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SYSTEM ANALYSIS OF SCALING PROBLEMS WHILE BIOGAS PLANTS DESIGN IN THE CONTEXT OF ENERGY

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Abstract. The literature review indicates that the design of environmentally friendly biogas plants is associated with solving scaling-up problems that account for biogas production, purification, and upgrading processes. Many existing models of membrane gas separation lack a unified character and require adaptation to specific membrane types and gas mixture compositions. In this regard, the development of a generalized model structure suitable for describing separation processes while considering purification features remains a relevant task. From the standpoint of environmental and energy efficiency, there is a need to develop effective solutions aimed at improving productivity and system sustainability. The paper is devoted to a systems analysis of biogas plant design, with particular emphasis on scaling-up issues and their influence on the energy and environmental performance of the plant. The main levels of problems arising in the design of biogas plants are formulated,

taking into account the combined impact of biogas production and purification units on the overall efficiency and environmental performance of the technological process. Key factors determining the efficiency of biogas production and purification are identified, and the features of their manifestation during the transition to large-scale systems are analyzed. Systems analysis is used to determine approaches for increasing separation efficiency, improving final product quality, and developing biogas plants with higher specific productivity under a moderate increase in energy consumption, contributing to the reduction of methane emissions. The feasibility of applying two-stage purification schemes in membrane systems and column apparatuses is demonstrated in terms of energy efficiency and environmental safety. It is concluded that the scaling-up problem requires a comprehensive approach, including mathematical modeling and process control optimization, particularly under significant variability in feedstock composition and properties, to ensure the economic, energy, and environmental efficiency of biogas plants.

Key words: system analysis, biogas plant, design, scaling

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ЭНЕРГЕТИКА КОНТЕКСТІНДЕГІ БИОГАЗ ҚОНДЫРҒЫЛАРЫН МАСШТАБТАУ МӘСЕЛЕЛЕРІН ЖҮЙЕЛІ ТАЛДАУ

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Аннотация. Әдебиеттерге талдау экологиялық тұрғыдан таза биогаз қондырғыларын жобалау биогаз өндіру, оны тазарту және кондицияланған күйге жеткізу процестерін ескеретін ауқымдандыру мәселелерін шешумен байланысты екенін көрсетеді. Газдарды мембраналық бөлуге арналған көптеген қолданыстағы модельдер әмбебап сипатқа ие емес және нақты мембрана түрлеріне әрі газ қоспаларының құрамына бейімдеуді талап етеді. Осыған байланысты тазалау процесінің ерекшеліктерін ескере отырып, бөлу процестерін сипаттауға жарамды жалпыланған модель құрылымын әзірлеу өзекті болып табылады. Экологиялық және энергетикалық тиімділік тұрғысынан жүйенің өнімділігі мен орнықтылығын арттыруға бағытталған тиімді шешімдерді әзірлеу қажеттілігі туындайды. Мақала биогаз қондырғыларын жобалау мәселесін жүйелік талдауға арналған және ауқымдандырудың қондырғының энергетикалық және экологиялық сипаттамаларына әсеріне ерекше назар аударылады. Биогаз қондырғыларын жобалау кезінде туындайтын негізгі мәселелер деңгейлері биогаз өндіру мен тазалау процестерінің технологиялық процестің жалпы тиімділігі мен экологиялық қауіпсіздігіне бірлескен әсерін ескере отырып айқындалды. Биогаз өндіру мен тазалаудың тиімділігін айқындайтын негізгі факторлар анықталып, ірі ауқымды жүйелерге көшу кезіндегі олардың көрініс беру ерекшеліктері талданды. Жүйелік талдау бөлу дәрежесін арттыру, соңғы өнімнің сапасын жақсарту және энергия шығындарының қалыпты өсуі жағдайында меншікті өнімділігі жоғары биогаз қондырғыларын әзірлеу жолдарын анықтау үшін қолданылды, бұл атмосфераға метан шығарындыларын азайтуға ықпал етеді. Мембраналық жүйелер мен колонналық аппараттарда екі сатылы тазалау сұлбаларын қолданудың энергетикалық тиімділік пен экологиялық қауіпсіздік тұрғысынан орындылығы көрсетілді. Ауқымдандыру мәселесі бастапқы шикізаттың құрамы мен қасиеттері айтарлықтай өзгерген жағдайда экономикалық, энергетикалық және экологиялық тиімділікті қамтамасыз ету үшін математикалық модельдеу мен процестерді басқаруды оңтайландыруды қамтитын кешенді тәсілді талап ететіні жөнінде қорытынды жасалды.

