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Mathematical and Technical Model Biogas Plant with a Membrane Separator

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Abstract. The given mathematical model describes biogas plant with a membrane separator. There is separation of multicomponent gas flow in modules of hollow fiber membranes in co-flow and counter flow. The solution of the system, modeled by us, can be made with the help of Runge-Kutta method, traced to Cauchy problem. Counter current configuration with component gases, having high selectivity, requires more computing time.

Penetration of gas mixture similar to biogas, consisting of three components: methane, carbon dioxide and oxygen have been presented in correspondence with the experiment. The results of modeled gas separation correspond to observed estimations well. The highest indicator has been achieved at counter current configuration.

Keywords: Mathematical model, Membrane Separation, Biogas, Permeate, Retentate.

1. Introduction

Biogas production, as a source of energy, is increasing annually in most countries of the world, which do not have natural gas. For these countries biogas employment as fuel for gas-engines, for producing electro energy and heat as well have three advantages: first, it reduces dependence of its economy from importers of natural gas; secondly, it realizes the international policy on carbon dioxide burst, thirdly, it supports its producer economically.

Besides, insignificant content of harmful components, unlike natural gas, containing large volume of sulphur compounds, creating significant expenditure in its purification, biogas contains from 45 up to 70% of methane, from 30 to 45% of carbon dioxide and less than 10% of ammonia, hydrogen sulphide, nitrogen and oxygen totally, and also insignificant amount of water vapour. To approximate biogas in quality to supplied market natural biogas technological transformations are necessary. Separation of harmful substances [1], drying and evolution of carbon dioxide, as inert one for constituents combustion, that is biogas enrichment are the most important of them.

2. Statement Of The Problem

The main stages of technological processes of producing enriched biogas are shown in Fig.1.

To cheap *market* biogas technologies, combining two-three stages into one are possible. The most important problem of preparing biogas is separation it from carbon dioxide. Several technologies to solve this problem are known, some of them have been introduced in European countries.

The most perspective technology of biogas separation is membrane separation or membrane biogas separation [2]. This process has a range of advantages over other separation: continuous work, low energy consumption, cheap regeneration of membranes and low controllability. All these advantages in total with transportation through existing pipelines for natural gas give high efficiency of biogas employment.

The simplified scheme, showing the principle of biogas separation with the use of polymer membranes is given in Fig.2.

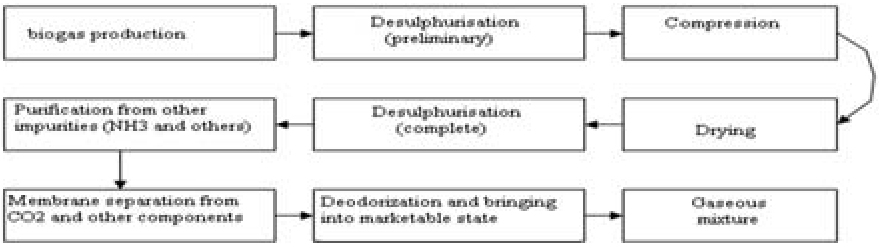

Fig.1. Main stages of market biogas production.

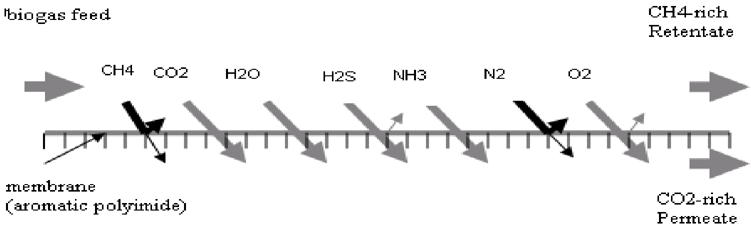

Fig.2. The principle of biogas separation, using membrane method of separation.

