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Mathematical model of biopower fluidizer for autonomous energy provision at agricultural enterprises

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Abstract. The device developed by a mathematical model is intended for a bioenergy plant for alternative energy and gas production. The main goal is to optimize energy parameter settings. The reason is an urgent need for energy provision through alternative methods of electricity production and processing of biomass at high quality biofertilizers. The mathematical models of the unit used will improve the existing methods to calculate technological and design parameters of bioreactors and power equipment for the production of biofertilizers, energy biogas, and electricity.

Key words: Bioenergy plant, alternative renewable energy sources, energy complex, biochemical conversion, component installation, gas-turbine electric station, gas-piston electric station.

INTRODUCTION

A power complex (PWC) from new (non-traditional) and renewable power sources (NTRPS) is a complex computerized system that has many properties of a substandard system in terms of distribution of the structure. It enables multiple measurements and indefinite parameters to be done and the state and operating conditions of the complex to be defined. Such systems may be designed in the conditions where aims are not specifically defined and restricted, data are not specific and undefined, and, in addition, where there is an unspecified priority setting for the definite criteria (Kini & Raifa, 1981).

In this investigation methods of probability are required because of the undefined events and the processes featured by statistical stability and subordinated to the laws of probability. However, a number of power supply system parameters have no fixed values and only probable descriptions (change of loads, reliability indices, losses of the national economy).

Power supply systems from NTRPS are characterized by a number of features and properties, reflecting an interaction of elements with external and internal ties, a considerable part of which are not subject to the current monetary calculation, but rather to the quantitative calculation of the raw material. It follows that PWCs from NTRPS are multi-purpose by nature, and their optimization must be performed with the totality of the effectiveness criteria under the task of decision making which involves numerous criteria, application of special mathematical methods, considering the specific character of the task, i.e. the joint application of the theory of undefined sets, expert appraisals and vector optimization (Kini & Raifa, 1981).

Thus, investigation and optimization of the PWC using the totality of the NTRPS of different nature is a complex problem because of the indefinite outgoing information to be calculated and its ability for multiple criteria. The immediate investigation of such systems in a full-scale study involves considerable difficulties and material expenditure. Therefore, to study the PWC and the processes involved, modelling is required to take into account the multitude of alternative variants for the perfection of the decision making procedure and for the prediction of their consequences more precisely.

ANALYSIS OF RECENT RESEARCH

Physical, mathematical and hybrid models may be applied when investigating and optimizing a PWC. A physical model of a PWC is an analogue model, where there is definite correlation between the parameters of the object and the model (Venikov, 1976). In such a case, the physical equivalents reproducing the structure, main properties, and correlation of the study object correspond to the system elements. At physical modelling, which is based on the similarity theory, the peculiarities of the specific performance of the experiment are preserved, observing an optimal range of changes in the relevant physical parameters.

The mathematical model of the PWC (Sovetov & Yakovlev, 1985) is a system of mathematical correlations describing the object under study. The processes of power provision from the sources of its transformation in the generators and energy consumption by load correspond to mathematical equivalents, possessing input and output parameters, providing synthesis of the system into the mathematical model. In case there are no analytical ways to describe the model or in case they are inconvenient, imitation modelling is used (Shennon, 1978), i.e. numeric experiments are performed on the computing device (PC) with a mathematical model describing the behavior of the system within the periods of time of the set duration. The analysis and optimization of the PWC are provided by numeric experiments on the PC, describing the functioning of system. At the same time, one of the most important characteristics of the mathematical model of the PWC is the degree of its adequacy to the real procedures, which in the conditions of high uncertainty of the outgoing information demands detailed experimental investigations to be conducted. Hybrid models are used for this purpose at a restricted possibility of conducting natural experiments on the PWC.

Hybrid model of the PWC (Simankov at al., 1987) is a model connecting mathematical and physical equivalents of the PWC elements by means of the PC and the connection device in a unified modelling contour. Such a union permits creation of a more flexible modeling system, connecting advantages of both methods. In a number of cases, when the PWC elements do not have an adequate mathematical and physical equivalent, real objects may be included in the closed contour of modelling to investigate the system as a whole. At the same time a really functioning PWC may be supplemented with a mathematical or physical equivalent of objects the creation of which is only anticipated.

