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Effect of Transmembrane Pressure on Microfiltration Concentration of Yeast Biomass

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Abstract—An experimental study on the separation of mature molasses broth using a microfiltration unit with a plate-and-frame module has been carried out, and data on the flux and the rejection factor for MMPA$^+$ (P = 0.05 or 0.1 MPa), MPS (P = 0.3 or 0.5 MPa), and MFFK (P = 0.05, 0.1, 0.3, or 0.5 MPa) membranes have been obtained. The revealed relations of the flux to the separation time and the transmembrane pressure for the membranes under study indicate that a dynamic membrane forms during the separation of the molasses broth. This dynamic membrane serves as an additional barrier to the solvent and is eventually compacted to retard yeast cells and polysaccharides and pass more than 80% of ethyl alcohol. The flux for the MFFK and MPS membranes in the separation of mature molasses broth increases with increasing transmembrane pressure, a change that is associated with an increase in the working pressure as the driving force of the process, in contrast to the MMPA$^+$ membrane, whose performance is affected by rapid pore clogging and adsorption phenomena, as well as by the appearance of pressure-induced deformations in the form of profiled lines along and across the membrane. Visual analysis of the spent sample of the MFFK membrane, obtained at P = 0.05 MPa and subjected to flushing the dynamic membrane with distilled water for 1200 s, has revealed that the membrane after disassembling the device shows accumulations of various membrane-forming substances (yeast and polysaccharides) in isolated areas at the exit of the flat channel of the device. It is noted that the closer the outlet of the flat channel of the membrane unit, the darker the areas because of the greater accumulation of the membrane-forming yeast and polysaccharide particles.

Keywords: microfiltration membrane, rejection factor, flux

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INTRODUCTION

The feedstock used in the biochemical production of ethyl alcohol in the industry is sugar beet molasses, whose main component is sucrose—essential for the yeast metabolism—making from 40 to 50 wt % of molasses. The molasses also contains organic compounds; potassium, sodium, and iron salts; phosphates; and nitric, sulfuric, and hydrochloric acids [1–3].

Fouling of distillation columns with yeast biomass entails shutdowns of biochemical equipment a few times a year, which reduce the output of ethanol. Daily losses by an enterprise, for example, OAO Biokhim in Rasskazovo, due to shutdown, are estimated at 1000 dal (decaliters) of the finished product.

From the literature it is known that feed solutions are prepared using various separation methods, including ultrafiltration, microfiltration, nanofiltration, etc. [4, 5]. Existing scanty data on the preparation of mature molasses broth for use in distillation units characterize complexity of the technological equipment and do not account for the specifics of alcohol production from sugar beet molasses, which usually comprises a bacterial flora that comes with the feedstock from sugar factories and lives in supplier containers because of their poor treatment (sterilization) [1, 6].

Analysis of published data [7–11] shows that the use of membranes for purification and concentration of biological solutions containing yeast and colloidal particles is always carried out under special experimental conditions. For example, Lewis et al. [7] used hydrodynamic measurement (calibration) to study fouling during microfiltration of inactive *Saccharomyces cerevisiae* yeast through cellulose ester membranes with a nominal pore size of 5 μm. By this method, the thickness of the deposit layer was studied in the online mode; the initial growth rate was approximately 0.81 μm s^{-1} at a transmembrane pressure of TMP = 35 mbar and Re = 1000. It was found that preformed deposits of more than 250 μm in thickness were deformed by a shear stress of <10 N m^{-2}, which was explained by the loose adhesion of the yeast to the membranes surface and the deposits. It was noted that the range and accuracy of the measurement of the thickness of the deposits depends on the strength of

the fouling of the layers and the operating conditions of the apparatus [7].

Gençal et al. [8] studied the filtration of yeast suspensions on profiled and nonprofiled membranes. Chemical components for the fabrication of microfiltration membranes were 10% polyester, 60% polyethylene glycol 400 (PEG 400), 5% water, and 25% *N*-methyl-2-pyrrolidone (NMP). These membranes were tested in the tangential mode of filtration of yeast suspension and at various flow rates. It was noted that the nonprofiled and profiled membranes differed insignificantly in the rate of fouling [8].

Lemma et al. [9] investigated the ability of nylon-6 nanofibrous membranes prepared by electroforming to remove bacterial microflora and yeast. It was noted that nanofibrous membranes are applied as affine membranes for selective capture of molecules on the membrane surface but they are practically not used in the food industry. Experiments were conducted in the dead-end filtration mode at a fixed flow rate with samples of beer enriched in yeast (*Saccharomyces cerevisiae*) and bacteria (*Flavobacterium johnsoniae* and *Iodobacter fluviatilis*) in the range of 1.0×10^4 to 5.1×10^8 CFU/mL (colony-forming unit). As a result of the study, it was shown that the flow resistance is proportional to the pore size. It was noted that the yeast forms soft deposits with the lowest resistance. Lemma et al. [9] suggested that the bacteria of these species form a pack mechanism that affects denser, pore-reducing deposits, leading to an increase in resistance. Their study has shown that it is possible to completely remove *S. cerevisiae* from aqueous solutions, in contrast to bacteria of one species, which could not be removed in all separation cycles. Good filtration results were obtained by mixing two strains of bacteria, which led to the complete removal of the bacteria [9].