Түйін сөздер: жүйелік талдау, биогаз қондырғысы, жобалау, масштабтау

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СИСТЕМНЫЙ АНАЛИЗ ПРОБЛЕМ МАСШТАБИРОВАНИЯ БИОГАЗОВЫХ УСТАНОВОК В КОНТЕКСТЕ ЭНЕРГЕТИКИ

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Аннотация. Анализ литературы показывает, что проектирование экологически чистых биогазовых установок связано с решением задач масштабирования, учитывающих процессы производства биогаза, его очистки и доведения до кондиционированного состояния. Многие существующие модели мембранного разделения газов не обладают универсальностью и требуют адаптации к конкретным типам мембран и составам газовых смесей. В связи с этим разработка обобщённой структуры модели, пригодной для описания процессов разделения с учётом особенностей очистки, является актуальной задачей. С позиций экологической и энергетической эффективности возникает необходимость разработки решений, направленных на повышение производительности и устойчивости системы. Статья посвящена системному анализу проблемы проектирования биогазовых установок с акцентом на вопросы масштабирования и их влияние на энергетические и экологические характеристики. Сформулированы основные уровни проблем, возникающих при проектировании биогазовых установок, с учётом совокупного влияния процессов производства и очистки биогаза на общую эффективность и экологичность технологического процесса. Выявлены ключевые факторы, определяющие эффективность производства и очистки биогаза, и проанализированы особенности их проявления при переходе к крупномасштабным системам. Метод системного анализа использован для определения путей повышения степени разделения, улучшения качества конечного продукта и создания биогазовых установок с повышенной удельной производительностью при умеренном росте энергозатрат, что способствует снижению выбросов метана в атмосферу. Показана целесообразность применения двухступенчатых схем очистки в мембранных системах и колонных аппаратах с точки зрения энергетической эффективности и экологической безопасности. Сделан вывод о том, что проблема масштабирования требует комплексного подхода, включающего математическое моделирование и оптимизацию управления процессами, особенно при значительной изменчивости состава и свойств исходного сырья, для обеспечения экономической, энергетической и экологической эффективности биогазовых установок.

Ключевые слова: системный анализ, биогазовая установка, проектирование, масштабирование

Introduction. Since the role of alternative energy is currently rapidly increasing, the problem of developing high-performance efficient installations for producing energy by alternative methods is very relevant. The above fully applies to biogas production installations (Yoshida and Shimizu, 2020). Biogas is one of the key sources of renewable energy, as it can serve as fuel for generators, as well as for the production of electricity and heat, thereby ensuring the sustainability of energy systems.

Biogas has a complex composition, which can vary depending on the raw materials used and process conditions (Poschl et al., 2010) Technological parameters such as the composition of raw materials, temperature, fermentation time and purification modes have a significant impact on the energy efficiency of biogas production, which makes the design and optimization of such installations a difficult task.

Many biogas installations currently in use are designed and installed by artisanal methods without solving the problems of increasing efficiency and cleaning gases (Henrik et al., 2022). This results in a low-quality product and environmental pollution. Problems related to the efficiency of biogas purification and its quality are especially important from the point of view of energy aspects, since low-quality biogas with a high admixture of carbon dioxide or hydrogen sulfide reduces energy efficiency and can lead to additional costs for purification. These issues require an integrated approach and solution taking into account the problems of large-scale transition when designing more powerful installations (Spyridon et al., 2017).

The problem of the influence of a large-scale factor on the efficiency of biogas production plants cannot be reduced only to hydrodynamic aspects, since technological and operational aspects in this case also play an important role in optimizing the energy efficiency and environmental friendliness of the plant (Jozef et al., 2023). In the general case, the efficiency of a biogas production plant should be calculated taking into account the efficiency of the main reactor unit and the purification unit (Obaideen et al., 2022).