MATERIALS AND METHODS OF RESEARCH

The main purpose is to optimize energetic indices. The reason is the urgent problem to save the power supply in the production, using an alternative method and processing of biological mass for high quality biological fertilizers. The mathematical model of a power unit enables us to improve the existing calculation methods of technological and constructive parameters of the biological generator and power generating equipment used for the production of biological fertilizers, energetic biological gas and power supply.

RESULTS AND DISCUSSION

Description of the biogas power unit shown in Fig. 1.

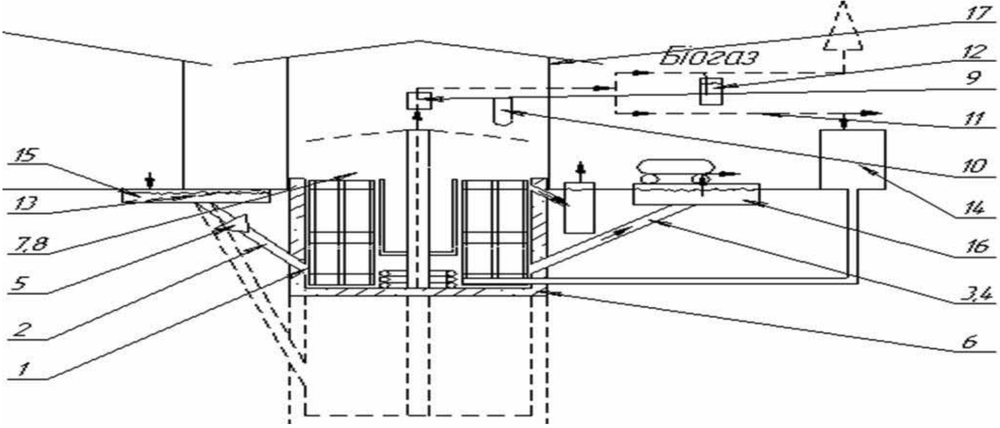

Figure 1. Scheme of biogas power unit: 1) biological reactor; 2) loader; 3) loading pipe; 4) hydraulic valve; 5) mixing unit; 6) heat exchanger; 7) gas exchanging units; 8) heater; 9) geno-moisture exchanger; 10) preventing-reduction device; 11) mains; 12) measuring device; 13) grating; 14) gas water heater; 15) receiver; 16) capacity of fermenting mass; 17) frame.

Processes of biochemical transformation in the biogas power unit

Methane fermentation or biomethan genesis is a well known process of converting organic agents into energy under anaerobic conditions by bacterial flora. It was discovered in 1776 by Volta who determined the presence of methane in marsh gas. Biogas, which is formed during biomethan genesis, is a mixture of 50...80% methane, 20...50% carbon dioxide, up to 1% hydrogen sulphide, minor amounts of nitrogen, oxygen, hydrogen, ammonia, and nitrous oxide emissions.

Anaerobic conversion of almost any biomass to methane occurs in three successive phases. In the first stage of the anaerobic fermentation of organic agents by biochemical decomposition (hydrolysis), a high decomposition of high-molecular formations (carbohydrates, fats, proteins) into low-molecular organic compounds initially occurs. In the second stage, with the participation of acid forming bacteria, further expansion with the formation of organic acids and their salts, and also alcohols, CO_2 and H_2, and then H_2S and NH_3 occurs. Final bacterial conversion of organic agents into CO_2 and CH_4 happens in the third stage of the process (methane fermentation) and an additional amount of CH_4 and H_2O (Table 1) is formed from CO_2 and H_2.

These reactions occur simultaneously, and the bacteria that make methane impose much higher demands on their existence conditions than the bacteria that form acid. For example, they require completely anaerobic environment and require longer time for reproduction. This whole complex set of transformations is provided by many microorganisms, by some estimates up to thousands of species. The speed and extent of anaerobic fermentation by the creation of methane bacteria depends on their metabolic activity.