Gabrus and Szaniawska [10] reported the results of a study of the microfiltration separation of yeast-containing solutions using inorganic TiO_2/Al_2O_3 membranes with varying the transmembrane pressure in the range of 120–320 kPa and the circulation rate of the solution in the membrane module of 2.73–4.55 m/s. The microfiltration process was carried out at a constant temperature of 20°C and a yeast content of 510 mg/L. It was noted that the microfiltration membranes were subjected to backwashing every 10 min at constant operating parameters, the transmembrane pressure of 150 kPa and the process time of 60 s. It was proposed to use the experimental data [10] for analysis of mathematical equations obtained using semiempirical models of filtration in stationary flows.

Maruf et al. [11] studied the separation of colloidal solutions through ultrafiltration membranes with a profiled surface. They noted that the critical flow for these membranes increases with increasing particle size, cross-flow velocity, profile height, the angle between the directional flow and the surface profile. It was proposed to use the obtained data to study the solution separation process and the membrane fouling mechanism.

The actively developing line in the treatment of biological solutions is processes using various membrane bioreactors [12–14]. Although there is the problem of membrane fouling (clogging) during pervaporation, it can be solved using domestic membranes, such as PTMSP 1-8 (polytrimethylsilylpropyne), which can be regenerated sufficiently well with ethanol after separation of the fermentation mixture [15].

However, there is no data in the literature on the universality of the above discussed membrane technologies for the treatment of various kinds of fluids; whereas for the efficient separation of yeast-containing biological solutions of particular productions it is necessary to employ elaborated membrane technologies using commercially available materials, for example, microfiltration membranes.

Studies on broth separation conducted in cooperation by the Belarusian State Technical University, the Institute of Applied Mechanics, and the Institute of Physical and Organic Chemistry (National Academy of Sciences of Belarus) proved some advantages of using microfiltration, which include maintaining a high concentration of ethanol. But the application of the hand-made microfiltration membranes fabricated at the IAM and IPOC by sintering expensive materials (titanium, stainless steel) shows the complexity of the technological equipment for production on a commercial scale [16].

A promising direction is the use of the microfiltration separation process for the treatment of mature molasses broth with the use of domestic polymeric membranes manufactured by Technofilter (Vladimir).

The purpose of this study was to use the microfiltration process for recovery of yeast biomass from mature molasses broth with varying transmembrane pressure and the membrane type (MFFK, MPS, and $MMPA^+$).

The objects of the study were

—commercially available (Technofilter, Vladimir) porous microfiltration membranes MFFK, 0.45 μm (hydrophobic film made from fluoroplastic F42L (tetrafluoroethylene copolymer with vinylidene fluoride) reinforced with nonwoven polypropylene); MPS, 0.45 μm (hydrophilic polyethersulfone membrane with an asymmetrical pore structure); and $MMPA^+$, 0.45 μm (hydrophilic polyamide (nylon-6 and nylon-66) membrane with a positive potential); their main characteristics are given in Table 1 [17–19].

—industrial solution of mature molasses broth produced by Biokhim (Rasskazovo), the main characteristics of which are presented in Table 2.

Table 1. Qualitative characteristics of the membranes under study [17–19]

No.	Parameter	Microfiltration membrane		
		MFFK [17]	MPS [18]	$MMPA^+$ [19]
1	Appearance	White microporous film on a nonwoven substrate without visible defects, mechanical inclusions, and damages	White film without visible defects, mechanical inclusions, and damage	White porous film without visible defects: holes, scratches, and folds
2	Disk diameter, m	0.293	0.24	0.293
3	Disk thickness, μm	110	110	100
4	Membrane flux, $dm^3/(m^2\,h)$	Ethanol flux at a pressure of 0.05 MPa, at least 7500	Water flux at a pressure of 0.1 MPa (1 atm), at least 60	Distilled water flux at a pressure of 0.1 MPa (1 atm), at least 50
5	pH	1–13	1–14	2–13
6	Maximal temperature, K	353	373	338
7	Pore diameter, μm	0.45		
8	Price in 2016, rouble/m^2 (without VAT)	308	635	231

Table 2. Main properties and characteristics of mature molasses broth produced by Biokhim (Rasskazovo)

Main properties and characteristics	Unit of measurement	Value
Fermentation tank no. 3		
Color	–	Dark brown (black) cloudy solution
pH	–	5.25
Alcohol content	vol %	9.20
Yeast biomass content	kg/m^3	11.50
Unfermented sugars	g/cm^3	0.525
Fermentation tank no. 10		
Color	–	Dark brown (black) cloudy solution
pH	–	5.34
Alcohol content	vol %	9.60
Yeast biomass content	kg/m^3	14.0
Unfermented sugars	g/cm^3	0.550

EXPERIMENTAL

The mature molasses broth for processing in a microfiltration unit was randomly sampled from fermentation tanks of the production department in equal portions into 10-liter containers to be analyzed at the factory laboratory for the following parameters (Table 2): the pH of the solution, the yeast biomass content (by centrifugation), the alcohol content by distillation, and the amount of unfermented sugars by colorimetry [20–23].

