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Research Article

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SUBSTITUTION OF THERMAL-TECHNICAL AND GEOMETRIC PARAMETERS OF A SMALL-SCALE BIOGAS PLANT

Sharipov M.Z.[1*,2], Majitov J.A.[3], Ergashev Sh.H.[4], Shodiyev E.B.[3], Narzullayeva Z.M.[1,5]

[1] Bukhara State University, Bukhara, Uzbekistan
[2] Bukhara State Pedagogical Institute, Bukhara, Uzbekistan
[3] Bukhara State Technical University, Bukhara, Uzbekistan
[4] Karshi State Technical University, Karshi, Uzbekistan
[5] Bukhara State Medical Institute, Bukhara, Uzbekistan
**Corresponding author:* m.z.sharipov@buxdu.uz

Abstract. *This article is devoted to the issues of justification of thermal-technical and geometric parameters for small-scale biogas devices. The growing demand for sustainable and renewable energy resources has increased the importance of biogas technologies, particularly at the small-scale level for rural and agricultural applications. However, the efficiency and stability of biogas production largely depend on the thermal-technical conditions of the digester and the optimization of its geometric parameters. The purpose of this study is to analyze the effect of substituting thermal-technical and geometric parameters on the performance of a small-scale biogas plant. The research object is a laboratory-scale biogas digester with adjustable design features. Methodologically, the work is based on mathematical modeling, computational analysis, and experimental validation of heat transfer and mass balance processes inside the digester. From the results of the resulting study, it can be seen that the methods of determining the optimal geometric dimensions (diameter and length) of the bioreactor structure and reducing heat losses have been analyzed. Mathematical modeling methods have been used to calculate the optimal reactor diameter for various thermal insulation thicknesses and biomass dosing, and the optimal diameter for a 30 m*^{3} *bioreactor is 2800 mm, while the length is 4900 mm, the proportion of biomass in the reactor volume is expressed by the central sector angle.*

Keywords: biogas plant, thermal parameters, reactor insulation, fermentation process, biomass, anaerobic conditions, energy efficiency.

1. Introduction

In recent decades, many countries around the world have been carrying out large-scale and long-term reforms in both the economic and social spheres, with the primary objective of increasing overall energy efficiency, ensuring sustainable use of resources, and at the same time improving the ecological balance as well as the epidemiological situation of the environment in which people live. Within these processes, special attention is being given to encouraging and supporting the widespread use of renewable energy source (RES)-based technologies and devices in different branches of the national economy, since this direction is recognized as one of the most important priorities of modern state policy.

Biomass is one such RES, encompassing organic materials such as agricultural, livestock, and poultry waste, as well as other biological products. Following solar, wind, hydro, and geothermal energy, bioenergy derived from biomass is ranked as the fifth most efficient RES. Approximately 170 billion tons of primary biological mass are accumulated annually on the Earth's surface, with nearly the same amount of biomass being reprocessed and utilized for various purposes [1,2]. Harnessing biomass for energy production presents a complex challenge from the perspective of ecological sustainability and efficiency. The development and implementation of novel devices and technologies that minimize environmental impact, maximize energy output while utilizing resources most effectively, are of paramount importance [3]. Currently, various digester designs are employed worldwide to generate biogas through the anaerobic digestion of biomass. However, most of these digesters possess large volumes, leading to high energy consumption. The widespread adoption of such systems is limited under the conditions prevalent in our Republic.

This article is dedicated to the development of small-scale, energy-efficient biogas digesters based on renewable energy sources, designed for individual consumers. Research is focused on improving the design of the digester, enhancing operational productivity, optimizing thermotechnical parameters, and modeling heat transfer processes within the digester. The objective is to develop an energy-efficient design of a metered biogas digester, which ensures the effective anaerobic fermentation process through the regulated processing of organic waste under anaerobic conditions, and to optimize its key energy parameters. This constitutes an important and topical task in the field.