Table 1. Steps in the process of anaerobic fermentation.

Stage I **Hydrolysis**	Stage II **Formation of acids**	Stage III **Formation of methane**
Main components: **Fat** – *highly molecular fat acids, glycerite of starch* **Protein** – *amino acids, low molecular peptides* **Polysaccharides** – *monosaccharides, disaccharides*	Bacteria reproduction **Bacterial forming acids** *flying fat acids, spirit, aldehydes, ketones, ammonia, carbon dioxide, hydrogen, water*	Bacteria reproduction **Bacterial forming methane** *methane, carbon dioxide, hydrogen, hydrogen sulphide, water*

Modelling of a gas power unit

Hybrid models can be distinguished according to the modelling time scale and its impact on the model. In the first case the models fall into patterns which operate in real conditions, and the models that allow use in any technical realization time regimes. In the second case, the interaction of different parts of hybrid models is considered. If the mathematical equivalent of the model can change the state of the physical equivalent, the model will be considered as active. If the mathematical equivalent is changed under the influence of external conditions only, or the physical equivalent, the model is considered as passive.

The general algorithm for solving the problem of energy system design from NTRPS objects consists of the following basic steps:

a) formation of an alternative set of optimal variants of systems for alternative energy systems by different levels of autonomous subsystems of power and heat supply facilities the use of fuzzy set theory (previous sub-stages optimization);

b) selection of a rational design solution of a set of alternative variants using the reproduction cost concept (sub-stages of the final optimization).

The algorithm for rational technical solutions in the preliminary stages of optimization depending on the importance of performance criteria includes the comparison of alternatives using a generalized preference relation by unbalanced criteria and through maximal combining areas of maximal non-predominance of design alternatives by equivalent criteria.

The algorithm of the phase of the previous power supply system optimization with NTRPS consists of the following sequence of procedures: (Simankov at al., 1998)

- construction of fuzzy relations of weak variant preference on each performance index;

- identification of a fuzzy subset of non-predominance options by fixed performance criteria;
- construction of the matrix of induced fuzzy relation benefits on the set of initial options at all considered performance indices;
- finding the corresponding induced fuzzy subset of non-dominant variants of design solutions;
- selection of the most efficient design solution for the considered levels of autonomy systems of electricity and heat supply, and formation of alternatives for further improvement.

Fuzzy relations benefits of weak predominance in the class of fuzzy efficiency criteria are constructed by the following expression (Orlovskyy, 1981):

$$Y(a_i, a_j, p) = \sup_{\substack{z, y \in R^1 \\ z \le y}} \min \left\{ Y(a_i, z), Y(a_j, y) \right\}, \tag{1}$$

where *Y(a_i, z), Y(a_j, y)* – unclear descriptions of criteria performance values *p*, respectively for the *i*-th and *j*-th option.

The algorithm enables us to determine the fuzzy relation of weak domination of design variants by stepwise and piecewise-linear fuzzy description of performance criteria, as well as a direct assignment matrix of an add ratio of weak benefits.

To determine the performance criteria, the relation of the quality of the variants of such technical solutions is determined by normalizing them to the minimal value:

$$Y(a_i, a_j, p) = \begin{cases} 1, IF\ f_i(a_i) \le f_i(a_j); \\ f_i(a_j) \big/ f_i(a_i), IF\ f_i(a_i) > f_i(a_j) \end{cases}, \tag{2}$$

where $f_i(a_i)$, $f_i(a_j)$ – determined performance criteria by the value *p* according to the *i*-th and *j*-th option. The fuzzy relation of weak advantages obtained allows the subset of non-dominant alternatives of the considered efficiency criteria to be selected in the multiple options:

$$\underset{i=1,\dots,n}{Y^{H\partial}}(a_i, p) = \inf_{a_i \in A} [1 - Y^S(a_j, a_i, p)] = 1 - \sup Y^S(a_j, a_i, p)\ . \tag{3}$$