The target criteria for using the microfiltration method in the separation of mature molasses broth were

—production of a yeast-free permeate stream;

—insignificant loss of alcohol during the processing of molasses broth.

The separation of the mature molasses broth was studied according to the experimental procedure for determining the flux and the rejection coefficient of polymer membranes on a microfiltration unit equipped with a typical plate-and-frame membrane apparatus, the process flow diagram of which is shown in Fig. 1.

The main element of the process flow chart of the baromembrane unit for the separation of molasses broth (Fig. 1) was a flat chamber microfiltration appa-

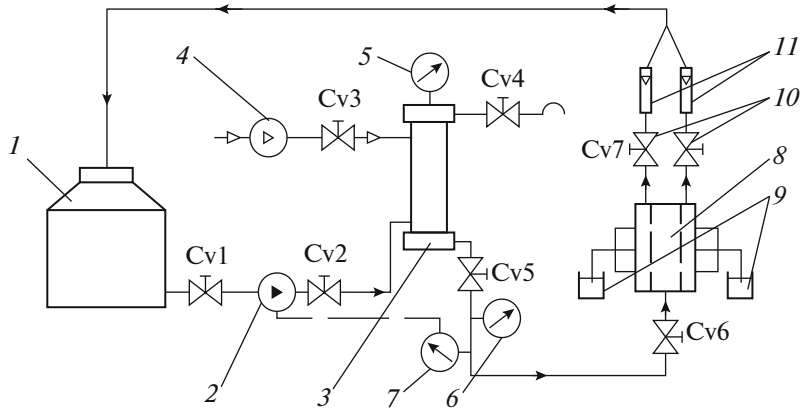

Fig. 1. Process flow diagram scheme of the microfiltration unit: (*1*) feed tank, (*2*) metering pump (ND-120), (*3*) hydraulic accumulator, (*4*) air piston compressor, (*5*) pressure gauge, (*6*) standard pressure gauge, (*7*) electric-contact pressure gauge, (*8*) plate-and-frame membrane apparatus, (*9*) permeate containers, (*10*) choke, and (*11*) flow meter Cv denotes control valve.

ratus equipped with a given type of microfiltration membrane.

The material from which the parts of the membrane module and the unit were made is 12Kh18N10T stainless steel.

Prior to the microfiltration concentration process, a mature molasses brew from a 10-L container was poured into feed tank *1* until it was completely filled (Fig. 1). Then, the flow rate of the solution was set by adjusting the stroke of the plunger, as well as the flow rate of tap water for cooling the stuffing boxes of dispenser pump *2* (ND-120). The unit was connected to the mains, and metering pump *2* was switched on (from the control panel of the unit). The molasses broth from feed tank *1* was pumped to the unit, passing through metering pump *2* and hydraulic accumulator *3*, and entered plate-and-frame membrane apparatus *8* with closed chokes *10*, the volume of the liquid sent to the separation being visually monitored. The filling of the unit with the feed solution was visually checked as the 50% decrease of the volume in feed tank *1*, after which metering pump *2* was switched off. Then the control valve installed on the pipeline connecting air piston compressor *4* with hydraulic accumulator *3* was immediately opened. Further, air piston compressor *4* was immediately turned on (from the control panel of the unit) to fill hydraulic accumulator *3* with compressed air to 30–40% of the working pressure, which was visually monitored by observing the readings of pressure gauge *5*. When the pressure in hydraulic accumulator *3* and in the system of the unit reached 30 to 40% of the working pressure (from the control panel), air piston compressor *4* was immediately switched off and the control valve connecting air piston compressor *4* through the pipeline to hydraulic accumulator *3* was closed. Then, metering pump *2* was instantaneously switched on (from the control panel), which forced the feed liquid into the system of the unit and, thereby, ensured an increase in pressure to the values required in the experiment with partially open chokes *10*. The molasses broth solution as the retentate after plate-and-frame membrane module *8* passed through chokes *10* and flow meters *11* and was recycled back to feed tank *1*. The permeate that had passed through pores of the microfiltration membrane and exited from membrane module *8* was retracted by gravity into permeate container *9*.

The pressure during the microfiltration separation of molasses broth in the experimental setup was monitored with MO 11202 standard pressure gauge *6* (P = 0.0–6.0 kgf/cm^2); for automatic regulation of the solution supply, the unit was equipped with EKM-1U electric-contact pressure gauge *7* (P = 0.0–6.0 kgf/cm^2), which disconnected metering pump *2* by means of a relay when the pressure in the unit raised above the working pressure.

