ІНЖЕНЕРНО-ТЕХНІЧНЕ ЗАБЕЗПЕЧЕННЯ ТЕХНОЛОГІЙ ХАРЧОВОЇ ІНДУСТРІЇ

UDC 663.81.05:664.857.081.6-93
DOI: https://doi.org/10.31359/2312-3990X-2025-38-2-126

IMPROVING THE DESIGN OF MEMBRANE EQUIPMENT FOR CONCENTRATING AND PURIFYING JUICES

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The article considers the theoretical principles of improving the design of membrane equipment for concentrating and purifying juices. The current state of membrane technologies is analyzed, the main problems of the operation of the devices are identified, and a design concept with turbulizing inserts is proposed, aimed at increasing the efficiency of mass transfer, reducing membrane contamination, and improving the energy efficiency of the process.

Keywords: *membrane filtration, fruit and berry juices, ultrafiltration, purification, membrane selectivity, product quality, technological parameters*

УДОСКОНАЛЕННЯ КОНСТРУКЦІЇ МЕМБРАННОГО ОБЛАДНАННЯ ДЛЯ КОНЦЕНТРУВАННЯ ТА ОЧИЩЕННЯ СОКІВ

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У статті представлено теоретичне обґрунтування удосконалення конструкції мембранного обладнання для концентрування та очищення соків, що є актуальним напрямом розвитку харчової промисловості. Мембранні технології дозволяють здійснювати процеси очищення, освітлення та концентрування продуктів при низьких температурах, що забезпечує збереження біологічно активних речовин, ароматичних компонентів та смакових якостей соку. Водночас існуючі промислові апарати мають певні обмеження, пов'язані з нерівномірним розподілом потоку по поверхні мембран, утворенням концентраційного шару, забрудненням мембран та високими енергетичними витратами.

У статті здійснено аналіз сучасних типів мембранних модулів – спірально-звитих, трубчастих та порожньоволоконних – і визначено їхні переваги та недоліки. На основі цього проведено формування концепції удосконаленої конструкції мембранного апарата, яка передбачає інтеграцію турбулізуючих вставок у канали фільтраційного модуля для забезпечення

рівномірного розподілу тиску та швидкості потоку. Така конструкція має потенціал зменшення концентраційної поляризації, підвищення коефіцієнта масоперенесення, зниження енергоспоживання та подовження терміну служби мембран.

У роботі наведено схему майбутнього апарата та таблицю очікуваних технічних параметрів, порівняно з традиційними установками. Акцент зроблено на необхідності подальшого моделювання гідродинамічних умов методом обчислювальної гідродинаміки, створення моделі та виготовлення дослідного зразка для експериментальної перевірки.

Отримані результати створюють науково-технічну основу для розробки ефективної мембранної установки, що сприятиме підвищенню продуктивності, покращенню якості кінцевого продукту, збереженню біоактивних речовин і енергозбереженню на підприємствах сокової промисловості, а також нададуть основу для впровадження інноваційних технологій у харчовому виробництві.

Ключові слова: *мембранна фільтрація, плодовоягідні соки, ультрафільтрація, очищення, селективність мембран, якість продукту, технологічні параметри*

Statement of the problem. The modern food industry, in particular juice production, is actively developing in the direction of increasing the efficiency of technological processes, preserving the naturalness of products and minimizing energy costs. One of the key stages in the production of juices is their concentration and purification, on which the quality of the final product, stability during storage and transportability largely depend. Traditional methods of concentration - evaporation or heat treatment - are accompanied by significant energy consumption and lead to the loss of biologically active substances, aromatic and flavor components. In this regard, the scientific and technical community is increasingly paying attention to membrane technologies as an effective alternative to classical processes [1]. Membrane methods, such as reverse osmosis, nanofiltration, ultrafiltration and microfiltration, allow for the purification and concentration of juices at low temperatures, ensuring the preservation of their natural composition and organoleptic properties. However, the implementation of membrane processes on an industrial scale faces a number of problems, including low productivity due to membrane contamination, high cost of their replacement, difficulty in ensuring a stable hydrodynamic regime and uneven distribution of flows in the module. That is why the issue of improving the design of membrane equipment aimed at increasing the efficiency of mass transfer, reducing the phenomenon of concentration polarization and increasing the durability of membranes is becoming particularly relevant [2].