The development of small-scale biogas plants has attracted significant attention in recent years due to their potential to improve energy self-sufficiency in rural areas while contributing to environmental sustainability. Previous studies have demonstrated that the efficiency of biogas production is strongly dependent on the thermal stability of the digester and the optimization of its structural parameters. For instance, Yan et al. [1] investigated energy conversion from food waste and highlighted the decisive role of operating conditions and reactor configuration in maximizing gas yield. Tagne et al. [2] emphasized the challenges of biogas technology implementation in agricultural regions of China and Africa, pointing out that economic viability and simplified designs are critical factors for adoption. A number of engineering-focused works, such as those by Conti et al. [3] and Vesvikar et al. [4], revealed that optimization of geometric parameters, particularly reactor diameter and length, significantly reduces heat loss and enhances fermentation uniformity. Schmidt et al. [6] and Rojas et al. [7] highlighted the importance of substrate composition and mixing, which are also closely linked to thermal management and microbial activity in the anaerobic digestion process. Despite these contributions, most published studies have concentrated either on large-scale industrial digesters or on specific substrate-related issues, while the adaptation of design parameters for compact digesters suitable for small farms and household applications remains underexplored. In this context, the present study addresses a clear research gap by providing a systematic methodology for determining the optimal thermal and geometric characteristics of a 30 m³ small-scale reactor, considering both insulation thickness and the proportion of liquid and gas phases.

Unlike the work of Yan et al. [1], which focused primarily on the conversion efficiency of organic waste through supercritical processes, the present study concentrates on classical anaerobic digestion with an emphasis on engineering optimization. Compared to Tagne et al. [2], who investigated socioeconomic perspectives of biogas adoption, our work provides a more technical and quantitative analysis of digester design. The modeling approaches of Conti et al. [3] and Vesvikar et al. [4] relied heavily on computational fluid dynamics and flow visualization, whereas this study proposes an analytical framework for determining optimal reactor dimensions supported by experimental validation. Similarly, while Schmidt et al. [6] and Rojas et al. [7] examined operational parameters such as trace elements, mixing, and substrate preparation, the originality of this work lies in minimizing heat losses through the combined optimization of insulation thickness and geometric design. Therefore, the novelty of the present research consists in developing a straightforward yet practical method for improving the thermal efficiency of small-scale digesters. This approach not only provides theoretical insight but also offers direct applicability to household and farm-scale biogas systems, which makes it a valuable contribution to the sustainable energy sector.

2. Experimental research results

Biogas plants consist of equipment designed to process organic matter under anaerobic conditions, producing biogas and organic fertilizers. The reactor, typically a horizontal or vertical cylindrical vessel, serves as the core component where organic material is processed. Maintaining a consistent temperature inside the reactor is critical—for instance, 35–37°C for mesophilic operation—throughout the fermentation period [1–4].Processing livestock waste in biogas plants requires thermal energy to sustain the desired operating temperature. The energy demand depends on multiple factors, making it essential to minimize reactor heat loss through optimized design parameters.

To reduce heat loss, the reactor's geometric parameters must be carefully justified. In the reactor's heat balance, heat loss primarily occurs through the heat exchange surface with the external environment [5–8].

$$Q = kF\Delta t \tag{1}$$

where, k is the heat transfer coefficient, W/(m^2·K); F is the surface area of the heat transfer (loss) surface, m^2; Δt is the temperature difference between the inside of the reactor and the outside air, ^{o}C;

During the fermentation process, the reactor is not completely filled and two media can be distinguished according to its volume: liquid (biomass to be fermented) and biogas formed during the decomposition of biomass. In this case, the heat balance equation for an unfilled reactor can be written as follows:

$$Q_g = \left(k_s F_s + k_g F_g\right)\Delta t \tag{2}$$

where, $k_s -$ heat transfer coefficient from biomass to the external environment, Vt/(m^2·K); F_s – surface area of heat transfer through biomass to the external environment, m^2; $k_g -$ heat transfer coefficient from biogas to the external environment, W/(m^2·K); F_g – surface area of heat transfer through biogas to the external environment, m^2;