To reduce the effect of pressure pulsations, the microfiltration unit was equipped with hydraulic accumulator *3*, in which an air cushion was previously created (shown above).

After the microfiltration separation of the mature molasses broth, metering pump *2* was switched off (from the control panel) with partially open chokes *10* and the concentrated molasses broth solution was drained into a utilization tank, in which laboratory testing for ethyl alcohol and yeast was carried out by distillation and centrifugation, respectively.

From the permeate volume obtained in the experiments, the flux for microfiltration membranes was calculated according to the formula [24]:

$$J = \frac{V}{F_m \tau}, \quad (1)$$

where V is the volume of the collected permeate, m^3; $F_m = 0.0078$ is the working area of the membrane, m^2; and τ is the time of the experiment, s.

The rejection coefficient of the membranes was determined from the amounts of yeast biomass and ethyl alcohol in the permeate and the feed solution [25]:

$$R = 1 - \frac{c_{perm}}{c_{feed}}, \quad (2)$$

where c_{feed} and c_{perm} are respectively the solute concentrations in the feed molasses broth solution and the permeate, kg/m^3.

The procedure for regeneration of microfiltration membranes was follows: (1) distilled water was poured into feed tank *1* (Fig. 1) and an experiment was performed after separation of the molasses broth by pumping the distilled water at the same transmembrane pressure for 1200 s; (2) the spent distilled water after the regeneration of the microfiltration membranes was discharged into a distilled water disposal tank; and (3) the plate-and-frame membrane apparatus was dismantled, and the spent samples of the test microfiltration membranes were extracted and photographed (images were taken with a 16-megapixel Samsung Galaxy S4 Zoom camera).

RESULTS AND DISCUSSION

The experiments on the separation by microfiltration of mature molasses broth made it possible to reveal the dependence of the flux on the time on-stream with varying the transmembrane pressure and the type of the microfiltration membranes MPS, MFPA, and MMPA$^+$ at a constant temperature of T = 293 K and the velocity of the solution in the channel of w = 0.25 m/s (Figs. 2–4).

For this kind of food production processes, it is worth to take into consideration that mature molasses broth is a multicomponent system containing polysaccharides, yeast, and (probably) bacterial microflora in addition to potassium, phosphorus, sulfates, nitrates, phosphates, and other substances [1, 6].

Analyzing the dependence of the flux for the MFFK and MPS membranes opon the time on stream (Figs. 2, 3), we note that the decrease in the flux with time is probably due to the formation of a dynamic membrane during the separation of the mature molasses broth. The curves in Figs. 2 and 3 illustrating the dependence of the flux for the test microfiltration membranes on the time of the experiment and transmembrane pressure during the separation of the mature molasses broth can be conditionally divided into the following time periods: (1) Initial period of 1200–3600 s (partial clogging of some membrane pores by the action of transmembrane pressure); (2) Intermediate period of 3600–9600 s (gradual formation of a dynamic membrane layer when the equilibrium between the wash-up and wash-off rates of yeast and polysaccharides over the membrane surface has not been established, since some of their particles

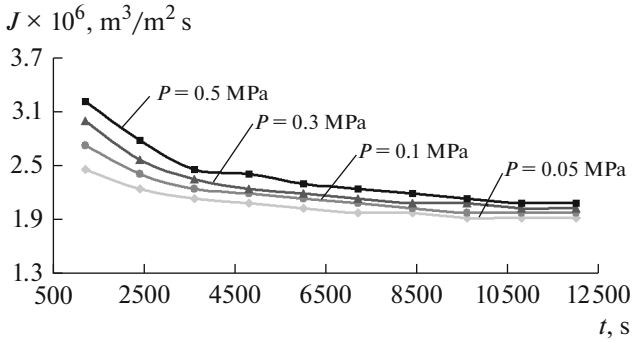

Fig. 2. Experimental dependence of the flux across the MFFK membrane of IFPC on the transmembrane pressure in the separation of mature molasses broth.

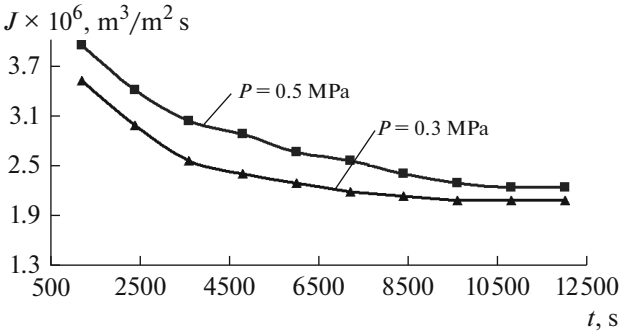

Fig. 3. Experimental dependence of the flux across the MPS membrane on the transmembrane pressure in the separation of mature molasses broth.

