The Development of a New Membrane Equipment Type and Modeling its Work

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Abstract. The article discusses the main advantages of the effective use of membrane technologies in industrial production. The key directions of development of membrane technology, their advantages and disadvantages are given. Various approaches are considered in the design of membrane devices. Methods of mathematical modeling are proposed. They allow analyzing various technological processes. A modeling technique based on transfer functions has been developed. This technique takes into account the influence of the most significant disturbing actions on the object under study. A transfer function in its general form has been constructed. The discrepancy between experimental and theoretical data does not exceed 10%, which indicates the adequacy and sufficient prognostic ability of the mathematical model. It makes it promising for the industrial equipment design.

1. Introduction
Membrane technologies are widely used now in various industries: food, chemical, biotechnological and pharmaceutical, etc. This is due to the high efficiency of their use. The main advantages include: high rates of obtained products without increasing the temperature in the processing operation, which is important in the treatment of biologically active media that are subject to inactivation; the possibility of creating low-waste and waste-free technologies due to wastewater treatment with the purpose of their reuse in technological cycles, as well as the extraction of valuable or environmentally hazardous substances that water contains; relatively low energy costs for carrying out the process [5,6,17].

Over the past 50 years, the global membrane market has been growing by 8–12% annually. At the same time, about 9% of it falls on the biotechnological industry. We obtain fairly stable ratios if compare the ratio of the membranes market volume to the volume of GDP in the developed countries.

Membrane processes can be used for separating biomass from the culture liquids, for isolating biosynthesis products, for desalting and purifying proteins, for concentrating target components, for cell cultivation in membrane bioreactors and for the liquids to be sterilized [1,2,3,18,19]. These processes are used in the production of vitamins, enzymes, amino acids, BAS, organic acids, carbohydrates, polysaccharides, antibiotics, etc. [14].

2. Results and discussion
Currently, several directions of membrane technology development have been formed:
– the use of additional coating of membrane elements with hydrophilic polymers that reduce the adhesion of the polarization layer [16];
– the increase of specific working surface of the apparatus, which allows to create compact equipment with a high filtering surface [4];
– the use of various methods and devices that reduce concentration polarization and increase productivity [15,21].

The analysis shows that polymeric materials are not universal for products with different properties, but are suitable only for certain groups [7,8]. In addition, there may be restrictions on their use in the food processing, in the processing of medicinal drugs and baby food.

The downside while creating compact devices with a high specific surface is the difficulty of operation due to the low maintainability.

The use of various methods and devices that reduce the concentration polarization leads to the cost increase and to the process complication.

In addition, a common drawback of these directions is the impossibility of a complete elimination of the retained substances layer formation on the membrane surface (the phenomenon of concentration polarization).

Nowadays a promising direction in the membrane technology is the use of a polarization layer [12]. The possibility of its use is due to the fact that it has a greater concentration than the solution in the membrane apparatus. Its use greatly intensifies the speed of the process and will reduce the concentration duration. The proposed approach involves the creation of new devices types, which fundamentally different from the standard ones, and the creation of membrane plants in which they can be used.

On the basis of the proposed method we have developed the designs of membrane devices and installations, the technical novelty of which is protected by 20 patents of the Russian Federation [13].

These types of devices can be divided into three groups:
– equipment in which the layer is removed;
– devices in which the membrane is cleaned periodically together with the removal of the layer;
– constructions that simultaneously remove the layer and clean the membrane.

Analysis of the first group shows this equipment is the simplest in technical design. Therefore, the cost of its manufacture will be low. Its disadvantage is a decrease in the concentration of the exhaust layer during the operation due to the accumulation of stationary sediment on the membrane. This leads to a decrease in the membrane permeability, which also reduces productivity.

A second group of devices was proposed, because of the drawbacks of the first group. The distinguishing characteristic of the second group is the possibility of carrying out periodic membrane cleaning. This allows getting rid of sediment accumulated on the membrane, and to increase the productivity of the filtrate, as well as to maintain the concentration of the withdrawn polarization layer at a sufficiently high level. However, the layer is not discharged at the time of cleaning, which means that the duration of the main work decreases and along with the productivity of these devices also decreases.

From the point of view of high performance, the third group of membrane constructions is the best. The main characteristic of these constructions is the possibility of joint work on the polarization layer removal and cleaning of the membrane. Various variants of technical solutions are used for this purpose. This allows maintaining a high membrane permeability for a sufficiently long time. It favourably affects the concentration of the polarization layer. The disadvantage of this group is a more complex apparatus design. As a result, this construction is of a higher cost.

On the basis of experimental samples, the industrial equipment was developed, which consists of a membrane apparatus and a diverter attached to it (Figure 1).