In addition, modern requirements for food production include not only technical efficiency, but also environmental safety and economic feasibility of processes. The development of innovative designs of membrane devices must take into account the optimization of energy consumption, the possibility of automated process control and ease of maintenance [3]. Thus, the current scientific and technical problem is the creation of improved membrane systems for concentrating and purifying juices, ensuring high product quality, energy saving and long-term stability of operation. Solving this problem will help increase the efficiency of processing enterprises, expand the possibilities of processing fruit and berry raw materials, and reduce the environmental burden on the environment.

Review of the latest research and publications. In recent years, membrane technologies for juice purification and concentration have attracted considerable attention from scientists as an energy-efficient and quality-friendly alternative to traditional thermal methods [4]. Review papers summarize that micro- and ultrafiltration are effective for preliminary classification and clarification of juices, while nanofiltration and reverse osmosis provide increased removal of trace elements and partial concentration at lower temperatures, which contributes to the preservation of aromatic and biologically active components [5]. This general trend is confirmed by a number of works that record the advantages of membrane operations in terms of final product quality and energy consumption [6].

One of the key problems that is repeated in modern publications is the fouling of membranes during juice processing (pectin, proteins, colloids, sucrose), which leads to a rapid drop in productivity and the need for frequent washing cycles [7]. Review studies classify the mechanisms of contamination, indicate the factors (feedstock composition, temperature, hydrodynamics, pressure) and describe existing approaches to control - chemical and mechanical cleaning, mode optimization, pre-treatment of feedstock [8].

A separate direction is the improvement of the design of modules and elements that affect the flow distribution and intensification of mass transfer: channel geometry, spacer network structure, the use of three-dimensional printed spacer elements, as well as the modernization of flat-film and tubular modules [9]. New studies show that optimized spacers and innovative module configurations can significantly reduce concentration polarization and contamination retention [10].

Another notable trend is the modification of membrane surfaces (hydrophilic coatings, nanocomposites, antimicrobial layers) to increase resistance to contamination and extend maintenance intervals [11]. Recent

reviews also highlight the potential of thermal-membrane hybrids (e.g. membrane distillation, forward/reverse osmosis combined with UF/MF) to achieve higher degrees of concentration without significant energy penalties [12]. Despite significant progress, gaps are identified in the literature: the need for standardized tests for different types of juices, economic evaluations of scaling up, and longer-term field tests of new designs [13]. Therefore, the scientific and engineering challenge of integrating material science approaches, hydrodynamic module optimization, and adequate fouling management strategies remains open and determines the direction of further research.

The objective of the research. The purpose of the article is to analyze the current state of development of membrane technologies for concentrating and purifying juices, to substantiate the directions for improving the design of membrane equipment in order to increase efficiency, energy saving, and quality of the final product.

Materials and methods. In the process of preparing the article, open scientific sources were used, containing modern approaches to the design, modeling and analysis of the operation of membrane equipment intended for the concentration and purification of food liquids, in particular juices. The main attention is paid to the methods of comparative analysis of scientific works, technical standards and patent decisions, which allows systematizing information on the principles of constructive improvement of membrane modules and factors that determine their efficiency in the food industry [14].

The method of structural and functional analysis was used to summarize information on the structure of membrane elements of various types - tubular, spiral-wound, plate and capillary. This made it possible to identify key structural parameters, such as the geometry of the channels, the type of material, the thickness of the selective layer, hydrodynamic conditions in the module, as well as to determine their influence on the mass transfer resistance and the intensity of membrane surface contamination [15].

The critical review method was used to evaluate the technological regimes used in ultrafiltration and reverse osmosis of juices. Based on the analysis of scientific publications, the parameters that most often vary in studies were considered: flow rate, pressure, temperature, turbulence level, mechanisms for preventing fouling, methods of hydrodynamic amplification.

The comparative systematization generalization method allowed to structure approaches to optimizing the design of membrane equipment: by improving the movement of fluid in the channels, using turbulization inserts, changing the configuration of the flow part, using the latest polymer and

composite materials, increasing the resistance of the membrane layer to colloidal and organic contaminants.

In addition, the classification generalization method was used to organize the criteria for the effectiveness of membrane processes - productivity, degree of selectivity, stability of filtration characteristics, energy consumption and resource of membranes. This made it possible to determine which parameters of the device design are the most promising for further improvement.

Thus, the methods used provided a comprehensive overview of existing engineering solutions and scientific approaches, which allows us to form a holistic vision of the directions for improving the design of membrane equipment for juice production.