In this equation, the first term represents the heat loss from the biomass, and the second from the gas phase. The temperature difference Δt for biomass and biogas is assumed to be the same. In this case, the heat transfer coefficient through the reactor wall can be expressed as follows [9,10]:

$$k = \frac{1}{\frac{1}{\alpha_1}+\sum_{i=1}^{n}\frac{\delta_i}{\lambda_i}+\frac{1}{\alpha_2}} \tag{3}$$

The heat transfer coefficient for the biomass-filled part of the reactor is $\alpha_1 = 350\ W/(\mathrm{m}^2 \cdot \mathrm{K})$, for the gas part – $\alpha_1 = 8{,}7\ \mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})$. $\alpha_2 = 23\ \mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})$ –is the heat transfer coefficient from the reactor wall to the external environment, and the same value is obtained for both cases [4].

The bioreactor is made of chromium-molybdenum steel with a thickness of $\delta_d = 5\ mm$ a thermal conductivity coefficient $\lambda_d = 37{,}7\ \mathrm{W}/(\mathrm{m} \cdot \mathrm{К})$ and a thermal conductivity coefficient of the external insulation material (glass wool) $\lambda_{iz} = 0{,}05 \mathrm{W}/(\mathrm{m} \cdot \mathrm{К})$ .Figure 1 shows the values of the heat transfer coefficient for the liquid and gas phases inside the reactor at different thicknesses of the external insulation layer.

3. Analysis of insulation thickness and heat loss reduction

Figure 1 demonstrates that with an external insulation layer thickness of 5 sm, the heat transfer coefficient to the external environment stabilizes across both phases (liquid and gaseous) and remains constant even with further increases in insulation thickness. This indicates that 5 sm is the optimal insulation thickness for the reactor, as additional layers do not yield further reductions in heat loss.

To enhance thermal efficiency, minimizing heat loss requires a holistic approach:

– Optimizing insulation thickness (with 5 cm being the cost-effective threshold).

– Reducing the heat-conducting surface area, since excessive insulation entails diminishing returns and added material costs.

Thus, reactor design should balance insulation efficacy with economic feasibility by considering both insulation thickness and surface area reduction strategies.

Then it is necessary to reduce the heat transfer surface to choose the optimal option. The optimal diameter can be chosen when the value representing the heat losses in a reactor with a horizontal location is minimal. The surface bounded by the liquid (biomass) part of the reactor is equal to the sum of the 2 side segments and segments and the front surfaces represented by the cylinder length, which can be expressed as [10 - 12]:

$$F_s = 2 \cdot F_{seg.1} + F_{old.1} \tag{4}$$

Depending on the degree of saturation of the reactor with biomass, the segment surface formed on the side of the cylinder can be written as

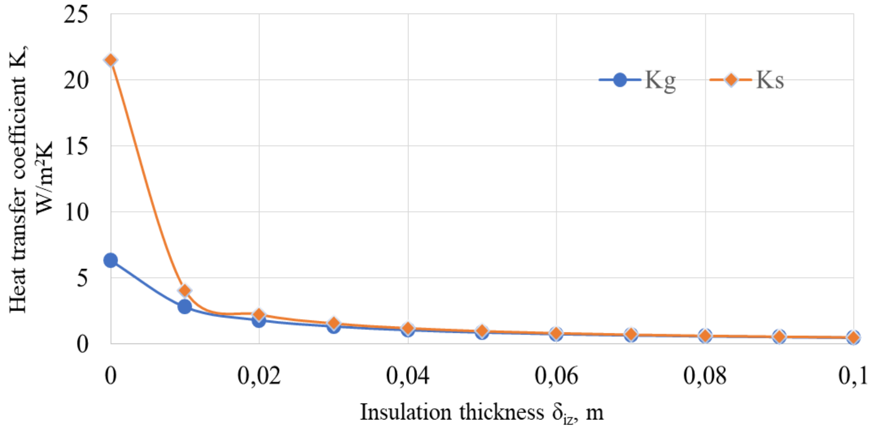

Fig. 1. Dependence of the heat transfer coefficient of the outer insulation layer for the liquid and gas phases inside the reactor.

