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Scale-Up of the Installations for the Biogas Production and Purification

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The current work deals with the scale-up phenomenon while designing the industrial scheme for biogas production. Within the framework of this problem the experimental investigations of the dependence of the biogas installation productivity on the work load have been carried out. The convincing data confirming the decrease of the work efficiency after increasing the work load beyond certain limit have been obtained, and the levels of this effect have been studied. The other result of the work is developing the model approach to the description of scale-up effect in the large-scale packing towers of wet-type for the purification of great volumes of biogas. The basic idea is to divide the whole height of a tower into several consecutive cells which are differ in different mass transfer coefficients averaged over the cross section of the column. The characteristic heights of the each such cell are determined on the basis of solving the hydrodynamic model, and the volumetric mass transfer coefficient corresponding to the average one in each cell is produced from the experimental data obtained on a small laboratory installation.

1. Introduction

Biogases have a complex composition which can vary depending on the used raw materials and technological conditions (Gigot et al., 2012). That is why the problem of scaling-up the installations for biogas production can't be reduced to the hydrodynamic aspects only, as it is often done (Brener, 2002), and the technological and regime aspects also play a great role for scaling-up while designing the biogas installations (Vargas and López-Serrano, 2014). After systematic analysis, the main technological and regime aspects which should be considered in the process of scaling-up the installations for biogas productions were formulated, and these aspects are listed below.

1. The heterogeneity of the chemical composition, the variability of the moisture and the consistency (Kreutzer et al., 2010), he different dispersity of the processed raw materials (Verpoorte et al., 2002).
2. Various climate conditions, what complicates the choice of the optimal technology and regimes of the fermentation (Shah et al., 2009). In this case, the choice can be made in favour of both mesophilic and thermophilic regimes (Hölker et al., 2004) with different inoculum sources (Silva and Dionisi, 2016).
3. Degree and the time mode of mixing, the optimal choice of which essentially depends on the composition of raw materials (Morelos et al., 2015) and on the scale of the reactor (Zaghloul et al., 2011).
4. The technological regime cannot be uniquely determined without specifying the performance of the installation (Coker, 2001), which in turn depends on the parameters of the raw materials (Tufvesson et al., 2010). However, the parameters of animal waste materials, for example, can hardly be given with the necessary certainty (Ghimire et al., 2015).
5. The capacity of the biogas plant is also determined by the quality and quantity of the injected mixture of enzymes, probiotics and microelements (Eibl et al., 2010).

The other class of scale-up problems are related to the devices of biogas installations which are intended for the gas purification.

Solid particles and the gas admixtures in biogases essentially decrease the quality of the product as well as pollute the environment. Solid particles contained in biogas can also deposit on the walls of gas lines and clog the valves. However, nowadays, many local devices for biogas production operate without equipment for gas purification (Ruiz-Ruiz et al., 2013). It leads at least to the environmental pollution. Especially, need of the deep

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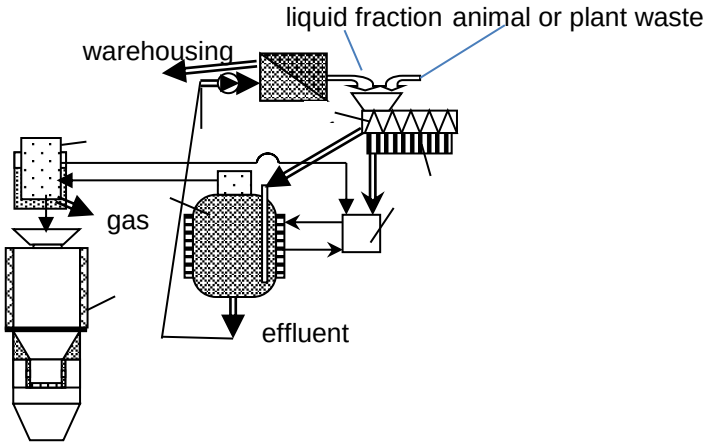
biogas purification increases when biogas is used as a motor fuel, as thereby a high calorific value and compliance with environmental requirements should be provided. Today several ways of the biogas separation have been used. Well-known methods such as selective adsorption through the solid adsorbent bed (Krooss et al., 2002), volumetric dissolution in the active liquids (Jacquemin et al., 2006) and the membrane separation (Madaeni et al., 2010) are sufficiently effective with applying to the biogas installations of low capacities.
However, when large volumes of the biogas must be purified it is advisable to carry out the stage of wet purification in the adsorption towers (Zondervan et al., 2011). A packed tower seems to be preferable for this case, as it provides reaching a lower power consumption compared with bubble tubes. In any cases the production of large volumes of biogas entails the additional scale-up problems while installation design (Ren et al., 2011).
The paper deals with the scale-up phenomena while designing the industrial scheme for biogas production. Within the framework of this problem both the experimental investigations of the dependence of the biogas semi-industrial installation capacity on the work load have been carried out and the theoretical model of the efficiency of biogas wet purification has been offered.