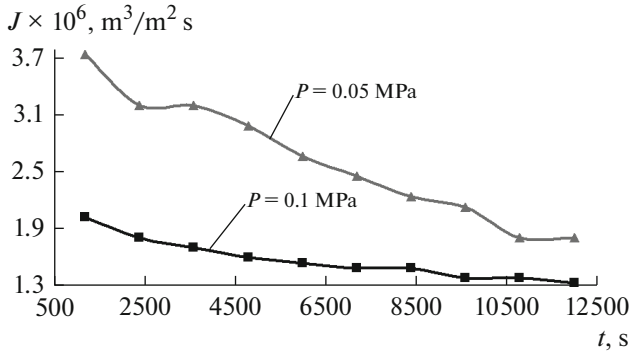

Fig. 4. Experimental dependence of flux across the MMPA$^+$ membrane on transmembrane pressure in the separation of mature molasses broth.

(yeast, polysaccharides) still partially block the membrane pores; (3) Final period of 9600–12000 s (steady state of the formed dynamic membrane layer, the rates of wash-in and flushing are constant, and the yeasts and polysaccharides in the channel are replaced by

other yeasts and polysaccharides; i.e., a gel-like layer is formed, and the MFFK or MPS microfiltration membrane itself acts as a course-pore substrate). The aforementioned final period over a larger range of variation in the experiment time is likely to expand with a slight decrease in the flux due to the greater compressibility of yeast and cells between themselves, associated with a changing flux through pores of the test membranes.

The time interval used in this study on the microfiltration separation of biological solutions differs little from published data on the use of these processes; for example, Stopka et al. [26] showed that the flux becomes almost invariable after 10800 s in the microfiltration of brewer yeast-containing solutions without backwashing on microfiltration ceramic membranes with comparable pores. In the same paper, the relationships of the flux with the time of the separation of yeast suspensions are presented, which are in good agreement with the proposed time periods of this study.

Similar relationships are observed in the processes run in membrane bioreactors with the use of ultrafiltration membranes operating under vacuum. For example, the stabilization of the flux with time in the process of separation of active sludge with different concentrations occurs at 7200 s [27].

The data obtained in this work on the time-dependent flux with time intervals correlate well with the relations obtained in [28] and are consistent with model concepts of the mechanism of filtration of low-concentration nonliving-yeast suspensions [29] with flux reduction (standard, intermediate, complete blocking, and sludge filtration).

The dependence of the flux through the $MMPA^+$ membrane on the separation time (Fig. 4) cannot be uniquely defined, since the main final period of the formation of the dynamic membrane is absent; i.e., the rate of the buildup of the membrane-forming substance is not equal to that of its flushing during the separation of the mature molasses broth. The flux decreases with the separation time, a change that is due not only to clogging of the membrane pores, but also to additional adsorption of electroneutral yeast and polysaccharides by the positively charged $MMPA^+$ microfiltration membrane, which also affects the separation process. The flux through the MFFK and MPS membranes depending on the time of the experiment increases with increasing transmembrane pressure, a behavior that is associated with the growth in pressure as the driving force of the process, unlike the case of the $MMPA^+$ membrane, since its performance is affected by rapid pore clogging and the absence of the washing-in of membrane-forming substances on the membrane surface and their washing-off, as well as by the appearance of pressure-induced deformations in the form of profiled lines along and across the membrane.

Analysis of the rejection factors depending on the time of the experiment shows that in the case of steady flow through the MFFK, MPS, and $MMPA^+$ membranes, the yeast biomass is rejected by 100% (Table 3). This is due to the small pore size of the membranes, 0.45 μm, which do not allow the breakthrough of the yeast into the permeate, and is also a consequence of the formed fluid dynamic membrane structure consisting not only of yeast, but also of polysaccharides.

Another no less important parameter in the separation of the molasses broth solution is the volume fraction of ethyl alcohol, with the optimal separation having been achieved at a transmembrane pressure of $P = 0.05$ MPa on the MFFK membrane, which is suitable for the separation of alcohol-containing liquids on membranes of this type. This fact can be explained by the partial blocking of pores of the MFFK microfiltration membrane with membrane-forming substances (proteins, polysaccharides) at a transmembrane pressure of $P = 0.05$ MPa, in contrast to membrane operation at a transmembrane pressure above $P = 0.1$ MPa.

The MPS and $MMPA^+$ membranes did not show such results and were found to be unsuitable for separation of molasses broth solution.

The quantitative and microbiological analysis for bacterial microflora and yeast did not reveal their presence in the permeate.

The data presented in Table 3 on the retentate over the total period of the experiment suggest that the resulting concentrated broth retentate stream containing yeast can be reused after preliminary treatment with disinfectant solutions to make a new brothing batch with periodic yeast settling at intermediate steps in special containers for further processing to animal feed. The permeate, obtained by the microfiltration separation of mature molasses broth solution without additional purification, is fed into a distillation column and, as such, prevents its fouling by yeasts and polysaccharides and is good for saving the material resources of the enterprise.