The difference of partial pressures of components before and after membrane is driving force of gas components diffusion through membrane. The great flow through membrane can be delivered with high pressure on the side of supply and low pressure (close to atmosphere pressure) on the outgoing side. Having chosen the necessary membrane the major part of undesirable components of gas can be removed [2]. Only nitrogen, having similar properties to methane, cannot be removed by the suggested technology, therefore it retains in the product, called a retentate. Removed undesirable products from nitrogen in our case, as a rule, are called permeate. As the mixture NH2, H2S in total with moisture can lay down at stake the damage of membrane material, some technological transformations to remove this mixture up to membrane separation are necessary. The moisture is removed by heating and cooling up to +70C, at which it is condensed. After that hydrogen sulphide is removed by adsorption. Gas purification from hydrogen sulphide is more complex process and two methods are practically used: first – desulfurization is carried out by adding special substances (liquid mixtures of metals salts); second – microbiological processing with the help of bacteria. Each method has its advantages and disadvantages. Chemical desulfurization allows to reduce the content of hydrogen sulphide up to 50%, microbiological one has higher rate of purification, however microorganisms need oxygen for oxidizing conversion of hydrogen sulphide, biogas enrichment by oxygen creates additional difficulties in producibility.

To minimize methane losses two stages of membrane modules are suggested. The retentate of the second stage, containing significantly higher quantity of methane in comparison with the first stage of membrane separation partially revert for recompression. Recycle stream creates increase of methane concentration, displacing non-linear dynamics of the process to the increase of methane concentration and decrease of nitrogen content. The amount of recycle stream is adjusted so that, methane content not less than 90% can be achieved in our opinion. The technological scheme with two membrane modules is shown in Fig.3.

Any technology of gas separation cannot transmit all the methane to market biogas. As a result, carbon dioxide contains slight amount of methane (about 2-3% from produced biomethane) and other separated components of biogas and can be combusted to produce additional energy [3].

To model mass transfer process in membrane contactor, we will take some assumptions:

In gaseous phase the impact of boundary concentration layer and pressure is low. That is concentration of component, pressure, viscosity, diffusion concentration can be considered constant in cross-section.

Impact of deflux for the velocity profile in gaseous phase is low and the velocity profile has a parabolic type.

The impact of convective transport across the channel can be ignored.

Longitudinal diffusion can be ignored.

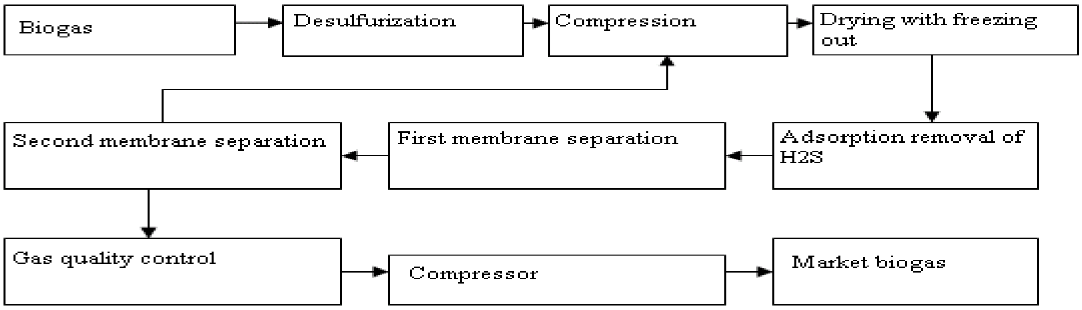

Fig.3. The process of market biogas production with two modules of separation.

Within the *framework* of assumptions and drawn conclusions the system has been got:

$$\frac{\partial^2 \tilde{c}_{il}}{\partial \tilde{y}^2} - Pe_{il}\delta_l \tilde{y}(2-\tilde{y})\frac{\partial \tilde{c}_{il}}{\partial \tilde{x}} = 0 \qquad (1)$$

where $\tilde{c}_i$ - concentration of i component, $\delta_l = \frac{b_l}{l}$ - half of correlation of interspace thickness to channel length, $Pe_{il} = \frac{V_{l\max} b_l}{D_{il}}$ - Peclet number, size Pe_{il} characterizes lateral diffusion impact, in comparison with longitudinal convective transport.