Presentation of the research material. Membrane technologies are currently one of the most promising areas for intensification of juice purification and concentration processes, as they provide high efficiency at low temperatures and allow preserving the natural properties of the product. Unlike thermal methods, membrane processes allow minimizing the loss of aromatic and biologically active substances, as well as reducing energy costs. However, despite significant progress in this area, most industrial plants have certain disadvantages, in particular, uneven flow distribution over the membrane surface, high susceptibility to contamination, reduced productivity during long-term operation, and significant costs for cleaning elements. That is why the current study is aimed at theoretical justification and development of a concept for an improved design of membrane equipment for juice concentration and purification. At this stage, the work is mainly analytical and design in nature and involves the creation of a model of a future plant, which will later be manufactured and experimentally tested [16].

Analysis of existing types of membrane devices shows that the most common are spiral-wound, tubular and hollow fiber modules. They are characterized by compactness, high specific productivity and ease of maintenance. However, during the operation of such systems, intensive formation of a concentration layer on the membrane surface is observed, which reduces the filtration rate [17]. Therefore, one of the main areas of improvement is the optimization of the hydrodynamics of the flow in the module channels, the creation of conditions for turbulization of the liquid movement, which will prevent the formation of stagnant zones and reduce the polarization effect [18]. The proposed conceptual scheme of the improved membrane device has the following form.

Figure 1 shows the conceptual scheme of the improved membrane device.

The design involves the use of a flat-film or tubular module with integrated turbulators (special perforated or spiral inserts), which ensure a uniform distribution of pressure and flow velocity. This will improve the conditions of mass transfer on the membrane surface and increase its efficiency.

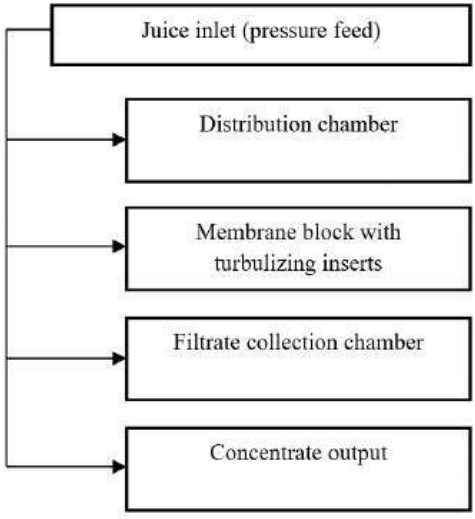

Fig. 1. Conceptual diagram of an improved membrane device

It is planned that the device will operate in reverse osmosis or nanofiltration mode, depending on the task at hand – purification or concentration of juice. The use of a combined approach (for example, sequential use of ultrafiltration and nanofiltration modules) will allow combining high transparency of the filtrate with an increase in the content of dry substances in the concentrate [19].

For further development of the design, it is planned to conduct modeling of the hydrodynamic characteristics of the flow using the computational hydrodynamics method. This will allow determining the optimal geometric parameters of the channels, the angle of inclination of the inserts, the intervals between them, as well as the ratio of pressure and juice flow rate.

In the future, it is expected that improving the design will allow achieving the results shown in table 1.

As can be seen, the predicted indicators indicate the prospects of the proposed direction, since they allow to improve not only the technical, but also the economic characteristics of the process.

In addition to hydrodynamic optimization, attention will be paid to the selection of membrane materials and structural elements of the apparatus. To minimize contamination, the possibility of using polymers with increased hydrophilicity (for example, polyamide or polysulfone membranes with a surface coating based on titanium or silicon oxides) is being considered. Such materials have high antifouling properties and a longer operational life.

Table 1

Expected performance of promising equipment (compared to traditional installations)

Indicator	Expected result (compared to traditional installations)
Uniformity of flow distribution	+15–20 %
Mass transfer coefficient	+25 %
Concentration polarization intensity	-20 %
Specific energy consumption	-10–15 %
Membrane cleaning frequency	-30 %
Expected membrane life	+25–30 %
Filtrate transparency	Improvement on 30 %
Preservation of bioactive substances	90–95 %

The structural design of the apparatus provides for the possibility of modular connection of elements, which will allow to easily adapt the installation to different production volumes - from laboratory to industrial scales. The modular structure also simplifies maintenance, repair and replacement of individual membrane elements without stopping the entire process.

