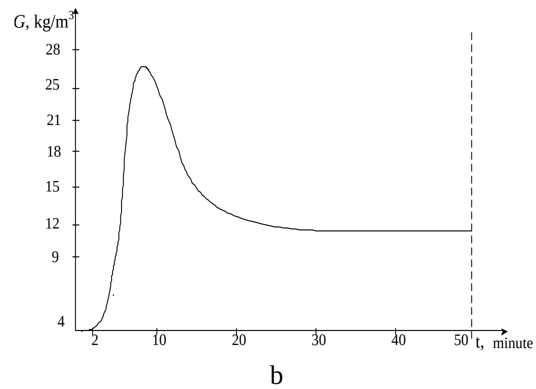
The main controlled parameters of bread-baking process are
$T_1 - T_4$ – temperature of the environment in the oven's zones;
$V_1 - V_4$ – the meaning of moisture in all the oven's zones;
$T_{rec_1} - T_{rec_4}$ – temperature of recirculation gases in all the zones;
Z – the oven load;
R_1 and R_2 – depression in the furnace plants.
The main control actions of bread-baking process are fuel consumption for the first Q_{fc_1} and the second Q_{fc_2} furnace plants;
Q_{ac_1} and Q_{ac_2} – air consumption for the first and the second oven contours;
$Q_{sc_1} - Q_{sc_4}$ – steam consumption in all the zones;
Q_{rec_1} and Q_{rec_2} – consumption of recirculation gases for two furnace plants.
The external disturbances consist in initial temperature of the dough pieces T_0; changing parameters of temperature conditions T_c; changing of baking duration T_d; heat retention of the oven I.
The quality ratings of bread-baking oven's work are determined as bread production of the oven, specific fuel consumption and quantity of spoiled goods.
During the control of bread-baking process the operator regulates such parameters as temperature in the bread-baking chamber, supplied fuel, traverse speed of hearth by the control board. The difficulty of temperature control is connected with the independent work of the operator, his choosing of bread-baking parameters and making decision during the bread-baking process. The formula of goods, oven load, and quality of raw materials can change in the process bread-baking. Therefore the human factor influences greatly on the results of bread-baking oven's work.
Thereby the operator's experience and knowledge are the important factors that ensure the quality of baking process. In the process of automation the operator's experience, knowledge and observations can be determined by the qualitative information and the decision rules.
Fuel consumption influences on the efficiency of baking process control. The value of temperature in the bread-baking chamber and baking duration depend on fuel consumption [13]. The heat dependence plots of bread-baking goods parameters are shown in Figure-2.
The technological bread-baking process consists of four conditions. The experience and observations are shown that for every condition there exist temperature and moisture values [13]:

- temperature of the bread-baking oven in the zone I (moistening zone): 120 - 160°C;
- temperature in the zone II (zone of higher temperature): 270 - 290°C;
- temperature in the zone III (transition zone): 270 - 220°C;
- temperature in the zone IV (zone of finish baking): 220 - 180°C.

It is necessary not only to maintain the given temperature values in consideration of all factors and external disturbances that influence on the production facilities such as bread-baking process but also fulfill the smooth transition from one condition to other [10, 11] **Figure-2**.
The process of temperature control in the bread-baking chamber applies the processes under uncertainty, because information about the process and the results is incomplete.
The process of temperature control in the bread-baking chamber occurs under the constantly changing and partially unknown factors: the formula of goods, quality of raw materials, duration, initial temperature of dough pieces.
Therefore it is necessary to design the control model of named production facility that could take into account a quantitative and qualitative information, expert knowledge and prior uncertainty and finally lead to optimization of the bread-baking process and getting of the required quality parameters.



a



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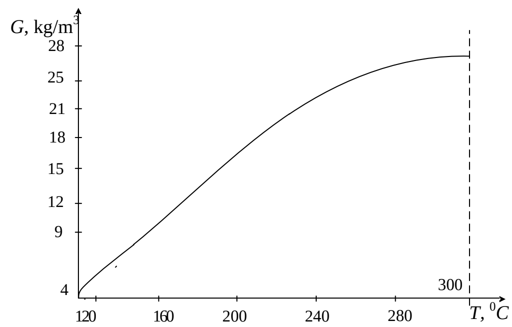

c

Fig. 2. The chart of heath dependence of baking process' parameters. a – the temperature relation to time; b – fuel relation to time; c – fuel relation to temperature

Fuzzy logic and fuzzy set theory [14°–°19] allow us to carry out the identification of parameters' production facility under uncertainty and design the decision model.

2.1 Development of the solution method for the control tasks under uncertainty.

The fuzzy model is understood as an information-logical model of a system that is implemented with the application of fuzzy set theory and fuzzy logic [20]. The opportunity of usage qualitative information and expert knowledge is appeared when the fuzzy logic is used for solving control tasks of production facilities.