$$F_{seg.1} = \frac{D^2}{8}(\beta - \sin(\beta)) = \frac{D^2}{8}\left(\frac{\pi\cdot\beta}{180} - \sin\left(\frac{\pi\cdot\beta}{180}\right)\right) \quad (5)$$

At the biomass saturation level, we represent the front surface as follows:

$$F_{old.1} = \beta\frac{D}{2}\cdot L = \frac{\pi\cdot\beta\cdot D}{360}L \quad (6)$$

For the non-fluid occupied part of the reactor i.e. for the biogas part, both (4)-(6) expressions are appropriate-the sector arc is represented by the retracted angle ($\gamma = 2\pi - \frac{\pi\cdot\beta}{180}$) - it is written as

$$F_g = 2\cdot F_{seg.2} + F_{old.2},\; F_{old.2} = \gamma\frac{D}{2}\cdot L = \frac{\left(2\pi - \frac{\pi\cdot\beta}{180}\right)\cdot D}{360}L$$

$$F_{seg.2} = \frac{D^2}{8}(\gamma - \sin(\gamma)) = \frac{D^2}{8}\left(2\pi - \frac{\pi\cdot\beta}{180} - \sin\left(2\pi - \frac{\pi\cdot\beta}{180}\right)\right), \quad (7)$$

Putting the expressions (4)-(7) in Equation (2) we obtain

$$\mathrm{Q} = k_s\left[\frac{D^2}{4}(\beta - \sin(\beta)) + \beta\frac{D}{2}\cdot L\right]\Delta t + k_g\left[\frac{D^2}{4}(\gamma - \sin(\gamma)) + \gamma\frac{D}{2}\cdot L\right]\Delta t \quad (8)$$

For the liquid biomass in the cylinder and the total volume of the cylinder, we can write:

$$V_s = \frac{D^2}{8}(\beta - \sin(\beta))\cdot L,\quad V = \frac{\pi D^2}{4}\cdot L,\; V_g = \frac{D^2}{8}(\gamma - \sin(\gamma))\cdot L,\quad V = \frac{\pi D^2}{4}\cdot L,\; V = V_s + V_g \quad (9)$$

From this

$$\beta - \sin(\beta) = \frac{8V_s}{D^2\cdot L},\quad L = \frac{4V}{\pi D^2},\quad \beta - \sin(\beta) = \frac{2\pi V_s}{V} \quad (10)$$

$$\gamma - \sin(\gamma) = \frac{8V_g}{D^2\cdot L},\quad L = \frac{4V}{\pi D^2},\quad \gamma - \sin(\gamma) = \frac{2\pi V_g}{V} \quad (11)$$

Taking into account that by putting the expressions (8) and (9) in the expression (10), D = 2R, we obtain

$$\mathrm{Q} = k_s\left[\frac{2\pi V_s}{V}R^2 + \beta\frac{V}{\pi R}\right]\Delta t + k_g\left[\frac{2\pi V_g}{V}R^2 + \gamma\frac{V}{\pi R}\right]\Delta t \quad (12)$$

To find the optimal radius, we examine this function to the extremum-that is, taking the derivative by radius from the amount of heat lost to zero:

$$\frac{dQ}{dR} = \left\{k_s\left[\frac{2\pi V_s}{V}R^2 + \beta\frac{V}{\pi R}\right]\Delta t + k_g\left[\frac{2\pi V_g}{V}R^2 + \gamma\frac{V}{\pi R}\right]\Delta t\right\} = 0 \quad (11)$$

After simplifications, we can write the optimal radius as:

$$R_{opt.} = \sqrt[3]{\frac{(\beta k_s + \gamma k_g)V^2}{(V_s k_s + V_g k_g)4\pi^2}} \quad (12)$$

The proportion of biomass in the reactor volume was represented by the central sector angle-$\beta = 2\pi, \gamma = 0$; 90 % in the full state; $\beta = 1{,}8\pi, \gamma = 0{,}2\pi$; 80 % full state,$\gamma$ $\beta = 1{,}6\pi,\ \gamma = 0{,}4\pi$; 70 % in the full state, $\beta = 1{,}4\pi,\ \gamma = 0{,}6\pi$ in the full state, and hokazo.