2. Experimental study

The main purpose of the experiment was to determine the energy efficiency of the technological scheme of biogas production on the installation of a semi-industrial scale, depending on the reactor loading and the time of fermentation. Thus, the experimental study was directed to the regime and technological aspects of scaling the process.

2.1 Description of the test rig and procedure

To carry out experimental studies of the biogas production process, a synthetic substrate consisting of sewage sludge from treatment plants, a lignin-containing component (paper), a co-substrate with a high content of organic matter (mixed fodder SK-8) and water has been used. Figure 1 depicts the experimental semi-industrial plant.



1-mixer; 2- heat exchanger; 3-boiler; 4-fermenter; 5- gasholder; 6 - fecal pump; 7 - separation unit

Figure 1: Technological scheme of the experimental biogas semi-industrial plant.

The unloading of the processed substrate (effluent) occurred automatically through the special device into the settler when the next portion of raw material is added. The produced biogas, the main constituent of which is methane, was collected in a wet gas tank and burned daily in a burner connected via pipelines to a wet gas holder through a hydraulic shutter.
The process temperature was determined by direct measurement using sensors installed in the reactors. The hydrogen indicator of the samples was determined by direct measurement using a pH meter. The amount of biogas released was determined by the volumetric method, i.e. by measuring the height of the lifting of the gasholder bell. The amount of substrate and effluent was measured by the volumetric method.
In the course of the experiment, the amount of biogas obtained with a retention time of 10 d was determined. On the first day, the influent portion of 200 g x 5 L of water was loaded, then the load was increased to 300 g x 5 L of water. The average content of the organic matter in the influent increased from 35 to 49 g/L and together with it the output of biogas increased.

2.2 Experimental results

The daily biogas production first increased with reaching a maximum on day 8 to 0.169 m^3. However, on the ninth day, the pH value in the bioreactor dropped to 6.2 and the process became acidified. It led to an essential decrease in the reactor productivity. Therefore, on the tenth day in order to stabilize the pH in the bioreactor, the reactor loading was not made.

Thus, further the ratio of components in the substrate was changed and its amount reduced to 150 g x 2.5 L of water + 3 L of fermented sediment. Then, on the seventeenth day, the output of biogas and pH in the bioreactor become stable. So, the topping up of fresh material in the experiment was terminated on the 19-th day.

As a result of the experiment, 1,230 L of biogas were formed during 19 d of the fermentation. Methane content in biogas also gradually increased, and then after about 8 d reached a maximum value of 65 %. As a result of the experimental data processing, the optimal residence time of the raw in the reactor has been determined as 10 d. The daily output of biogas and variation of pH indicator are shown in Figure 2 and Figure 3.