The application of fuzzy inference methods for production facilities control under prior uncertainty is considered by the example of temperature control in the bread-baking chamber. The main criteria of the efficient bread-baking process control are rational (optimal) consumption of resources and economical fuel consumption [9, 21].

The factors that influence on the choice of control method are determined as [5]:

- lack of adequate analytical model of baking process that is determined by the bread-baking conditions and features of baking chamber;
- availability of a prior unknown parameters that influence on the work and results of baking process. There are changeable formula of goods, oven load of the varying in the early uncertain ranges, quality of raw materials, temperature deviation from given values, baking duration, initial temperature of the dough pieces in the bread-baking oven;
- qualitative (verbal) information that is gotten by the experts,
- process control on the basis of expert or group of experts knowledge and observations;
- nonstationarity of baking process parameters during the work of the baking chamber.

Any mathematical model establishes relation between input and output parameters of the control object in the steady-state and transient behaviors. In order to develop an automatic control system by the usage of traditional methods of control theory it is necessary to divide the characteristics and parameters of the production facility into parts with stationary and linear indexes, to introduce some simplifying assumptions, to choose the optimal structural elements and compensating elements [11]. All of these actions lead to inadequacy of mathematical model of the control object.

The bread-baking oven in the structural relationship represents a complex non-linear object with distributed parameters and the great number of inherent feedbacks. The simplifying assumptions that are described above are introduced in order to get adequate mathematical model of the oven. The application of these assumptions assumes division of the oven into separate parts, each of them is described as a linear one-capacitive or two- capacitive objects with lumped parameters and their own inputs and outputs [22].

The control model of temperature in the baking chamber on the basis of traditional methods of control theory is described [22]. The mathematical model of kiln dynamics could be represented as an aggregate of three aperiodic links with the following transfer functions.

$$W_T(p) = \frac{K_{11}}{Tp+1}; W_p(p) = \frac{K_{12}}{Tp+1}; W_{Tp}(p) = \frac{K_{13}}{Tp+1}, \qquad (1)$$

Where

$W_T(p)$ –transfer function of kiln by the channels "fuel consumption – temperature of combustion products";

$W_p(p)$ – transfer function of kiln by the channels "consumption of recirculation gases that are come in the kiln – temperature of combustion products";

$W_{Tp}(p)$ – transfer function of kiln by the channels "temperature of recirculation gases – temperature of combustion products".

The constants T and gain K could be determined by the well-known methods and techniques of the control theory such as breakdown characteristics, structured tool and heat engineering data.

Equivalent transfer function of n-zonal oven with draw-through heating and controlled parameter – temperature of i-zonal baking chamber by the disturbance of channel gas consumption has the following view.

$$W_{eq_i}(p) = \frac{\Delta\Theta_{T_i}(p)}{\Delta B_F(p)} = \frac{W_{T_i}\left[W_F + W_{Tp}\sum_{i=1}^{n}(W'_{h_i} + W''_{l_i})\right]}{1 + W_{Tp}\sum_{i=1}^{n}(W'_{h_i} - W_{Tp})\sum_{i=1}^{n}W_{T_i}(W_{h_i} + W_{l_i})}, \qquad (2)$$

where

$\Delta\Theta_{T_i}$ – temperature deviation in the i-zone of the oven;

ΔB_F – deviation of fuel consumption that comes in the kiln;

W_{T_p} – transfer function of the kiln by the temperature of recirculation gases $\Delta\Theta_{rec}$;

W_F – transfer function of the kiln by the ΔB_F;

$W_{h_i}, W'_{h_i}, W''_{h_i}$ – transfer functions in the i-zone of upper flues by the disturbances of $\Delta\Theta_{ch}$, ΔB_F, $\Delta\Theta_{ps}$;

$W_{l_i}, W'_{l_i}, W''_{l_i}$ – transfer functions in the i-zone of lower flues by the disturbances of $\Delta\Theta_{ch}$, ΔB_F, $\Delta\Theta_{ps}$

$W_{n_i}, W_{T_i}, W_{hl_i}$ – transfer functions in the i-zone of the bread-baking chamber by the disturbances of ΔG_{st}, ΔG_{ps}, ΔG_{hl};

$n = \overline{1;4}$ – the number of oven zones.

This control model of temperature in the baking chamber is based on the usage of automatic control theory. In the automatic control systems the process of control is fulfilled by the disturbance. It makes measurements and temperature control in the more characteristic points of different oven zones. Temperature deviation of current values from given values is measured by the usage of sensors in order to providing of automatic control system work. Updating of fuel consumption is carried out when necessary.

The control object is the object with distributed parameters it is represented as aggregation of simpler objects with lumped parameters. Therefore temperature control is fulfilled on the basis of usage of several controllers for each oven zone. Finally, the control system on the basis of the traditional methods is represented as automatic control system with the some unconnected control channels.