Taking into account the above, we determine the optimal diameter of a 30 m^3 hajm reactor for an insulation coating of different thickness (Figure 4). For thermophilic and mesophilic modes on the basis of this diameter, we calculate the thermal loads depending on the insulation layer by formulas (3), (8) (figure 2,3).

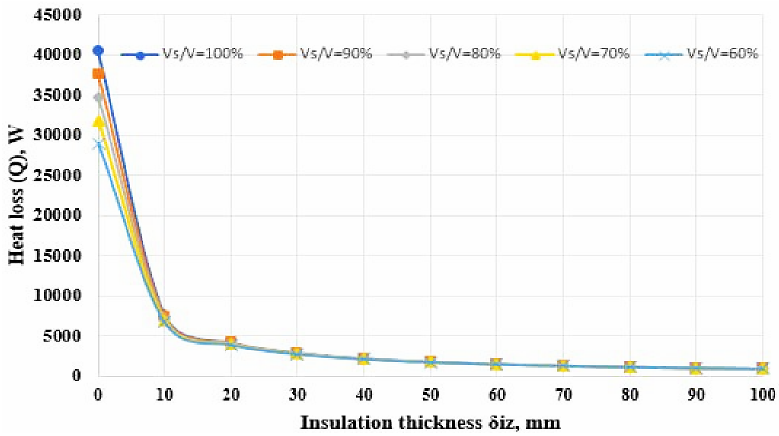

Fig. 2. Dependence of the thermal load on insulation thickness at a reactor volume of 30 m³ (thermophilic mode). The curves demonstrate that increasing the insulation thickness beyond 50 mm does not significantly reduce thermal losses, confirming that this value is the practical optimum.

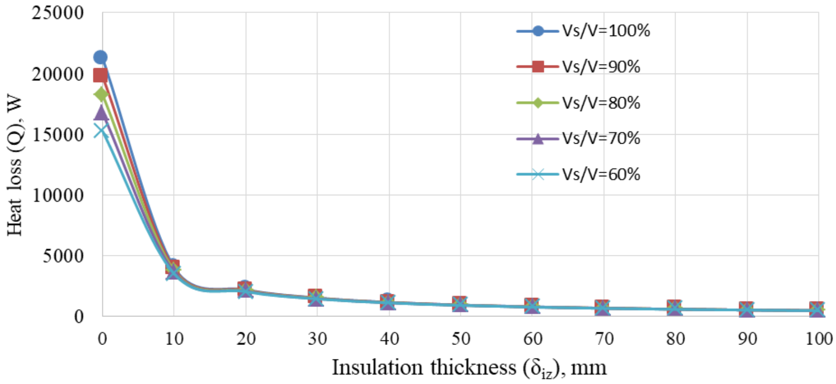

Fig. 3. Thermal load variation with insulation thickness at different biomass filling ratios in a 30 m³ digester (mesophilic mode). The graph highlights the effect of biomass distribution on energy demand and underlines the importance of insulation optimization for energy-efficient operation.