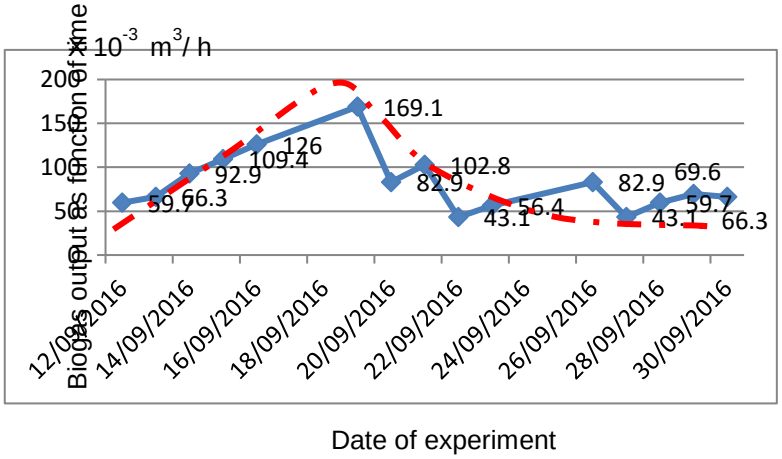


Figure 2: Daily output of biogas

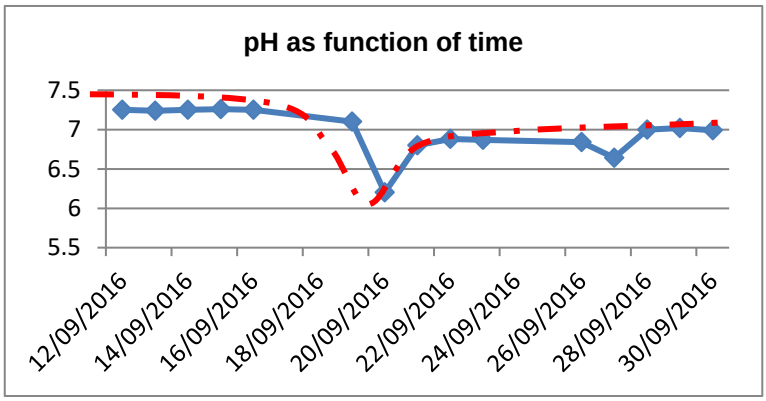


Figure 3: pH values of the substrate in the bioreactor by days

The experiments also showed that the thermophilic conditions accelerated the kinetics of the reactions, what in practice leads to the possibility of using the reactors of smaller scales without decrease in the productivity. The operation in thermophilic mode (55 ºC) allows essentially accelerating up the process of anaerobic decomposition of organic substances.

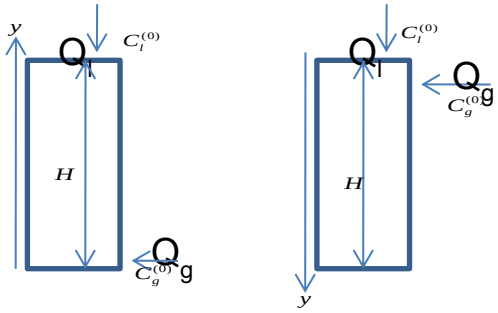
3. Scale-up modelling of biogas wet-purification devices

This theoretical part of the paper dedicates to the problem of scaling-up of devices for wet purification of the biogas. From the point of view of scaling-up the heat and mass transfer apparatuses, the most relevant types of devices left up to day the packed columns, as more uniform distribution of the interacting liquid and gas

phases can be organized in these devices even under increasing their diameters (Nauman, 1981). The main cause of the scale-up effect in this case lies in peculiarities of the hydrodynamic picture of interacting liquid and gas flows.

The real picture of the liquid distribution over the packed bed and the pattern of the gas flow past the bed are quite complex (Brener et al., 1981). However, assuming that the scale of the column and its diameter are much larger comparing the characteristic sizes of the packing units, the phase distribution in the apparatus volume and the processes of heat and mass transfer can be described by the equations of continuous phase interaction (Brener, 2002).

The flow diagrams for the counter-current and co-current flow modes are shown in Figure 4.



A - counter-current *B- co-current*

Figure 4: Flows diagrams in a column

The simplified mass transfer equation in an apparatus in the case of counter-current flows reads

$$K_v F dy = \frac{Q_g dC_g}{\beta C_l - C_g} \tag{1}$$

On the basis of Eq(1) using the linear work curve of the process the following integral equation of mass transfer can be obtained

$$\int_F \int_0^y K_v ds d\omega = \frac{Q_l}{\lambda - 1} \ln \left(\frac{C_g(\lambda - 1) - \lambda(1-\eta) C_g^{(0)} + \beta C_l^{(0)}}{C_g^{(0)}(\lambda - 1) - \lambda C_g^{(0)} + \beta C_l^{(0)}} \right) \tag{2}$$

Here Q_l and Q_g are liquid and gas loads, C_l and C_g are concentrations of the extracted component in liquid and gas phases, F is the column cross-section, K_v is the specific mass transfer coefficient, β is the Henry constant.