Though, the representation of the production facility of temperature control using only deviation is not efficient enough. The influence of external disturbances on the production facility and different kinds of uncertainties are not taken into account in the control model. All of those factors lead to the nonoptimal results of the control process. Therefore it is necessary to apply another approach that bases on such methods and algorithms that provide the finding of efficient solution of the problem of temperature control in the bread-baking chamber under uncertainty.

In summary, the analysis of the disadvantages of the existing traditional analytical models allows us to ground the usage of fuzzy inference methods and development of fuzzy models for the temperature control in the bread-baking chamber. The application of fuzzy inference methods for the described problem of the temperature control in the bread-baking chamber helps to solve the following tasks:

- design of multimode control model of temperature for the baking process, that could be applied in all the zones of the oven at the same time;
- efficient fuel consumption;
- taking into account of external disturbances such as oven load, changing of the formula, quality of raw materials, initial temperature of the dough pieces;
- taking into account of expert knowledge, observation of the operator, qualitative information;
- taking into account of a prior uncertainty, inauthenticity and incompleteness of production control object information and its environment.

Thereby, the application of the fuzzy inference methods allows us to develop a sufficiently full and an adequate control model of production facility by the example of the fuzzy model of temperature control in the bread-baking oven that takes into account a prior uncertainty and qualitative information.

Below the features of designing and application of fuzzy model of temperature control in the bread-baking process under uncertainty are described.

2.2 Setting and updating of fuzzy model parameters.

The fuzzy inference model allows us to design the effective control system of production facilities without determination of mathematical model of analytical view.

Fuzzy logic is an effective description tool of complex production facilities that uses means of natural language. Fuzzy logic doesn't require the accurate number crunching and prior setting parameters of the described object [23]. Fuzzy logic incorporates the qualitative and numerical approaches of decision making [24]. However the usage of expert judgments and qualitative information in the design process of fuzzy model can lead to appearance of subjectivity and ambiguity of the setting values [25, 34].

The errors of experts can't be excluded in the process of control system designing and its work. There errors lead to inaccurate setting of the fuzzy model parameters that bring to decreasing of the developed system efficiency, increasing of outputs deviation from given values and getting of ambiguous results. Also the decreasing of the developed system efficiency can be represented as inadequate decision-making. In the result the described control system can't allow us to get the goods of the required quality.

Therefore the analysis of fuzzy inference stages are hard to fulfill, because the fuzzy model bases on fuzzy-set theory and means of fuzzy logic. The analysis of fuzzy knowledge is impossible. Only by getting of output parameters of the system it could be judged about the model results. The analysis of output parameters is possible after the stage of defuzzification and getting crisp numerical values. It is necessary to take into account that the errors could be done in the process of the setting parameters during the development of fuzzy inference model. The fuzzy model could be represented as a graph in Figure 3 [26, 33]. In Figure 3 the following notions are used:

$X = \langle X_{11}, X_{12}, \ldots, X_{1f}, \ldots, X_{i1}, \ldots, X_{ij} \rangle$ – fuzzy set of the input variables;

$\mu_{x_{11}}, \mu_{x_{12}}, \ldots, \mu_{x_{1f}}, \ldots, \mu_{x_{i1}}, \ldots, \mu_{x_{ij}}$ – membership functions (MF) of the input variables;

$Y = \langle Y_{11}, Y_{12}, \ldots, Y_{1t}, \ldots, Y_{k1}, \ldots, Y_{ks} \rangle$ – fuzzy set of the output variables;

$P_z = \langle P_1, P_2, \ldots, P_z \rangle$ – set of the fuzzy rules;

$\mu_{y_{11}}, \mu_{y_{12}}, \ldots, \mu_{y_{1f}}, \ldots, \mu_{y_{i1}}, \ldots, \mu_{y_{ij}}$ – MF of the output variables.

The structure of fuzzy model graph shows that some stages of fuzzy model design base on expert judgment, on the one hand, and state of production control object, on the other hand. The state of control object is characterized by parameters of control.

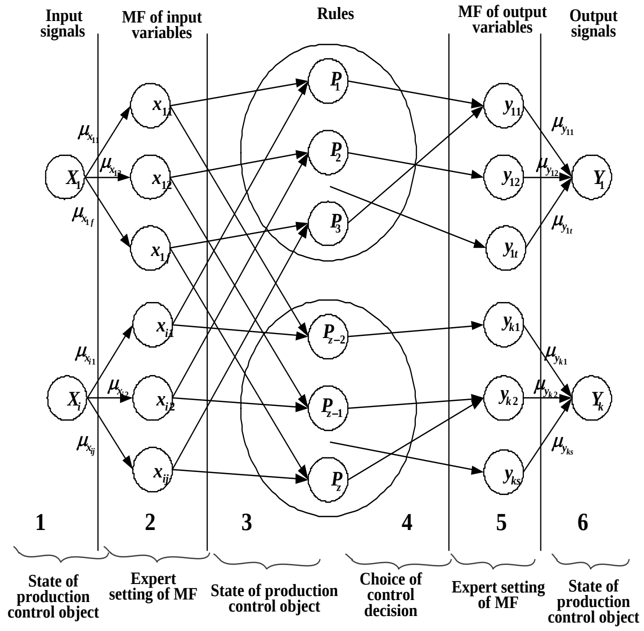

Fig.3. Graph of fuzzy model.