Among the tasks of the subsequent stages of the study are the creation of a model of the apparatus, calculation of operating parameters (flow rate, pressure drop, membrane layer resistance) and experimental verification of the obtained data. It is assumed that after confirmation of theoretical calculations, a prototype of the device will be manufactured, which will be tested on model juice solutions of different concentrations.

It is expected that the results of the experiments will allow to improve the design of the device, determine the optimal operating modes and

formulate practical recommendations for industrial implementation. In addition, the data obtained can become the basis for creating an automated control system for the membrane concentration process, which will increase the stability and controllability of juice production.

Thus, this study lays the scientific and technical foundation for the development of a new effective design of membrane equipment. At this stage, an analytical review of modern approaches was conducted, the concept of the future device was formed, the key parameters that affect its efficiency were determined, and the expected results after the development were presented. The next stage of the work will be the creation of a prototype and its testing in conditions as close as possible to industrial ones.

Conclusion. The conducted research is of a theoretical and design nature and is aimed at substantiating the concept of an improved design of membrane equipment for concentrating and purifying juices. Analysis of modern technologies showed that the main problems of existing systems are uneven flow distribution, formation of concentration polarization and rapid contamination of membranes. The proposed concept of the apparatus involves the use of turbulators in the filtration channels, which should ensure intensification of mass transfer, reduction of polarization and increase in process efficiency. It is expected that the implementation of such a design will allow to increase the mass transfer coefficient, reduce energy consumption and extend the service life of membranes. Further research involves the creation of a model of the apparatus, hydrodynamic modeling and the manufacture of a prototype for experimental verification of the results obtained.

Список джерел інформації / References

1. Lu, C., Bao, Y., & Huang, J. Y. Fouling in membrane filtration for juice processing. *Current Opinion in Food Science*, 2021, Vol. 42, pp. 76–85. https://doi.org/10.1016/j.cofs.2021.05.004.

2. Katibi, K. K., Mohd Nor, N., Yunos, K. F., et al. Strategies to enhance the membrane-based processing of fruit juices: A review. *Membranes*, 2023, Vol. 13(7), pp. 679. https://doi.org/10.3390/membranes13070679.

3. Sarbatly, R., Hashim, M., et al. Recent developments of membrane technology in the clarifying and concentrating fruit juice. *Processes*, 2023, Vol. 11(4), pp. 1012–1027. https://doi.org/10.3390/pr11041012

4. Khorshidian, N., Khademi, F., et al. Effect of membrane clarification on the physicochemical properties of juices. *International Journal of Chemistry and Chemical Engineering*, 2022, Vol. 16(2), pp. 45–56.

5. Cifuentes-Cabezas, M., et al. Deep study on fouling modelling of ultrafiltration membranes: Implications for juice processing. *Food and Bioprocess Technology*, 2023, Vol. 16, pp. 234–245. https://doi.org/10.1007/s11947-023-03033-0.

6. Kujawa, J., Rozicka, A., Cerneaux, S., & Kujawski, W. Raw juice concentration by osmotic membrane processes. *Journal of Food Engineering*, 2015, Vol. 158, pp. 59–68. https://doi.org/10.1016/j.jfoodeng.2015.03.012

7. Cherevko O.I., Deinychenko G.V., Dmytrevskyi D.V., Guzenko V.V., Heiier H.V., Tsvirkun L.O. Application of membrane technologies in modern conditions of juice production. Progressive technique and technologies of food production enterprises, catering business and trade, 2020, Vol. 2 (32). pp. 67-77. https://doi.org/10.5281/zenodo.4369743.

8. Bhattacharjee, C. Fruit juice processing using membrane technology: A review. *Food Engineering Reviews*, 2017, Vol. 9(1), pp. 35–48. https://doi.org/10.1007/s12393-017-9155-x

9. Deynichenko, G., Guzenko, V., Dmytrevskyi, D., Chervonyi, V., Omelchenko, O., Horielkov, D., Korolenko, O. Developing a technique for the removing of a gel layer in the process of membrane treatment of pectin extract. Eastern-European Journal of Enterprise Technologies, 2020, 4(11–106), 63–69. https://doi.org/10.15587/1729-4061.2020.208984.

10. Deynychenko, G., Guzenko, V., Dmytrevskyi, D., Chervonyi, V., Kolisnichenko, T., Omelchenko, O., Nykyforov, R. Study of the new method to intensify the process of extraction of beet pulp. Eastern-European Journal of Enterprise Technologies, 2018, 4(11–94), 15–20. https://doi.org/10.15587/1729-4061.2018.140126.