The following control parameters are introduced.

$$\lambda = \frac{\beta Q_l}{Q_g}, \quad \eta = \frac{C_g^{(0)} - C_g^{(H)}}{C_g^{(0)}} \tag{3}$$

From this it follows the formula for calculating a distribution of the concentration of the extracted component along a height of the apparatus.

$$C_g = \frac{C_g^{(0)}}{1-\lambda} \left[(1 - \lambda\eta) \exp\left(\frac{\lambda - 1}{Q_g} \int_F \int_0^y K_v ds d\omega \right) - \lambda(1-\eta) \right] + \frac{\beta C_l^{(0)}}{1-\lambda} \left[1 - \exp\left(\frac{\lambda - 1}{Q_g} \int_F \int_0^y K_v ds d\omega \right) - \lambda(1-\eta) \right] \tag{4}$$

An important feature of this approach is the explicit use of the idea of a scale effect (Nauman, 2008). This is expressed in the fact that the specific mass transfer coefficient is assumed to be depended on the point of its measurement localized in the cross section, and this coefficient averaged about the cross section depends on the cross-sectional height (Brener, 2002).

Namely, the averaging of the specific mass transfer coefficient on some characteristic cross sections of the apparatus is performed just as it is done applying to the diffusion mixing model (Brener, 2002). The whole height of the apparatus can be divided down into several consequent cells with different mass transfer coefficients averaged over the cross section of the column.
Determination of the characteristic height of the each such cell carries out on the basis of solving the hydrodynamic modelling problem (Brener et al., 1981), and the value of the corresponding mass transfer coefficient averaged in each cell is found from experimental data obtained on small-sized laboratory installations (Brener, 2002).
Using consistently this method, the following formulas for calculating the degree of absorption in the column apparatus, taking into account the uneven distribution of fluxes over the cross-section and along the height of the column have been derived.

$$\eta = \frac{\exp\left(\frac{\lambda-1}{Q_g} F \sum_{i=1}^{n} \overline{K}_{g(i)} H_i\right) - 1}{\lambda \exp\left(\frac{\lambda-1}{Q_g} F \sum_{i=1}^{n} \overline{K}_{g(i)} H_i\right) - 1} - \frac{\beta C_l^{(0)}}{C_g^{(0)}} \frac{\exp\left(\frac{\lambda-1}{Q_g} F \sum_{i=1}^{n} \overline{K}_{g(i)} H_i\right) - 1}{\lambda \exp\left(\frac{\lambda-1}{Q_g} F \sum_{i=1}^{n} \overline{K}_{g(i)} H_i\right) - 1} \tag{5}$$

It is seen from Eq(5) that the integral factor of the scale effect can be introduced in the form

$$\Phi = \frac{\lambda-1}{Q_g} F \sum_{i=1}^{n} \overline{K}_{g(i)} H_i \tag{6}$$

Then the expressions for calculating the total degree of absorption in the counter-current and, by analogous consideration, in the co-current regimes acquire compact forms.

$$\eta_{\uparrow\downarrow} = \frac{\exp(\Phi) - 1}{\lambda \exp(\Phi) - 1} - \frac{\beta C_l^{(0)}}{C_g^{(0)}} \frac{\exp(\Phi) - 1}{\lambda \exp(\Phi) - 1} \tag{7}$$

$$\eta_{\uparrow\uparrow} = -\frac{\exp(\Phi) - 1}{\lambda \exp(\Phi) - 1} + \frac{\beta C_l^{(0)}}{C_g^{(0)}} \frac{\exp(\Phi) - 1}{\lambda \exp(\Phi) - 1}$$

The expressions obtained have a singularity at $\lambda = 1$. Although such a situation is extremely unlikely, in this rare case the necessary formulas can be obtained by a simple limiting transition.

4. Conclusions

As it concludes from experimental and theoretical investigations the problems of scaling-up the installations for the biogas production and purification need integrated consideration with allowing for the technological, regime and hydrodynamic aspects. The experimental investigations confirm that a right choice of regime conditions can essentially accelerate the process kinetics in reactions, what leads to the possibility of using the reactors of smaller scales without decrease in the productivity. In our case it was a thermophilic mode at 55 ºC. The main theoretical result of our work is the model approach to the description of scale-up effect in the large-scale packing towers of wet-type which can be used for purifying large volumes of biogas. As a result, the expressions for calculating the total efficiency of purification process with allowance for the real non-uniformity of phases distribution have been derived. The results of the investigations are likely to be useful for designing the industrial installations for the biogas production.

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