Boundary conditions for the system are phrased as:

$$\tilde{c}_{li}\ (0,\tilde{y}) = \tilde{c}_{il0}, i = \overline{1,n} \qquad (2)$$

$$\left.\frac{\partial c_{il}}{\partial \tilde{y}}\right|_{\tilde{y}=1} = 0, i = \overline{1,n} \qquad (3)$$

$$\left.\left(\frac{\partial c_{il}}{\partial \tilde{y}}\right)\right|_{y=0} = -B_{ilm}\tilde{j}_{im}, i = \overline{1,n} \qquad (4)$$

Here the condition (2) occurs from balance of components' flows at the entry into the module, (3) – from problems symmetry, (4) – from balance of components' flows near the membrane.

For gaseous phase in the case of straight current:

$$\frac{d\tilde{P}}{d\tilde{x}} = -A_g \tilde{\eta}\frac{\tilde{q}}{\tilde{P}} \qquad (5)$$

$$\frac{d}{dx}\left(\tilde{q}c_{ig} - \tilde{P}c_{ij}\frac{1}{Pe_{ll}}\sum_{j=1}^{n}\tilde{D}_{ij}\frac{dc_{ij}}{d\tilde{x}}\right) = -\tilde{j}_m\chi, i = \overline{1,n-1} \qquad (6)$$

$$\frac{d}{d\tilde{x}}\tilde{q} = -\chi\sum_{j=1}^{n}\tilde{j}_{jm} \tag{7}$$

$\chi = \dfrac{H}{l}$ - non-dimensional width of the channel,

Boundary conditions for the system are phrased as:

$$\left\{\tilde{q}c_{ig} - \tilde{P}c_{ig}\frac{1}{Pe_{ll}}\sum_{j=1}^{n}\tilde{D}_{ij}\frac{dc_{ig}}{d\tilde{x}}\right\}\Bigg|_{\tilde{x}=0} = \tilde{q}c_{igf}, i = \overline{1, n-1} \tag{8}$$

$$\left\{\tilde{P}c_{ig}\frac{1}{Pe_{ll}}\sum_{j=1}^{n}\tilde{D}_{ij}\frac{dc_{ig}}{d\tilde{x}}\right\}\Bigg|_{\tilde{x}=1} = 0, i = \overline{1, n-1} \tag{9}$$

In (8), (9) correspondingly balance conditions of components at the entry and output from gaseous phase. Boundary conditions according to complete flow and pressure can be defined in following way:

$$\tilde{P}\Big|_{\tilde{x}=0} = 1$$

$$\tilde{q}\Big|_{\tilde{x}=0} = 1 \tag{10}$$

The problem (10) is the simplest for numerical algorithm realization. Then the solution always has physical meaning, if $\tilde{P}_{out} < 1$.

In the case of counter current we consider x-axis. Then equations for mass transfer for gas will be as:

$$\frac{d\tilde{P}}{d\tilde{x}} = A_g\tilde{\eta}\frac{\tilde{q}}{\tilde{P}} \tag{5'}$$

$$\frac{d}{dx}\left(\tilde{q}c_{ig} - \tilde{P}c_{ij}\frac{1}{Pe_{ll}}\sum_{j=1}^{n}\tilde{D}_{ij}\frac{dc_{ij}}{d\tilde{x}}\right) = \tilde{j}_m\chi, i = \overline{1, n-1} \tag{6'}$$

$$\frac{d}{d\tilde{x}}\tilde{q} = \chi\sum_{j=1}^{n}\tilde{j}_{jm} \tag{7'}$$

Boundary conditions are phrased in the following way:

$$\left\{\tilde{q}c_{ig} - \tilde{P}c_{ig}\frac{1}{Pe_{ll}}\sum_{j=1}^{n}\tilde{D}_{ij}\frac{dc_{ig}}{d\tilde{x}}\right\}\Bigg|_{\tilde{x}=1} = \tilde{q}c_{igf}, i = \overline{1, n-1} \tag{8'}$$

$$\left\{\tilde{P}c_{ig}\frac{1}{Pe_{ll}}\sum_{j=1}^{n}\tilde{D}_{ij}\frac{dc_{ig}}{d\tilde{x}}\right\}\Bigg|_{\tilde{x}=0} = 0, i = \overline{1, n-1} \tag{9'}$$

Conditions for complete flow and pressure are phrased in the following way.