11. Gulec, H. A., Bagci, P. O., & Bagci, U. Clarification of apple juice using polymeric ultrafiltration membranes: A comparative evaluation of membrane fouling and juice quality. *Food and Bioprocess Technology*, 2017, Vol. 10(5), pp. 875–885. https://doi.org/10.1007/s11947-017-1871-x

12. De Barros, S. T. D., Andrade, C. M. G., Mendes, E. S., & Peres, L. Study of fouling mechanism in pineapple juice clarification by ultrafiltration. *Journal of Membrane Science*, 2003, Vol. 215(1–2), pp. 13–24. https://doi.org/10.1016/S0376-7388(02)00615-4

13. Ilame, S. A., & Singh, S. Application of membrane separation in fruit and vegetable juice processing: A review. *Critical Reviews in Food Science and Nutrition*, 2015, Vol. 55(7), pp. 964–987. https://doi.org/10.1080/10408398.2012.679979

14. Fukumoto, L. R., Delaquis, P., & Girard, B. Microfiltration and ultrafiltration ceramic membranes for apple juice clarification. *Journal of Food Science*, 1998, Vol. 63(5), pp. 845–850. https://doi.org/10.1111/j.1365-2621.1998.tb17912.x

15. Dornier, M., Belleville, M. P., & Vaillant, F. Membrane technologies for fruit juice processing. In *Fruit Preservation* (pp. 211–248). Springer, 2018. https://doi.org/10.1007/978-1-4939-3311-2_8

16. Zhao, D., Lau, E., Huang, S., & Moraru, C. I. The effect of apple cider characteristics and membrane pore size on membrane fouling. *LWT – Food Science and Technology*, 2015, Vol. 64, pp. 974–979. https://doi.org/10.1016/j.lwt.2015.07.001

17. Verma, S. P., & Sarkar, B. Analysis of flux decline during ultrafiltration of apple juice in a batch cell. *Food and Bioproducts Processing*, 2015, Vol. 94, pp.

147–157. https://doi.org/10.1016/j.fbp.2015.03.002

18. Deynichenko, G., Dmytrevskyi, D., Guzenko, V., Omelchenko, O., Perekrest, V. Prospects of using equipment for membrane separation of food liquids**.** Scientific bulletin of the Tavria State Agrotechnological University, 2023. Vol. 13, № 2. С. 1-11. https://doi.org/10.31388/2220-8674-2023-2-12.

19. Deinychenko G.V., Dmytrevskyi D.V., Zolotukhina I.V., Perekrest V.V., Guzenko V.V. Directions of improvement of processes of membrane separation of juices from fruit and berry raw materials. Progressive technique and technologies of food production enterprises, catering business and trade, 2021. Vol. 1 (33). pp. 89–98. https://doi.org/10.5281/zenodo.5036090.

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Прийнято 18.11.2025 р. Оприлюднено 01.12.2025р.

УДК 621.798:664]:330.341.1
DOI: https://doi.org/10.31359/2312-3990X-2025-38-2-136

ІННОВАЦІЙНІ РІШЕННЯ У РОЗРОБЦІ ПАКУВАЛЬНОЇ ТАРИ ДЛЯ ПРОДУКЦІЇ ХАРЧОВОЇ ТА ПЕРЕРОБНОЇ ПРОМИСЛОВОСТІ

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У статті розглянуто сучасні інноваційні рішення у сфері розробки пакувальної тари для харчової та переробної промисловості. Проаналізовано тенденції застосування біорозкладних, активних і «розумних» пакувальних матеріалів, їх переваги та особливості впровадження. Визначено перспективні напрями удосконалення конструкцій тари з урахуванням екологічних і технологічних вимог виробництва.

Ключові слова: *пакувальна тара, інноваційні рішення, харчова промисловість, переробна промисловість, екологічна упаковка, біорозкладна тара, бар'єрні властивості, стійкість, дизайн упаковки, зберігання продуктів*

INNOVATIVE SOLUTIONS IN THE DEVELOPMENT OF PACKAGING FOR FOOD AND PROCESSING INDUSTRY PRODUCTS

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The article explores innovative approaches to the development of packaging for food and processing industry products in the context of modern environmental, technological and economic challenges. The current trends in the development of packaging materials are analyzed, in particular the introduction of biopolymers, active and intelligent packaging systems that are able not only to ensure product