Visual analysis of the images in Figs. 5a and 5c of the spent membrane samples after separation and regeneration shows that the $MMPA^+$ membrane at $P = 0.05$ MPa and the MPS membrane at $P = 0.5$ MPa are susceptible to numerous pressure-induced deformations in the form of profile lines along and across the sample, which probably depend on the membrane structure and the material from which the active layer was made, in contrast to the more rigid hydrophobic fluoropolymer membrane MFFK for which no any deformation appeared at $P = 0.05$ MPa and a deformation as a single line along a shaped membrane sample was observed at $P = 0.5$ MPa above its manufacturer's specified values.

It is noteworthy that the adsorption of polysaccharides on the surface of membranes made of various materials containing polypropylene or polyethersul-

Table 3. Target parameters of permeate and retentate after separation of molasses broth Biomass of, g/dm^3

Sample	Volume fraction of ethyl alcohol, vol %		Yeast biomass, g/dm^3	
After fermentation tank no. 3	c_{perm}	R	c_{perm}	R
Permeate after MMPA$^+$ at $P = 0.05$ MPa	7.6	0.174	–	1.0
Permeate after MMPA$^+$ at $P = 0.1$ MPa	8.2	0.109	–	1.0
Permeate after MFFK at $P = 0.05$ MPa	8.0	0.130	–	1.0
Permeate after MFFK at $P = 0.1$ MPa	8.7	0.054	–	1.0
Microbiological analysis of permeate	Bacterial microflora and cultured yeast were not detected			
Retentate at $P = 0.05$ MPa	8.2		12.0	
Retentate at $P = 0.1$ MPa	9.2		12.5	
After fermentation tank no. 10	c_{perm}	R	c_{perm}	R
Permeate after MPS at $P = 0.3$ MPa	8.2	0.146	–	1.0
Permeate after MPS at $P = 0.5$ MPa	8.8	0.083	–	1.0
Permeate after MFFK at $P = 0.3$ MPa	8.6	0.104	–	1.0
Permeate after MFFK at $P = 0.5$ MPa	8.8	0.083	–	1.0
Microbiological analysis of permeate	Bacterial microflora and cultured yeast were not detected			
Retentate at $P = 0.3$ MPa	9.0		18.4	
Retentate at $P = 0.5$ MPa	9.4		20.6	

fone also imposes restrictions on the membrane separation process; e.g., a polyethersulfone membrane used for wine treatment was shown to adsorb polysaccharides from the wine in a four times greater amount than a polypropylene membrane [30].

Thus, by pumping distilled water over the membrane surface, it is possible to regenerate MFFK microfilters, as evidenced by the appearance of spent samples of the membranes (Figs. 5b, 5d). The differences between the spent MFFK microfilter samples at $P = 0.05$ MPa and $P = 0.5$ MPa at the same on-stream and regeneration times of 1200 s and the same pressure are visible to the naked eye. At a lower pressure, membrane pore clogging is less intense and, hence, the