The equipment includes a discharge device (1), which has a fitting for the polarizing layer removing (2). The discharge device is connected to the membrane apparatus (3). The initial solution enters the membrane apparatus through the fitting (4). The depleted stream is discharged through the fitting (5). The filtrate formed during the concentration process leaves through the fitting (6).
The principle operation of such equipment is as follows: the initial solution enters the apparatus and, using membranes, is separated into a filtrate that is withdrawn from the body, a lean stream and a more concentrated polarization layer, produced in the diverter. When concentrating the solutions, the final product is a polarization layer. Its quantity and concentration depend on the design of the diverter. Therefore, special attention was paid to the diverter development. There are several approaches to its design:
- the manufacture of individual components and parts and their subsequent assembly to obtain a finished sample;
- the use of 3d modeling to produce a finished model.

The second method is more expedient, since it is less labour intensive. However, the accuracy of manufacture in this case is somewhat lower and it is inferior in quality to the first.

An important role in the study of membrane processes is the mathematical modeling. When modeling these processes, different methods of research are the most widely used. These methods are as follows: analytical research, mathematical statistics and the cybernetic approach, implemented on the basis of the transfer function mechanism [11].

Analytical studies of membrane processes allow creating systems of differential equations which describe membrane processes. This equation most accurately reflects the nature of the processes, their behaviour, structure and properties, i.e. fully reflect the theory of their work. Such theoretical models are the best in terms of predicting the results of technological processes. But the creation of such models is a time-consuming process that requires fundamental theoretical knowledge of a particular process. Unfortunately, not all technological processes have such a scientific basis for the research.

In addition to the difficulties in compiling theoretical models, there are difficulties in analyzing them. It is easy to analyze the low-order differential model (1st and 2nd), but the analysis of high-order models is more complex and often is made by numerical methods. Therefore, in cases where it is not necessary to delve into the nature of the technological process, and it is only needed to make a prediction of the process, it is perfectly acceptable to use other methods of mathematical modeling.

One of the most common methods for identifying dependencies in objects and making predictions of their work are the methods of mathematical statistics. They allow making empirical stochastic models on the basis of experimental data. These models give results with satisfactory accuracy. The disadvantage of this type of modeling is a strong attachment to experimental data.

The method of mathematical modeling, which is at least inherent in the above disadvantages, is a cybernetic approach. The cybernetic approach together with the system approach allows representing the technological process as a system that operates according to its nature and principles. The structure of the system is a so-called “black box”. The structure helps to study the behaviour of system, i.e. its reaction to various external influences, abstracting from its internal structure. Many systems are so complex that even with the complete information about their elements state, it is almost impossible to
associate this information with the behaviour of the system as a whole. In such cases, the representation of such a complex system in the form of a “black box” functioning in a similar way facilitates the construction of a simplified model. Analyzing and comparing the behaviour of the model with the behaviour of the system, we can draw a number of conclusions about the properties of the system itself.

An important factor in the use of this approach is the possibility of carrying out complex process automation, including the use of feedback. This allows you to influence the work of the working bodies that ensure the operation of the equipment in order to optimize the process.

With regard to the new type of devices described above, a modeling technique has been developed based on the transfer functions. Due to the fact that all membrane devices with the removal of the polarization layer are a combination of a membrane module and a diverter, an information (structural) scheme (Fig. 2) is proposed for them, which includes the membrane module and the diverter.

![Figure 2. Information scheme membrane devices with the removal of the polarization layer. I - membrane module; II – diverter; X1 - Input signals; α, β1, γ1 - disturbing signals; Z1 - intermediate signals; Y1 - output signals.](image)

To make a mathematical model according to the above scheme (Fig. 2), it is logically must be divided into its component parts, transfer functions for the latter being selected. Then the obtained functions are sequentially combined in accordance with the nature of the described system. Thus, the obtained model shows the influence of all the above disturbing actions on the object under study.

As a result of the described calculations, the transfer function was obtained in a general form (1):

\[ Y = f(\beta) \]

To confirm the universality and adequacy of the proposed modeling methodology, an analysis of the experimental data was carried out. These experimental data were obtained on a pilot plant. The obtained theoretical data based on the mathematical model were compared with the obtained experimental data. The discrepancy between theoretical and experimental data does not exceed 10%, which indicates that the model is sufficiently adequate and makes it promising for the design of industrial equipment.

3. Conclusion

Based on the conducted research and calculations, conclusions about the prospects, high productivity, economic and environmental efficiency of a new type of equipment were made. The use of polarization concentration phenomenon for the improving performance of membrane equipment allows you to create high-tech and highly efficient low-waste production and to carry out the most complete processing of raw materials without a significant increase in energy costs.

The possibility of simulating this equipment with cybernetics methods helps accelerate the introduction and launching membrane processing lines into the production. The described modeling methodology can be implemented programmatically. It will significantly reduce the labour costs of the preparatory implementation phase.
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