Beer microfiltration under conditions of hydrodynamic instability at the "membrane - product" interface

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Abstract. The basic principles and practical implementation of methods for beer media microfiltration processes intensifying due to the creation of hydrodynamic instabilities in the near-membrane zone of the membrane device were considered. Prerequisites for the development of membrane devices with a concentration polarization low level were also studied in the work. The creation of hydrodynamic instabilities in the near-membrane zone is provided with their help. This is achieved not only due to the installation of various design turbulizing devices in the membrane module channels, but also due to their operation according to a specific algorithm interconnected with the membranes specific permeability. This algorithm should certainly allow to influence the high-concentration near-membrane layer with varying degrees of intensity and cause no deviations from the quality indicators of the processed liquid food media.

1. Introduction

An important quality indicator of beer is its biological stability. Classic filtration does not completely free the beer from the microorganisms it contains. The filtering membrane mainly retains large yeast. Smaller cultured cells of yeast and bacteria freely pass through the filtering membrane. That is why, the competent use of the beer microfiltration process will allow to resolve the above disadvantages of classical filtration and achieve certain success in stabilizing the quality indicators of the drink. [1 – 3].

Currently, the greatest scientific interest is the research devoted to the development of membrane device designs, which make it possible to fully implement hydrodynamic methods of intensification in solving practical problems of processing liquid food media.

The further development of the theory, technique and technology of membrane processes is first of all associated with the creation of scientific approaches to the development of membrane processes and equipment that provide a comprehensive solution to the problems of separation (concentration) under developed hydrodynamic regimes reducing concentration polarization. This approach to membrane processes development is an urgent problem.

There are only some papers giving a slight review of the processes of microfiltration of liquid food media using different variable states of the hydrodynamic picture in a membrane module of various types. The well-known works of Russian and foreign scientists describe mainly a certain solution of a
particular technological problem in relation to a specific design of a membrane apparatus or device [4 – 6].

2. Materials and methods
Ceramic membranes of INSIDE CéRAM™ brands from TAMI Deutschland GmbH (table 1), Ceramic membrane filter elements (CMFE) from Research and Production Association “Keramikfilter LLC” were used to study the microfiltration processes of unfiltered unpasteurized beer (figure 1 and table 2).

| Membranes of INSIDE CéRAM™ brand from “TAMI Deutschland GmbH” |
|---------------------------------------------------------------|
| Outer diameter, mm (L = 1178 mm³) | 10 | 10 |
| Number of channels, pcs. | 1 | 7 |
| Hydraulic diameter, mm | 6 | 2 |
| Filtration surface, m² | 0.02 | 0.06 |
| Application | MF, UF, final UF |

*a can be produced in lengths of 580, 850, 1000, 1020, 1178 mm.

| Membranes of CMFE – 1 From RPA “Keramikfilter LLC” |
|------------------------------------------------|
| Outer diameter, mm | 10 |
| Channel diameter, mm | 6.0 |
| Number of channels, pcs. | 1 |
| Length, mm | 800 |
| Filtration surface, m² | 0.015 |

Figure 1. Composition and microstructure of CMFE ceramic membranes: a) openings and fragments of the membrane bearing in section; b) a fragment of a two-layer membrane.

Ceramic membranes from TAMI Deutschland GmbH were single and multi-channel tubes made of titanium oxide or zirconium oxide based materials. They are available in 15, 50, 100 and 300 kDa pore diameter. Ceramic CMFE membranes were single-channel tubes made of a material based on electrocorundum (α-alumina) or/and titanium dioxide (anatase or rutile modifications), having on the inner surfaces of the channels a porous membrane based on α-alumina or/and β silicon carbide in the
form of short-fiber whisker monocrystals, titanium dioxide (anatase or rutile modifications), zirconium dioxide.

The study of the microfiltration process with hydrodynamic instability was carried out using the experimental device shown in figure 2. The pulsating modes of action on the "membrane-product" interface were implemented as follows.

![Figure 2. The implementation scheme of the pulsation effect on the treated initial solution.](image)

At first the pre-washed and disinfected hydraulic system of the experimental device was filled with sterile water, the valve was opened on the supply container with the initial solution and the water was displaced on the concentrate line, after which the required pressure difference was gradually created by the valves installed before and after the tubular membrane module, which was controlled with the help of pressure gauges.