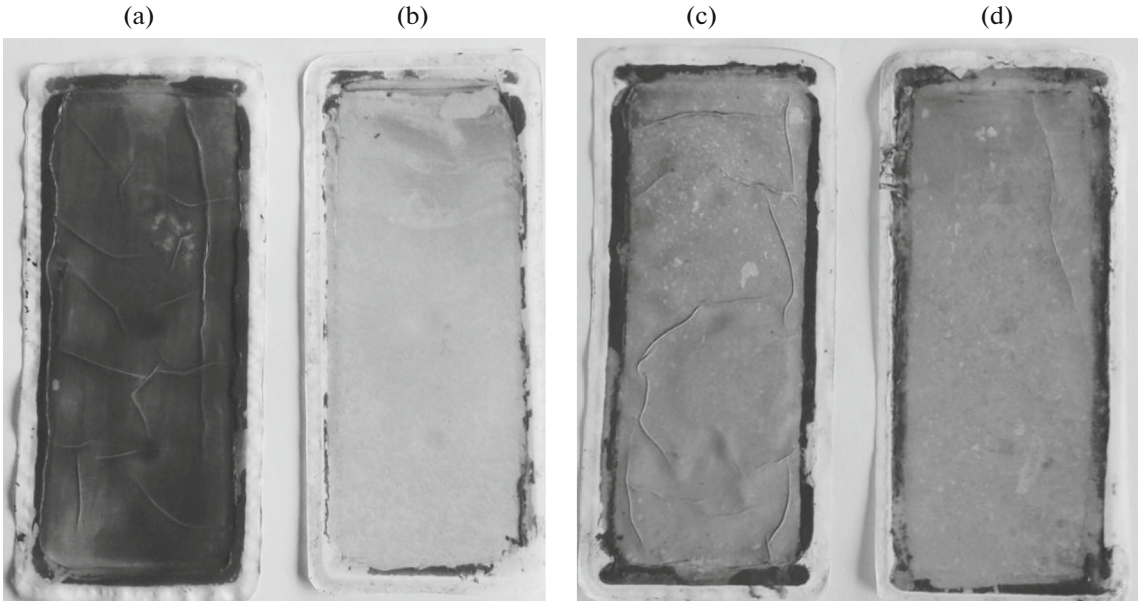

Fig. 5. Spent samples of microfiltration membranes after separation of mature molasses broth: (a) MMPA$^+$ at $P = 0.05$ MPa, (b) MFFK at $P = 0.05$ MPa, (c) MPS at $P = 0.5$ MPa, and (d) MFFK at $P = 0.5$ MPa.

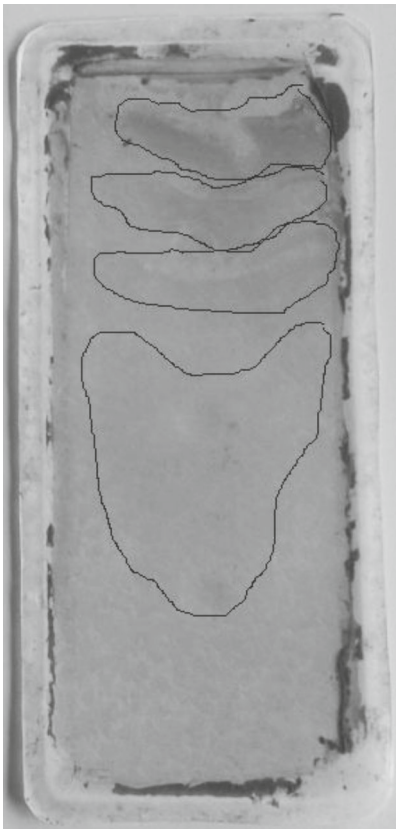

Fig. 6. Spent sample of the MFFK microfiltration membrane at $P = 0.05$ MPa with marked isolated areas.

dynamic membrane layer is easier to wash off, as can be observed for the MFFK membrane at $P = 0.05$ MPa (Fig. 6) with the marked areas, in contrast to the MFFK membrane at $P = 0.5$ MPa (Fig. 5d).

In a visual analysis of the spent sample of the MFFK membrane (Fig. 6) at $P = 0.05$ MPa, it can be seen that after the flushing of the dynamic membrane with distilled water for 1200 s and dismantling of the unit, the membrane shows the presence of isolated areas that can be characterized by the accumulation of various membrane-forming substances (yeast and polysaccharides) at the outlet of the flat channel of the device. The closer the distance to the outlet of the flat channel of the membrane apparatus, the darker the areas because of the greater accumulation of membrane-forming yeast and polysaccharide particles.

CONCLUSIONS

(1) Data on the flux and the rejection factor for $MMPA^+$ ($P = 0.05$ or 0.1 MPa), MPS ($P = 0.3$ or 0.5 MPa), and MFFK ($P = 0.05$, 0.1, 0.3, or 0.5 MPa) membranes, depending on time, in the separation of mature molasses broth have been obtained. The data show that the processing of the solution is accompanied by the formation of a dynamic membrane, which serves as a 100% barrier to yeast biomass and passes through more than 80% of ethyl alcohol. It has been established that the flux through the MFFK and MPS membranes increases with an increase in the driving force of the process, in contrast to the positively charged $MMPA^+$ membrane, which presumably adsorbs not only electrically neutral yeast and polysaccharides, but also other ions leading to further membrane clogging. The MPS and $MMPA^+$ membranes were found to be unsuitable for the separation of molasses broth solution because of the emergence of numerous pressure-induced deformations in the form of profiled lines along and across the samples depending on the membrane structure and material, unlike the more rigid hydrophobic fluoroplastic MFFK membrane on a polypropylene substrate, for which the deformation was absent altogether at $P = 0.05$ MPa and a single profiled deformation line along the membrane sample appeared at $P = 0.5$ MPa above the manufacturer's specified application value. It has been shown that after flushing the dynamic membrane with distilled water at a pressure of $P = 0.05$ MPa for 1200 s and dismantling the apparatus, the surface of the MFFK membrane exhibits isolated areas characterized by the accumulation of membrane-forming substances (yeast and polysaccharides).

(2) The results obtained using the commercial MFFK membrane at $P = 0.05$–0.1 MPa show that the yeast contained in the retentate is concentrated. Thus, the retentate can be reused for new batch brothing after its treatment with disinfectant solutions, including periodic settling of the yeasts in intermediate containers for their further processing into animal feed. The permeate, obtained by the microfiltration separation of the molasses broth solution on the investigated membranes without additional purification, is fed to a distillation column; this feedstock prevents column fouling by yeasts and polysaccharides and saves the enterprise funds for quarterly dismantling.