Matrices of the fuzzy relation of strong advantages have the form

$$\underset{\substack{i=1,\dots,n \\ j=1,\dots,n}}{Y^S(a_j, a_i, p)} = \begin{cases} Y(a_j, a_i, p) - Y(a_i, a_j, p), IF\, Y(a_j, a_i, p) \ge Y(a_i, a_j, p); \\ 0, IF\, Y(a_j, a_i, p) < Y(a_i, a_j, p) \end{cases}. \tag{4}$$

When choosing a design decision on one performance, the most rational option is the one at the highest value of $Y^{H\partial}(a_i, p)$. As the variants of the power supply system will be compared on several grounds, the weak ratio of a fuzzy advantage of two alternatives on the whole performance criteria has to be found.

The matrix of the induced fuzzy relation of the advantage over the set of considered options by many parameters is determined by the following expression:

$$\eta\left(a_i, a_j\right) = \sup\min\left\{Y^{H\partial}\left(a_i, p\right), Y^{H\partial}\left(a_j, p\right), M\left(p, p\right)\right\}. \tag{5}$$

The most efficient design option (or some restriction of subset variants) of the power supply system selected at the considered level of autonomy is justified at the adjusted set of non-domination:

$$\begin{gathered}
\underset{i=1,\dots,n}{\tilde{\eta}^{H\partial}(a_i)} = 1 - \sup_{a_j\in A}\eta^{3}(a_j, a_i) = 1 - \sup_{a_j\in A}[\eta(a_j, a_i) - \eta(a_i, a_j)]; \\
\eta^{H\partial} = \bigcap[\tilde{\eta}^{H\partial}(a_i), \eta(a_i, a_j)] = \min\left\{\tilde{\eta}^{H\partial}(a_i), \eta(a_i, a_j)\right\} . \\
A^{*} \Rightarrow \max_{a_i\in A^{H\partial}}\eta^{H\partial}(a_i) .
\end{gathered} \tag{6}$$

Equivalence selection of the criteria of the rational option is conducted on the basis of the maximal areas of non-domination under efficiency criteria.

$$A^{*} \Rightarrow \max\left\{\min\begin{bmatrix} Y^{H\partial}\left(a_1, p_1\right), \\ Y^{H\partial}\left(a_1, p_2\right), \dots \\ \dots, Y^{H\partial}\left(a_1, p_s\right) \end{bmatrix}, \dots, \min\begin{bmatrix} Y^{H\partial}\left(a_n, p_1\right), \\ Y^{H\partial}\left(a_n, p_2\right), \dots \\ \dots, Y^{H\partial}\left(a_n, p_s\right) \end{bmatrix}\right\}. \tag{7}$$

As a result of multiple run of the procedures in the stage of prior optimization at different levels of autonomy in power and heat supply systems, many alternative design solutions are formed. Further, the most promising and economically feasible alternative energy supply system is selected by minimizing the criterion of reduced total costs that includes losses of incomplete energy delivery, environmental effects of traditional energy source use, resultant costs of the centralized energy supply system and a positive additional effect of the use of bioenergy plants (receiving high-quality fertilizers, providing environmental cleanliness, etc.) and a vapor-hydrothermal heating supply system.

In general, at different levels of energy supply system autonomy, total energy costs are determined by the following expression:

$$\begin{gathered}
\text{Ç} = \mathring{A}_{\text{Í}} * \hat{E} + \hat{I} + \left(\frac{1-\gamma_{E}}{\gamma_{E\text{Ð}}}\right) * \hat{A}_{E} * \ddot{I}_{\mathring{A}} + \left(\frac{1-\gamma_{\text{Ò}}}{\gamma_{\text{ÒÐ}}}\right) * \hat{A}_{\text{Ò}}\ddot{I}_{\text{Ò}} + \ddot{I}_{0}\Delta W + \mathring{A}_{\text{Í}}\hat{E}_{\text{Ñ}} + \hat{I}_{\text{Ñ}} + \\
+ \ddot{I}_{0\text{Ñ}}\Delta W_{C} + \left(\frac{1-\gamma_{\text{Ò}}}{\gamma_{\text{ÒÐ}}}\right) * \hat{A}_{\text{Ò}} * (\ddot{I}_{\text{ÅØ Â}} * \hat{E}_{\text{ÂÂ}} + \ddot{I}_{\text{ÅØ Í}} * \hat{E}_{\text{ÂÍ}} + \ddot{I}_{\text{ÅØ Ã}} * \hat{E}_{\text{ÂÃ}}) - \mathring{A}_{\text{Ï ÃÒ}} - \mathring{A}_{\text{Á²Î}}
\end{gathered}, \tag{8}$$