The rationale for the need to conduct research work was the need to study the influence of the scale factor on the energy efficiency of biogas plants (Tabatabaei et al., 2020), due to the lack of a set of studies of this problem, taking into account the reactor unit and the cleaning unit (Borjesson and Berglund, 2006).

The initial data for the work were many modern works on technological aspects and design of biogas production plants, as well as problems of large-scale transition when designing medium and high-power plants (Borjesson and Berglund, 2007). The methodology of the work is based on theoretical research methods (a systematic approach, mathematical modeling (Zhurinov et al., 2022) and computer experiment), as well as modern experimental research methods aimed at optimizing energy processes occurring in biogas plants. In particular,

the influence of various technological parameters on the energy efficiency of the process is analyzed, including the fermentation rate, temperature, raw material composition and purification modes (Dobre et al., 2014).

The diversity of technological factors casts doubts on the possibility of developing today a general mathematical model that describes the influence of modes and technological factors on the energy efficiency of the reactor unit in biogas plants and allows calculating the efficiency coefficient of the reactor block.

Another issue is related to the units of biogas plants that are designed to purify gas. Emissions from biogas production and the operation of engines running on insufficiently purified biogas can have a significant impact on the environment and the climate (Henrik et al., 2022).

The main purpose of the article is to conduct a systematic analysis of technological schemes of separation plants of biogas plants, their hardware, as well as models of separation processes with an emphasis on scaling and optimizing energy efficiency during the transition from laboratory stands to more productive industrial installations.

At the same time, the main factors determining the efficiency of the biogas production and purification process should be identified, and how these factors manifest themselves during a large-scale transition should be analyzed. Such an analysis is necessary for the correct formulation of modeling tasks, taking into account economies of scale and increasing the overall energy efficiency of biogas plants (Trois et al., 2019).

So, the object of research is the processes of obtaining and purifying biogas for use as an energy source. The subject of research is the influence of technological and regime aspects on the energy efficiency of the reactor unit and the biogas cleaning unit, as well as the analysis of the efficiency of the biogas plant taking into account the scale effect.

In accordance with the stated goal, the following task was solved:

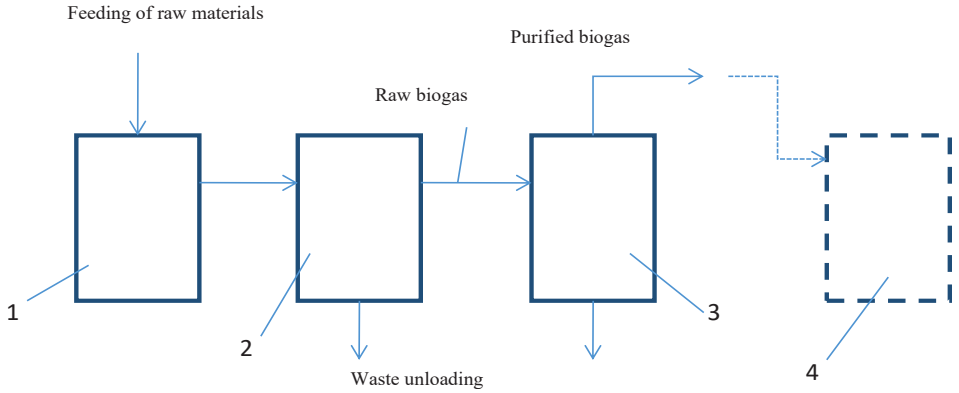
- to conduct a system analysis and studies of the aspects of the influence of scale factors on the efficiency and quality of the product in biogas plants.

Materials and methods. The basic block diagram of a biogas plant is shown in Figure 1.

The overall efficiency η_{gen} of a biogas plant can be represented as a product of two efficiency factors

$$\eta_{gen} = \eta_r \ \eta_r \qquad (1)$$

Here η_r is the efficiency factor of the reactor block and η_p is the efficiency factor of the separation unit of the biogas plant.