Then, membrane separation was carried out depending on the objectives of the study. After a decrease in the specific rate of the process (membrane permeability), a device was connected (fig. 2) to create a pulsating effect on the processed flow. The device consisted of a cylinder 4 with a piston, its rod was driven into reciprocating motion by means of a cam 5, which can rotate at a variable speed due to a frequency converter 7. Various characteristics of the pulsating field were obtained by changing the speed of the drive motor 6, the rod stroke, the profile of the cam used. The research of the kinetic and hydrodynamic characteristics of the studied membrane process at different duration, frequency and pulsation action interval was of practical interest.

When using ceramic membranes of the INSIDE CerAM™ brand, there was one membrane in the module, the filtering surface of which was 0.02 m².

The duration of microfiltration was determined with a stopwatch with an accuracy of up to tenths of a second, which provided greater accuracy in calculating the membrane permeability.

The experiment was started at 0.05 MPa, increasing the pressure with a step of 0.05 MPa in each subsequent experiment. The pressure growth limit depended on the proportional filtrate volume in subsequent experiments.

Since the pressure was determined not above the membrane, but in the branch pipe for returning the concentrated beer to the buffer tank (figure 3), it was recalculated with the well-known Bernoulli equation.

The total head losses are made up of head losses along the length (since the length of the sections is insignificant, they were taken equal to zero) and head losses in local resistances, the value of which was equal to 0.05 MPa, all the other values being determined during the experiment. The effect of the tangential velocity of the flow to be separated on its hydrodynamic characteristics and, as a result, on the level of concentration polarization is of particular interest.

It seems possible to determine the "critical" tangential flow velocity, exceeding of which would not lead to a noticeable decrease in the level of concentration polarization on the ceramic membrane surface due to a high concentration layer removal. The scheme for determining the separated flow average velocity above the membrane is shown in figure 4.
3. Results and their discussion

The permeability dependence on the duration in the beer filtering process on membranes with a delay threshold of 0.2 and 0.4 μm is shown in Fig. 5. As it can be seen from the figure, the membrane permeability dropped sharply in the first 5…10 minutes, and after 1 hour of operation it was practically zero for 0.2 μm membrane and after 2 hours for 0.4 μm membrane.

![Figure 5](https://via.placeholder.com/150)

**Figure 5.** Dependence of the specific velocity of beer microfiltration on a ceramic membrane with a pore size of 5.0 μm on the duration of the process at different velocities of tangential flow. 1 – 1,9; 2 -2,3; 3 – 2,7; 4 – 3,15; 5 – 3,85 m/s.

![Figure 6](https://via.placeholder.com/150)

**Figure 6.** Dependence of the specific velocity of beer microfiltration on a ceramic membrane with a pore size of 0.4 μm on the process duration at different velocities of tangential flow. 1 – 0,9; 2 – 1,1; 3 – 1,27; 4 – 1,6; 5 – 1,95; 6 – 2,3 m/s.

This can be explained as follows: in the first few seconds after the start of the membrane, a concentrated polarized layer forms on its surface (this is an inevitable, but reversible phenomenon), causing a change in concentration in the direction opposite to microfiltration. The decrease in flux due to concentration polarization can be reduced by the pressure decreasing, the velocity increasing or the concentration decreasing [7].

The next stage of contamination is a consequence of concentration polarization. Dissolved substances that accumulate on the membrane surface undergo irreversible changes over time and form pre-wash layers on the membrane surface. In this case, the concentration of the solute in the boundary layer at the membrane surface increases. An increase in concentration occurs until the diffusion flux of a solute from the boundary layer into the solution being separated is balanced by the flux of a solute through the membrane with the formation of the so-called dynamic equilibrium. The effect of concentration
polarization on the performance of membranes is negative, as the driving force of the separation process decreases due to an increase in the solution osmotic pressure.