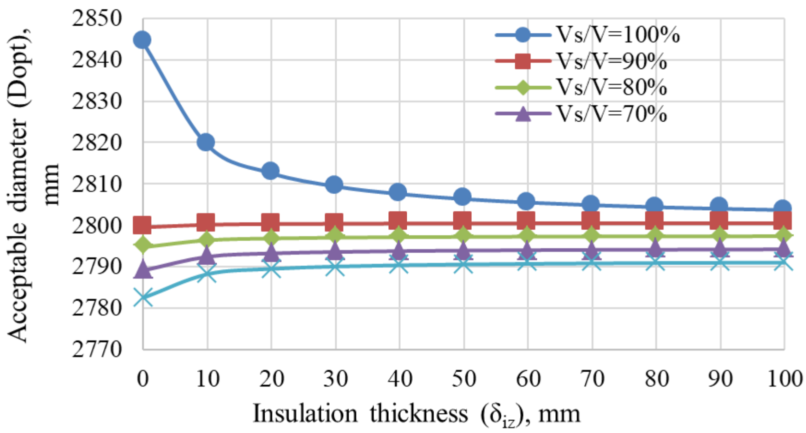

Fig. 4. Relationship between the optimal reactor diameter and insulation thickness for a 30 m³ digester. The analysis shows that an average diameter of 2800 mm ensures minimal heat loss under different biomass load conditions.

4. Conclusion

Based on the findings of this study, optimizing the thermal and geometric parameters is essential for enhancing the efficiency of small-scale biogas plants. The main outcomes include:

– Optimal insulation thickness: 50 mm for the reactor wall, which minimizes heat loss while avoiding unnecessary material costs.

– Reactor dimensions: For a 30 m³ bioreactor, the ideal diameter is 2800 mm and the length 4900 mm, ensuring a balance between heat retention and structural efficiency.

These parameters significantly improve energy efficiency and can be directly applied to the design and optimization of compact biogas plants.

– In addition to the immediate engineering benefits, the results of this research open several promising directions for application:

– Rural and household energy supply: The proposed methodology can be directly implemented in farm-scale or domestic digesters, helping to reduce reliance on traditional fossil fuels.

– Economic feasibility: Optimized designs with reduced thermal losses lower operational costs, increasing the competitiveness of small-scale biogas technology.

– Environmental impact: Improved reactor efficiency contributes to better utilization of organic waste streams, reducing greenhouse gas emissions and promoting sustainable agricultural practices.

– Scalability and adaptation: The analytical approach developed in this work can be adapted to other digester sizes and operational conditions, providing a flexible tool for engineers and policymakers.

Thus, the present study not only provides a practical framework for improving the technical performance of biogas digesters but also highlights the potential of optimized small-scale systems to play a significant role in advancing renewable energy adoption, particularly in rural and resource-constrained environments.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

Sharipov M.Z. - Conceptualization, Methodology, Supervision; **Ergashev Sh.H., Shodiev E.B.** - Investigation, Formal Analysis, Writing-Reviewing and Editing; **Narzullayeva Z.M., Majitov J.A.** - Writing - original draft, Review and Editing; The final manuscript was read and approved by all authors.

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AUTHORS' INFORMATION

Sharipov, Mirzo - Doctor of Physical and Mathematical Sciences, Professor, Head of Department, Bukhara State University, Bukhara, Uzbekistan; SCOPUS Author ID: 24177719300, https://orcid.org/0000-0003-0370-8066; m.z.sharipov@buxdu.uz; m.z.sharipov@rambler.ru

Majitov, Jurabek – Doctor PhD (Eng), Associate professor, Physics Department Bukhara State Technical University, Bukhara, Uzbekistan; SCOPUS Author ID: 57221226030; https://orcid.org/0009-0005-9453-279X; majitov@mail.ru

Ergashev, Shakhrier – Doctor PhD (Eng), Associate professor, Karshi State Technical University, Karshi, Uzbekistan; SCOPUS Author ID: 57862905100; https://orcid.org/0000-0002-3336-9942; strong.shakhrier@mail.ru

Shodiyev, Erkin – Doctor PhD (Eng), Associate professor, Bukhara State Technical University, Bukhara, Uzbekistan; https://orcid.org/0009-0008-0433-0679; erkin@mail.ru

Narzullayeva, Zilola - PhD student, Bukhara State University, lecturer at Bukhara State Medical Institute. Bukhara, Uzbekistan; https://orcid.org/0009-0003-4706-8889; narzullayevazilola1487@gmail.com