1-raw material preparation unit; 2- reactor block; 3- biogas cleaning (separation) unit; 4- biofuel preparation unit (compressor or gas holder)

Figure 1 – Basic block diagram of a biogas plant

Biogas has a complex composition, which can vary depending on the raw materials used and process conditions (Lubanska and Kazak, 2023). Therefore, the problem of scaling up in the calculation and design of biogas production plants cannot be reduced to hydrodynamic aspects only, as is often done (Czekala et al., 2023). Technological and regime aspects also play a major role in scaling up, especially in relation to the reactor block of the plant (Lubanska and Kazak, 2023). This problem is of particular importance from the point of view of geoecology, since during the production and subsequent use of biogas as an alternative energy source, two ways of environmental pollution can be distinguished. The first source of pollution is realized in the form of waste in biogas production units and requires disposal or burial. The second source is of a secondary nature and is realized in the form of air pollution during combustion of biofuel used in engines. The intensity of the second source of pollution depends, in addition to the operating mode of the engine unit, on the degree of purity of the biogas and its calorific value.

The first layer of problems is directly related to scaling up the reactor block of the biogas plant.

1 Heterogeneity of chemical composition, variability of humidity and consistency (Lubanska and Kazak, 2023), different dispersion of processed raw materials (Ismail et al., 2012).

2 Different climatic conditions, which complicates the choice of optimal technology and fermentation modes (Czekala et al., 2023). In this case, the choice can be made in favor of both mesophilic and thermophilic modes with different sources of inoculum.

3 The degree and time mode of mixing, the optimal choice of which significantly depends on the composition of the raw materials and the scale of the reactor (Ismail et al., 2012).

4 The impossibility of unambiguous fixation of optimal parameters of the

technological mode in conditions of changing and uncertain parameters of raw materials. This is due to the fact that the parameters of animal waste in most cases cannot be specified with the necessary certainty.

5 The capacity of a biogas plant is also determined by the quality and quantity of the injected mixture of enzymes, probiotics and microelements (Henrik et al., 2022).

Another layer of scaling problems is associated with the devices of biogas plants, which are designed for gas purification. Solid particles and gas impurities in biogases significantly reduce the quality of the product and pollute the environment.

Another level of problems is related to scale formation and reduced energy efficiency of biogas plants. Solid particles and gas impurities in biogas clog filters and other system elements, so additional energy is required to maintain the required pressure and gas flow, which reduces the overall energy efficiency of the installation.

However, at present, many local devices for biogas production operate without gas purification equipment. This leads, at the very least, to environmental pollution. The need for deep cleaning of biogas increases especially when biogas is used as motor fuel, since it must provide high calorific value and meet environmental requirements. In any case, the production of large volumes of biogas entails additional problems with scaling when designing the plant. At the same time, the main factor in reducing the efficiency of gas cleaning plants is of a hydrodynamic nature.

Therefore, in contrast to the scaling of the reactor block, in this case there are effective mathematical models for describing the influence of the hydrodynamics of phase flows on the efficiency of separation.

The biogas separation unit can be organized in the form of two blocks: a preliminary purification block and a deeper purification block. One of these blocks, as a rule, is a membrane unit in which it is possible to separate some gas components (for example, hydrogen sulfide) with a sufficiently high degree of selectivity. In this case, the components separated at this stage may not find further use and are useless waste.

The second block is necessary in cases where components can be extracted from raw biogas in sufficient volumes that can be utilized for energy purposes. First of all, this concerns components containing ammonia and ammonia compounds.

Results. This section devotes to the main results of systems analysis of biogas membrane separation models from the standpoint of scale transition. Continuous models used to analyze gas separation processes in adsorbent layers are a system of differential equations that take into account the complex irregular structure of the gas mixture flow filtered through a layer of porous adsorbent grains, and the mass and heat exchange processes between the gas and the adsorbent (Borjesson and Berglund, 2006).

From the point of view of mass and heat exchange between the sorbent and the gas flow, two types of mathematical models are distinguished: equilibrium models, which assume that the equilibrium in the sorbed components and the thermal

equilibrium between the gas phase and the sorbent are established instantly; non-equilibrium models, which take into account the heat and mass exchange between the phases and the transfer of components inside the sorbent grains.

The simplest models of adsorption separation of a gas mixture are based on the following approximations:

- the process is one-dimensional, when gradients of the process parameters across the flow are neglected;
- the process is isothermal, when temperature changes along the layer and over time can be neglected;
- the process is isobaric, when pressure changes along the layer can be neglected.

We will consider only equilibrium models, neglecting the final transfer rate of the adsorbed component in the volume of the adsorbent grain.