REFERENCES

1. V. L. Yarovenko, V. A. Marinchenko, V. A. Smirnov, et al., *Alcohol Technology* (Kolos-Press, Moscow, 2002) [in Russian].
2. A. V. Onopriiko, V. A. Onopriiko, and N. A. Ryabchenko, *Alcohol from Edible Raw Materials: Production, Purification, and Use: A Tutorial* (SevKavGTU, Stavropol, 2001) [in Russian].
3. A. K. Dorosh and V. S. Lysenko, *Production of Hard Drinks: Feedstock, Equipment, and Technologies of Manufacturing Alcohol and Vodka with Recommendations for Individual Manufacturers* (Libid', Kiev, 1995) [in Russian].
4. V. G. Myronchuk, I. O. Grushevskaya, D. D. Kucheruk, and Yu. G. Zmievskii, Pet. Chem. **53**, 439 (2013).
5. V. M. Sedelkin, A. N. Surkova, O. V. Pachina, et al., Pet. Chem. **56**, 367 (2016).

6. V. V. Biryukov, *Fundamentals of Industrial Biotechnology* (Kolos, Moscow, 2004) [in Russian].
7. W. J. T. Lewis, Y. M. J. Chew, and M. R. Bird, J. Membr. Sci. **405/406,** 113 (2012).
8. Y. Gençal, E. N. Durmaz, and P. Z. Çulfaz-Emecen, J. Membr. Sci. **476**, 224 (2015).
9. S. M. Lemma, A. Esposito, M. Mason, et al., J. Food Eng. **157**, 1 (2015).
10. E. Gabrus and D. Szaniawska, Desalination **240**, 46 (2009).
11. S. H. Maruf, A. R. Greenberg, J. Pellegrino, and Y. Ding, J. Membr. Sci. **471**, 65 (2014).
12. I. L. Borisov, V. V. Volkov, V. A. Kirsh, and V. I. Roldugin, Pet. Chem. **51**, 542 (2011).
13. I. L. Borisov, P. Yu. Temnikov, and V. V. Volkov, Ser. Krit. Tekhnol. Membr. **48** (4), 16 (2010).
14. G. S. Golubev, I. L. Borisov, E. G. Litvinova, et al., Pet. Chem. **57**, 498 (2017).
15. V. V. Volkov, A. G. Fadeev, V. S. Khotimskii, et al., Ross. Khim. Zh. **47** (6), 71–82 (2003).
16. A. I. Lembovich, N. S. Ruchai, I. N. Kuznetsov, et al., Tr. BGTU: Khim., Tekhnol. Org. Veshchestv Biotekhnol., No. 4, 174 (2014).
17. http://www.vladipor.ru/catalog/show/&cid=015&id=1. Accessed March 21, 2017.
18. http://www.technofilter.ru/prod/filtry_i_oborudovanie_dlya_laboratornoj_filtracii/filtr_disc/membrana_ poliefirsulfonovaya_marki_mps. Accessed March 21, 2017.
19. http://www.technofilter.kiev.ua/ru/filter-production/filtering-disc/membrane-mmpa.html. Accessed March 21, 2017.
20. G. G. Yagafarov, *Microorganisms as Producers of Biologically Active Substances: A Textbook* (Khimiya, Moscow, 2002) [in Russian].
21. T. P. Zyubr and I. B. Vasil'ev, *Use of Ethyl Alcohol in Medicine Drug Production Technology: A Tutorial* (IGMU Roszdrava, Irkutsk, 2008) [in Russian].
22. V. L. Yarovenko, B. A. Ustinnikov, Yu. P. Bogdanov, and S. I. Gromov, *Handbook of Alcohol Manufacture and Technical Chemistry Control* (Legkaya i Pishchevaya Promyshlennost', Moscow, 1981) [in Russian].
23. A. P. Rukhlyadeva, T. G. Filatova, and V. S. Cherednichenko, *Handbook for Alcohol Factory Laboratory Technicians* (Pishchevaya Promyshlennost', Moscow, 1979) [in Russian].
24. V. L. Golovashin, S. I. Lazarev, and A. A. Lavrenchenko, Vestn. Tambov. Gos. Tekh. Univ. **20**, 86 (2014).
25. M. Mulder, *Basic Principles of Membrane Technology* (Kluwer Academic, Dordrecht, 1996).
26. J. Stopka, S. Schlosser, Z. Domeny, and D. Smogrovicov, Pol. J. Environ. Stud. **9**, 65 (2000).
27. S. Subagjo, N. Prasetya, and I. G. Wenten, J. Membr. Sci. Res., No. 1, 79 (2015).
28. L. F. Song, J. Membr. Sci. **139**, 183 (1998).
29. B. Keskinler, E. Yildiz, E. Erhan, et al., J. Membr. Sci. **233**, 59 (2004).
30. M. Ulbricht, W. Ansorge, I. Danielzik, et al., Sep. Purif. Technol. **68**, 335 (2009).

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