Mass transfer through the membrane is defined by the formula:

$$\tilde{j}_{im} = \tilde{R}_{im}\left(\tilde{P}_g(\tilde{x})\tilde{c}_{gi}(\tilde{x}) - \tilde{P}_i(\tilde{x})\right) \tag{11}$$

Where

$$\tilde{R}_{im} = \frac{D_{im}HlP_{in}}{q_{in}h_m K_{im}} = \frac{Q_{im}AP_{in}}{q_{in}} \tag{12}$$

$$\tilde{P}_i^{\cdot}(x) = P_i^{\cdot}(c_l(\tilde{x}, 0)) / P_{in} \tag{13}$$

Here A – membrane area, м2; Q_{im} - membrane permeability mole/(Pa*s*m2); R_{im} - non-dimensional permeability of the membrane.

Non-dimensional parameters, used in the system, are defined in the following way:

$\tilde{c}_{il0} = \dfrac{c_{il0}K_{i0}}{P_m}$, here Henry constant for the system of i component in the case of high dilution.

$B_{ilm} = \frac{K_{i0} b_l q_{in}}{D_{il} P_m}$, size $B_{ilm} \tilde{R}_{im}$ characterizes impact of limited productivity of membrane that is it means that diffusion in membrane is a limiting stage.

$$A_g = \frac{3}{\chi B_g * \mathrm{Re}_g * \delta_g} \quad (14)$$

Here $\mathrm{Re}_g = \frac{b_g * V_0}{v_0}$, $\delta_g = \frac{b_g}{l}$, $B_g = \frac{P_m}{\rho_0 V_0^2}$, $\chi = \frac{H}{l}$, V_0 - average velocity at the entry into the module, v_0 - kinetic viscosity at the entry into the module m2/s, $Pe_{ll} = \frac{q_m l R T}{D_0 P_{in} H b_g}$ - Peclet number for gaseous phase, characterizes impact of longitudinal diffusion.

Thus, mathematical model of mass transfer process in membrane contactor has been formulated.

$$\tilde{P}_{out} = \frac{P_{out}}{P_{in}} \quad (15)$$

3. Results

The set problem is integrated with Runge-Kutta method of the fourth degree. While establishing initial conditions, the problem amounts to Cauchy problem.

As a result of numerical experiments data, reflected in Fig.4, in comparison with experimental data from [4] have been got.

4. Conclusions

It can be said that considered system in this work is completed, and describes membrane contactor as a separating device for gas mixture. Moreover considered condition of mass transfer through membrane is more general, than considering one of porous membranes. So that the outlined system well describes systems on porous membranes it is sufficient to use membrane permeability, typical for them.

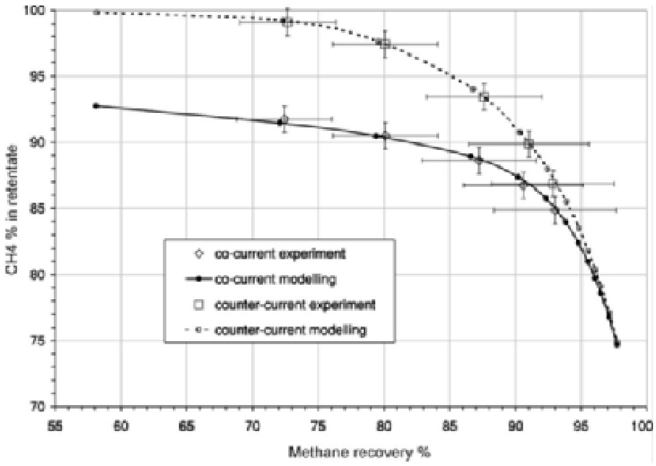

Fig.4. Change of methane concentration at straight current and counter current arrangement of flow.

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