where E_H – the normative coefficient of the efficiency of capital investments;
K, O – capital investments and operating costs of the energy supply system with NTRPS;

K_C, O_C – capital investments and operating costs of the system of centralized energy supply of the agricultural object;
B_E, B_T – replaced annual electricity and heat consumption of the object:

$$\hat{A}_{\AA} = 0.123*10^{-3}*\frac{\gamma_{\AA}}{\eta_{\AA}}*\tilde{N}_{\AA} \quad , \quad \hat{A}_{\grave{O}} = 0.143*\frac{\gamma_{\grave{O}}}{\eta_{\grave{O}}}*\tilde{N}_{\grave{O}}, \tag{9}$$

where C_E, C_T – annual electricity consumption (in kW/hour) and annual heat consumption of the object (Gcal);
γ_E, γ_T – coefficients of autonomy of electricity and heat supply systems;
γ_{EP}, γ_{TP} – transformed coefficients of autonomy for determining the total final cost of the basic variant with the use of centralized power and heat supply system;
Π_E, Π_T – specific final costs in the centralized power and heat supply system;
Π_0, Π_{0C} – specific loss of incomplete energy delivery respectively in the local (on NTRPS) and centralized power energy supply systems.

ΔW, ΔW_C – incomplete energy delivery respectively in the systems of local and centralized power energy supply systems due to crashes and scheduled outages:

$$\Delta W = \left(\tilde{N}_{\AA} + \hat{E}_{\ddot{I}} * \tilde{N}_{\grave{O}}\right)\pi_{\acute{I}} \ , \tag{10}$$

where K_Π – correction factor;
π_H – relative insecurity of energy;
$\Pi_{ЕШВ}$, $\Pi_{ЕШН}$, $\Pi_{ЕШГ}$ – specific environmental loss from the use of traditional fuels (coal, black oil, natural gas);
K_{BB}, K_{BH}, $K_{BГ}$ – coefficients of coal, black oil, and natural gas use in the centralized energy supply system;
$E_{ПГТ}$, $E_{БІО}$ – annual positive effect acquired by the use of steam-hydro-thermal heating systems and bio-energy plants.

To take the final decision many alternatives are complemented by the basic version of the power system of the object from the centralized energy and heat supply.

The best system of the energy supply system is the variant that provides

$$A_0^* \Rightarrow \min_{a_i^* \in A_0^*} 3(a_i^*) , \tag{11}$$

where A_0* – set of alternative promising energy supply options, including the basic version.

CONCLUSIONS

The paper proposes a methodology for problem solving and multi-criteria optimization of PWC with NTRPS different nature with the uncertainty of initial information. A general algorithm for solving the problem of designing power supply systems with NTRPS is shown, as well as the mathematical model of the choice of management options using fuzzy sets theory. Last years have seen increased interest in biological gas production. It is revealed both in the growing number of planned and constructed biogas units and in increased figures by farmers, communal utilities, enterprises, politicians, and private enterprises who closely follow the developments in this sector. However, in the power sector inadequate attention is paid to the decentralization of production due to the construction of biogas units. The technology of biogas production enables organic wastes and residues of food products to be utilized cheaper in biogas units, which is useful to agriculture, food industry, gastronomy, large restaurants, public catering, and food waste processing plants. Furthermore, this technology holds numerous adherents among people who are personally convinced in its usefulness for the environment. Constantly increasing consumer power costs have promoted the set up of biogas industry during the last twenty years. Biological gas has changed from an alternative source of energy into a regular source for many enterprises all over the world.

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