Hydrodynamic methods for reducing concentration polarization during beer processing by membranes

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Abstract. The use of baromembrane processes, in particular, microfiltration, allowed us to form a whole area consisting in the development of beer clarification technologies with qualitatively new properties. The microfiltration process, in comparison with classical pasteurization with the help of immobilized enzymes, with adsorbing agents, has indisputable advantages, because phase transformations are completely absent, low processing temperatures are used, the process can be carried out in several stages, the processing time and energy consumption are reduced, the conditions of microbiological resistance are increased. The decisive role in the course of the microfiltration process is played by the movement mode of the initial solution, physicochemical properties and the geometry of the membrane channel. It is known that the diffusion coefficient can be significantly increased by increasing the temperature of the solution to be separated, which is not always technologically possible, and in some cases, simply unacceptable, therefore, the above parameters are the most promising options for increasing the mass transfer coefficient.

1. Introduction
The formation of a gel layer on the membrane surface in which the concentration of the solute is greater than in the bulk of the solution is called concentration polarization. The negative impact of this phenomenon on the membrane processes of process liquids treating is caused by the following aspects:

- the pressure drop above and below the membrane decreases. The osmotic pressure of the initial process fluid, accompanied by a decrease in specific permeability and selective retention of membranes, is increasing;
- the operational period of the membranes use is reduced. The cost of the membrane process depends on this.
- There are ways to reduce concentration polarization used in experimental and industrial practice, which can be divided into the following three main groups.
  - methods aimed at maintaining a low transmembrane flow;
  - methods that provide a small difference in concentrations between the volume flows of the initial solution and the sediment layer;
  - methods aimed at ensuring a low concentration of dissolved substances in the initial solution.

In practice, they are usually not limited to any one of the described methods, but a combination of them is used. [1, 2].
2. Materials and methods

Let’s examine the physical picture of the occurring phenomena in a flat membrane channel with known geometric dimensions (figure 1).

In section 1 of the concentration profile, the constituent parts of the flows of the initial solution and permeate flowing along the membrane surface prevail. The assumption of the invariance of the physicochemical properties of the components of the initial solution and permeate can be made for an approximate estimate of mass transfer.

![Physical model of microfiltration process.](image)

Section 2 is a boundary layer of thickness $\delta$, characterized by a concentration gradient $D(d\sigma/dy)$, pressure $\Delta P$, and velocity in the direction perpendicular to the membrane surface. The dissolved substance is transported to the membrane surface by the main flow $Gc_3$ in the thickness of the boundary layer, one part of it is transferred in the opposite direction due to molecular diffusion, the other part is transmitted through the membrane with possible adsorption on its surface. In section 3, diffusion and adsorption processes can occur simultaneously, both on the membrane surface and inside it. Section 4 is a membrane, with its various layers, depending on the material and the method of its manufacture. Mass transfer processes are carried out due to diffusion and convection. The presence of various layers that make up the membrane, their quantity and properties will affect the total hydraulic resistance of the membrane, permeability and selectivity.

Beer was used as a process fluid, as a multicomponent substance with protein inclusions. A study of the dependence of the rotational speed on the specific microfiltration rate under the frontal mode of process organization was carried out using a membrane module with a mixing device (figure 2). It consisted of: upper and lower covers 1 and 2, ring 3, tightening brackets 4, a tap (valve) for entering the initial process fluid 5, a permeate outlet pipe 6, a retentate removal valve 7, an electric motor 8 for driving an axial mixing device 9, a sampler 10, pressure gauge 11, perforated drainage substrate 12, membrane 13. Beer microfiltration in the frontal mode of process organization was carried out with a membrane module with a mixing device at the following technological parameters: temperature 2 ... 6 °C, operating pressure 0.08...0.15 MPa.
Figure 2. Membrane module for the frontal microfiltration of beer study.

The membrane module (figure 3) for flowing beer microfiltration study included: lower 1 and upper 2 pressure plates, support element package 3 with nuclear filter clamps, fabric substrate 4, tie bolts 5, permeate outlet pipe 6, input of process fluid 7, retentate outlet 8, pressure gauge 9, set of gaskets 10 of various heights, nuclear filter 11, laid on a sheet of drainage material and secured with clamps (not shown conventionally in figure 3).

Figure 3. Membrane module for flowing beer microfiltration study.

3. Results and their discussion

Beer microfiltration in a flow-through mode of the process organization with a flat membrane module was carried out at the following process parameters: temperature 2 ... 6 °C, operating pressure 0.08 ... 0.15 MPa, shared flow velocity above the membrane surface 2 m / s [3 - 5].

Direct beer microfiltration, at a dead end organization mode, is practically impossible without special techniques for creating hydrodynamic instabilities at the membrane-product interface. If this condition is not met, after a few minutes of the microfiltration process, the specific permeability of the track membrane decreased to zero. Therefore, product clarification was carried out for all used membranes during the axial mixing device rotation in the range of 85 ... 1160 rpm.

A further increase in the rotational speed of the axial mixing device was considered inappropriate. However, there was no significant increase in the specific membranes permeability. There was a danger of high shear stresses resulting into a violation of the unfiltered beer colloidal state with subsequent gelation. There was also a significant deterioration in the organoleptic quality indicators of clarified beer. This is considered to be unacceptable. Analyzing the graphical dependence (figure 4) of the specific rate of beer microfiltration on a track membrane with a pore size of 0.9 μm on the rotational speed of the mixing device, it is possible to show the minimum specific permeability of the membrane equal to 51.2 · 10^{-6} m / s at 260 rpm min.
With an increase in the angular velocity of rotation to 980 rpm, the permeability of a nuclear filter with a resolution of 0.90 μm increased to \((50... 55) \cdot 10^{-6} \text{ m/s}\). A further increase in the angular velocity of rotation to 1160 rpm led to a decrease in membrane permeability. When the mixer rotates, the intensity of the shared stream (unfiltered beer) mixing at the membrane module walls is significantly higher than in its central part. The linear velocity at the ends of the mixer blades reaches maximum values, while on the rotation axis it is equal to zero.