Based on the above assumptions, we can obtain material balance equations for the process of adsorption separation of a three-component gas system in a one-dimensional sorbent layer.

Material balance equation for the inert component of the gas flow reads (Sakhmetova et al., 2016).

$$\varepsilon = \frac{\partial c_0}{\partial t} = -\frac{\partial j_0}{\partial z} \tag{2}$$

where i = 1,2...

Material balance equations of the sorbed components of the gas flow:

$$\varepsilon \frac{\partial c_i}{\partial t} = -\frac{\partial j_i}{\partial z} - q_i \tag{3}$$

Material balance equation of the sorbed components in the sorbent phase:

$$\rho \frac{\partial a_i}{\partial t} = q_i \tag{4}$$

In macroscopic kinetics, local flows of individual components are represented as the product of the average velocity of molecules of a given type at the point under consideration i u by their concentration:

$$j_i = u_i c_i \tag{5}$$

Accordingly, the total flow of the mixture, equal to the sum of the flows of individual components, is determined as the product of the convective velocity u, m/s, by the total concentration of the gas mixture:

$$j_t = \sum_1 j_i = uC_t \tag{6}$$

In fact, this is the definition of the convective velocity of a gas flow consisting of several components (Ismailet al., 2012**)**.The local flow of an individual component can now be represented by the sum of the convective component and the residual, called the dispersion (diffusion, conduction) component. For the dispersion component, Fick's law is usually used in the form:

$$j_i = (u_i)c_i + j_d = u_i - E_i C_t \frac{\partial x_i}{\partial z} \quad (7)$$

where i = 0,1,2...

Discussion. The system analysis shows that the known models describing the processes of membrane separation of gases do not have a uniform character and require adaptation to specific types of membranes for different gas mixtures.

Equations (2) – (7) should be supplemented with conditions reflecting the specifics of the problem under consideration at the layer boundaries during the entire process and inside the layer at the initial moment of time. Depending on the structure of the boundary and initial conditions, one or another solution method is selected.

Thus, in this case, the problem of large-scale transition in biogas plants engaged in waste processing into a useful energy resource leads to the need to solve the related problem of a system of equations of hydrodynamics and equations of heat and mass transfer. It is not possible to offer a general scheme for solving such models aimed at obtaining an optimal strategy for selecting control parameters. The problem is especially aggravated by the above-mentioned uncertainty and variability of the characteristics of raw biogas.

Therefore, we see the only realistic solution to the problem of large-scale transition in this case by introducing a raw material preparation unit, which will ensure stabilization of the composition of raw biogas and allow for the correct calculation of the separation unit according to the scheme described above.

By this, two continuous models of adsorption separation of gases can be used: an equilibrium model with longitudinal dispersion and an equilibrium model of ideal displacement.

Conclusions.

1. As a rule, the complex, multicomponent composition of gases is not taken into account, which is typical, for example, for biogases. However, these problems are extremely important for obtaining environmentally friendly biogas with a sufficiently high calorific value for the production of thermal and electrical energy. Therefore, it is necessary to develop models that take into account the complex mechanism of gas phase separation in membranes, namely: the combination of filtration, adsorption and evolution of active centers in the membrane depth.

2. The analysis showed that today there is no clearly defined block of control parameters, which complicates the development of automated control systems for

membrane separation of complex multicomponent gas mixtures, and the appropriate problem becomes open.

3. The need to use a two-stage cleaning scheme in membrane systems and irrigation column devices is substantiated, which will increase the degree of separation, improve the quality of the final product and ensure the creation of biogas plants with increased specific productivity with a moderate increase in energy costs.

4. It can be established that in the general case, the scaling problem cannot be effectively solved not only by design methods, but also by methods of mathematical modeling and optimization of the process control process. This applies to cases of significant variability in the composition and characteristics of the feedstock. In this case, the most effective way to solve the problem seems to be the optimization of an additional unit for preliminary preparation of raw materials in order to stabilize its characteristics.

5. It is shown that if it is impossible to bring the initial raw materials to standard compositions, the problem of obtaining the required volume of biogas with the achieved minimum required content of the main component (hydrocarbon), at which economically feasible production is possible, should be experimentally debugged, and the biogas purification unit is subject to scaling in the literal sense of the word in this case.

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