The expert uses his/her or group experience and observations, when he/she or group develop the rule base (stages 3, 4) and set the MF (stages 2, 5). Every expert can have his/her own point of view about qualitative characteristics of production facility parameters. There are no standard authentic means of expert knowledge [27]. Therefore, the fuzzy model can have subjective nature. Inaccurate set of fuzzy model's parameters can lead to nonoptimal solution and deviation of getting results from required values.

Therefore, to solve the control problems of production facilities under uncertainty fuzzy logic and fuzzy inference should be applied together with other methods in order to provide the optimal results.

On the one hand, fuzzy inference methods are the effective means that are used by experts in the process of uncertainty description and qualitative information determination by the development of control systems. On the other hand, by the design of fuzzy model the opportunity of the expert errors or inaccurate setting of parameters values can't be excluded, that can lead to decrease of given control ratings. It is necessary to develop and use the methods of expert knowledge estimation and updating in order to eliminate the possible inaccurate set of fuzzy model parameters.

The work of production facilities requires quick decision making. It is necessary to develop an updating algorithm of expert knowledge that provides the adequacy of fuzzy model parameters and given accuracy of results for the short time.

The updating of fuzzy model parameters appears after estimation of results if the getting values don't correspond to given ratings. The metaheuristic and probabilistic methods are considered for solving this problem [28 – 30].

The base of metaheuristic methods is proximity to nature, biological, chemical and physical processes. The main point of the metaheuristic method consists in search of optimal solution on the given value area. The optimal solution corresponds to given fitness function. The consecutive examination of options is fulfilled, until the getting solution will satisfy fitness function.

However, the metaheuristic methods require the great computational and time resources and also can lead only to approximate solution. In order to eliminate these defects the probabilistic methods are offered to apply. Fuzziness and probability are similar notions [31] that describe uncertainty from different points [20]. The distinction between their conceptions bases on different nature: fuzziness is subjective notion and probability is objective notion.

The main advantages of probabilistic methods over other optimization methods of setting of fuzzy model parameters are the following [32]: - well elaborated mathematical tool, accuracy of computations and received results;

- taking into account probabilistic uncertainty of data;
- search of global extremum;
- transparence of actions;
- getting of optimal values for few number of iterations;
- little computational and time resources.

Conclusion

The paper offers the programmatic decision of the quality measurement improvement both of a parameter, amplitude, and signal phase. The offered algorithm is investigated both on the theoretical model of a signal, and according to its practical application. The paper has shown that the offered algorithm gives the best results without a considerable delay of results measurement. Also the offered algorithm has much the best results in the presence of harmonic components in comparison with other algorithms.

In this paper, the production facilities, particularly the thermal processes that operate under uncertainty are described as control objects. This control problem is solved by the example of the development of the model of temperature control in the bread-baking oven.

After the examination of the thermal processes by the example of temperature control in the bread-baking chamber, it becomes possible to name the features of this production facility. They are: lack of common mathematical model of baking process, heat retention of the oven, influence of external disturbances, information lag about control object state, qualitative characteristics of unknown parameters. In this paper all the named disturbances and factors cause the existence of a prior uncertainty.

In order to control the production facilities under uncertainty it is necessary to choose the adequate method of control. The traditional methods of control theory and methods of artificial intelligence were described and compared. The conclusion is made that application of the traditional methods under uncertainty can lead to inefficient solutions and results. The methods of artificial intelligence, such as fuzzy inference method should be applied.

Application of fuzzy inference methods for the temperature control in the bread-baking chamber allow to solve the following problems: design of multimode control model of temperature for the baking process without authentication of production facility; efficient energy consumption, taking into account the external disturbances and uncertainty. The

solution of these problems allows us to supply the optimal control process and increase the values of quality ratings.
The subjectivity of fuzzy model parameters set requires the estimation results of fuzzy control model of production facilities and if it is necessary to carry out the updating of its parameters.
In this paper, the conclusion is made that application of updating probabilistic method of fuzzy model parameters is more efficient than metaheuristic methods. The methods of probability theory allow us to develop the updating probabilistic algorithm and fulfill the correction of expert knowledge by using of the fuzzy model parameters.

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