This contributed to the formation of a high concentration layer in the central part of the nuclear filter. With an increase in the angular velocity of mixer rotation, the intermolecular bonds of the high concentration layer with the formation of a concentration gradient with a maximum value in the center of the membrane module intensified [6, 7].

Over time, in the center of the track membrane, a “non-working” area, impervious to clarified beer, was formed due to its increased hydraulic resistance. As a result, the effective filtering surface of the track membrane decreased. At 35 minutes of microfiltration, the membrane permeability did not depend on the angular velocity of the mixer rotation and ranged \((7.5 ... 8.0) \cdot 10^{-6} \text{ m/s}\). The results emphasize the inappropriateness of angular rotational speeds using in excess of 800 rpm. To reduce the negative effect, it is possible to use sponge bodies with a diameter of 5 ... 7 mm in combination with a working mixer.

With an increase in the shared flow speed over the membrane, a linear increase in its permeability with a resolution of 0.90 μm can be shown (figure 5). Upon reaching flow velocities of 3.5 ... 4.5 m/s, the membrane permeability reached \(45.6 \cdot 10^{-6}, 48.7 \cdot 10^{-6}\) and \(52.3 \cdot 10^{-6} \text{ m/s}\) for membrane channel heights 2.7, 1.47 and 0.5 mm, respectively.

With the selected range of tangential velocity of 3.5 ... 4.5 m/s and the correct organization of the membrane device hydraulic system, it is possible to prevent the sedimentation of protein suspensions particles, yeast and bacteria on the membrane. The magnitude of the pressure loss for a flat membrane module will be no more than 0.2 ... 0.3 MPa [8]. Exceeding the tangential velocity range is accompanied by significant pressure losses up to 0.6 ... 0.8 MPa, which is irrational due to energy costs increasing. It should be emphasized that conducting experiments at a tangential velocity of more than 5 m/s was accompanied by a significant increase in the volume of the forming concentrate, with a large amount of the target component [9]. Concentrate for deeper cleaning was forced to return to the circulation circuit, which caused a deterioration in the quality of the product being filtered. To change the height of the membrane channel of the flat membrane module, a set of gaskets with a height of 0.5, 1.45 and 2.7 mm was used. The analysis of the obtained dependence (figure 6) indicates a significant effect of the membrane channel height at the time of the high concentration layer formation on the membrane.

Figure 4. Dependence of the specific rate of beer microfiltration on the track membrane with a pore size of 0.9 μm on the rotational speed of the mixing device.
After 5 ... 10 min of the process, the membrane permeability was \((55 \ldots 58) \cdot 10^{-6}\) m/s in the membrane channel with a height of 0.5 mm. As the kinetic dependence shows, the permeability curves go to a constant level, which indicates an insignificant effect of the height of the membrane channel.

It is generally recognized that the mode of fluid movement in the membrane channel affects the high concentration layer directly, i.e. with the channel height increasing, the tangential velocity, the Reynolds number decrease and, as a result, the membrane permeability decreases too.

4. Conclusions
Beer contains substances consisting of high molecular weight compounds or complex structural formations. According to Kunze [9], these substances under the influence of shear stresses caused by the work of the mixer can change their structure or completely lose it. Using β-glucan as an example, we can consider the effect of shear stresses on the structure of a protein molecule. Due to the action of shear stresses, β-glucan molecules are stretched, which leads to gelation. At high concentrations of β-glucan gel, the filtering ability of beer is significantly impaired, therefore, it is necessary to ensure conditions that minimize the occurrence of high values of shear stresses.

When using front microfiltration, these conditions can be achieved by reducing the peripheral speed of rotation of the mixer in the case of using large blades of the mixing device [10].

For example, the mixing device in the experimental apparatus of frontal microfiltration is made in the form of a perforated disk 1.5 mm thick with blades 3.5 mm high. According to Kunze, to make the effect of shear stresses as small as possible, it is necessary to ensure the operation of the mixing device at peripheral speeds of less than 1 m/s.

The analysis of experimental data showed the track membranes maximum permeability of at the membrane channel height of 0.5 mm. The thickness of the indelible layer depends, to a large extent,
on the membrane module geometry, the mode of movement. Therefore, it is important to use a membrane channel with the correct ratio of length and height to create optimal conditions for the hydrodynamic instabilities action. For practical use, flow rates in the range of 3 ... 4 m/s can be used, at which we should expect the prevention of sedimentation on the membrane surface of yeast cells and particles with sizes greater than 15 ... 30 microns (without preliminary clarification), and pressure loss in the flow module will be about 0.25 MPa. A further increase in the tangential velocity to 6 ... 7 m/s and higher increased significantly the pressure loss to 1.0 ... 1.2 MPa. Volumes of concentrate, which had to be regenerated again (returned to the system in recirculation mode) increased significantly as well. It affected the quality of clarified beer negatively. The results of mathematical modeling of the mass transfer process in a membrane channel of rectangular cross section show good agreement with the experimental data for a speed range of 2.0 ... 4.5 m/s.

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