Flow turbulization can be implemented in three ways: by using high speeds (3... 5 m/s), rigidly fixed turbulizing inserts and not rigidly fixed turbulators. The application of not rigidly fixed turbulators is difficult to implement in practice. Rigidly fixed turbulators create high hydraulic resistance and promote the stagnant zones formation.

The influence of the tangential velocity of the separated flow over the membrane surface on its permeability was studied in the work. It is impossible to change the speed by adjusting the valves on the retentate and retentate outlet pipes, because the pressure drop changes. Therefore, to control the speed, the number of membranes in the module of the experimental device was changed with a change in the equivalent diameter (channel cross-sectional area). As a result, the dependence of the membrane permeability of 0.4 and 5.0 µm on the filtration duration for different speed modes was studied (fig. 5, 6). To facilitate the perception of the dependence of the device productivity at different speed modes, a graph of the dependence of the membrane permeability on the Reynolds number was built (fig. 7). The complete destruction of the gel layer on the membrane surface occurred: 0.4 µm - Re_{edge} = 10700, 5 µm - Re_{edge} = 16450. For a given standard size of membranes, the Reynolds numbers obtained correspond to the following velocities: 0.4 µm - \nu_{middle} = 3.7 m/s, 5 µm - \nu_{middle} = 2.3 m/s. But the application of high speeds leads to a sharp increase in energy consumption for solution recovery and a significant increase in its temperature. Moreover, a prolonged exposure to high speeds of tangential flow can lead to biologically active macromolecules inactivation.

Therefore, in our opinion, the application of the pulsed mode is one of the most promising areas, since this method does not have the above-mentioned disadvantages and is quite easy to implement in practice [8-10].

In the pulse mode, the destruction and loosening of the polarization layer is achieved by the concentrate reciprocating motion, reverse pumping with filtrate, or periodic membranes regeneration by tangential flow. In our experiments, a pulsating flow was applied with a periodic membrane regeneration by a tangential flow with the following characteristics (5 µm): frequency \nu = 0.002 Hz; ripple duration \tau_2 = 5 s; duty cycle \Omega = 0.83%; amplitude \Delta P_b = 0.1 MPa; flow velocity \nu = 3 m/s.

The experimental results are given in fig. 8, which proves that the application of the pulsed mode made it possible to increase the average productivity by 96% and to exclude an overcoat layer formation.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure7.png}
\caption{The dependence of the specific rate of beer microfiltration on ceramic membranes with different pore sizes on the Reynolds number Re. 1 - 0.4; 2 - 5.0 µm.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure8.png}
\caption{The dependence of the specific rate of beer microfiltration on ceramic membranes with different pore sizes with the application of pulsations. 1 - 0.4 µm; \Delta P_b = 0.25 MPa; \tau_1 = 3 s; T = 600 s; 2 - 5.0 µm; \Delta P_b = 0.10 MPa; \tau_1 = 5 s; T = 600 s.}
\end{figure}
4. Conclusions
The overwhelming majority of membranes and devices produced today are designed to solve a wide range of technological problems. However, intensification of micro- and ultrafiltration processes due to the creation of hydrodynamic instabilities at the “membrane - product” interface is limited by the design features of the membrane system, and by a complex of properties of various nature of the processed solutions. Moreover, certain methods of combating concentration polarization, which have a permanent effect on the near-membrane layer (limited possibilities for intensification), are introduced in existing membrane devices, e.g. in spacers that are fixedly installed in the membrane channel.

The design features of some membranes, e.g. ceramic multichannel ones, do not physically allow placing technical means aimed at hydrodynamic conditions intensifying inside them. Therefore, it is necessary to resort to such intensification methods, which would make it possible to influence the near-membrane layer, leading to its removal from the membrane surface. Membranes should be able to move (and/or rotate) relative to each other, creating channels of variable cross-section by combining their geometrical shapes. In this case, enough opportunities appear to create hydrodynamic instabilities of varying intensity, the level of the imposed intensity having the ability to be regulated within a fairly wide range. The combination of various geometrical forms of technical means placed in the membrane channel, their dynamic characteristics, motion algorithms, with the hydrodynamic parameters of the separated flow create conditions for a conceptual approach to the creation of membrane devices with a concentration polarization low level [11, 12].

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