Development of hollow fiber reverse osmosis membranes and modules

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Abstract. Perspectives of the hollow fiber reverse osmosis membranes and modules development have been analysed. Comparative analysis with other types of membrane modules and tentative calculation of module's design considering the hydrodynamic parameters of separation has been made.

1. Introduction
Modern industrial enterprises must meet the principles of energy and resource conservation and environmental safety requirements. Membrane technology fully meets these criteria, it is an effective method of processing, separating and concentrating both liquid and gas mixtures. Reverse osmosis, as a separation method of inorganic compounds aqueous solutions, has found wide application in industries, in medicine and other fields [1].

To carry out the reverse osmosis process, membrane modules are used. They can have a different design. At the present stage, almost 90% of the market, both in kind and in money terms, is occupied by spiral-wound modules (SW) [2]. They have a sufficiently high packing density of membranes (up to 1000 m² / m³), a well-established system of production, installation and maintenance. However, such a design has a number of drawbacks [3]. So, for the formation of high pressure and drainage channels special grids - separators are necessary. Their presence affects hydrodynamics, contributes to increased hydraulic losses and, as a result, increases both capital costs during production (complex stages of sealing and winding), and operational ones. These disadvantages can be solved by switching to a different type of module design using membranes in the form of hollow fibers (HF).

The first experience of creating HF membranes and modules based on them was made by the American company DuPont in 1974 [4]. Module B-9 measuring 245 x 1016 (diameter x length) mm contained approximately 4.4 million fibers, the membranes operational surface being 1200 m². Fibers with an outer diameter of 85 μm and an inner one of 42 μm were made of an aromatic polyamide [4, 5]. However, the development have not took into account the hydrodynamic parameters of liquid flow. The high hydraulic resistance of the drainage channel reduced the process' driving force - the pressure difference on both sides of membrane. Despite the high packing density of the hollow fibers (~ 20,000 m²/m³), the module's performance remained fairly low (~ 0.03 l/m²·bar·h) [5, 6].

Comparative analysis of advantages and disadvantages of SW and HF reverse osmosis modules allows drawing a conclusion about the prospects of modules based on HF. The estimated calculation was carried out taking into account the following assumptions:
- filtration from membrane outside space to inside one;
- specific productivity of both modules (SW and HF) remains equal;
- membrane specific productivity along the length of the high pressure channel (HPC) is constant;
- the density and viscosity of the liquid to be separated are constant along the length of the HPC;
- cocurrent flow of concentrate and permeate;
- standard overall dimensions of the module (module 8040: length 1016 mm, diameter 200 mm).

2. Calculation method

Optimization of membrane module design consisted in choosing the diameter of the fibers and, consequently, membranes packing density.

The flow velocity $w_{\text{in}}$ (m/s) at the module input is calculated as:

$$w_{\text{in}} = \frac{L_{\text{in}}}{S} = \frac{L_{\text{in}}}{\frac{\pi D^2}{4} \frac{\pi n_{HF} d_{od}^2}{4}}$$

where:
- $L_{\text{in}}$ - volumetric feed flux, m$^3$/s;
- $S$ - the cross section area, m$^2$;
- $D$ - the internal diameter of the membrane module, m;
- $n_{HF}$ - total number of HF in module;
- $d_{od}$ - outer diameter of the fiber, m.

The fluid velocity in an arbitrary cross section is equal to:

$$w = \frac{L}{S} = w_{\text{in}} - \frac{4G d_{od} d_{od}^2 n_{HF}}{D^2 - d_{od}^2 n_{HF}}$$

where:
- $L$ - change in the liquid flow rate along the length of HPC, m$^3$/s. $L$ is calculated from the material balance equation;
- $G$ - specific productivity of the membranes, m$^3$/m$^2$ s.

The general expression for calculating the hydraulic losses along the length of the module HPC are determined by the Darcy equation, which, after substituting expressions for all the quantities entering and integrating it, has the form of:

$$\Delta P_a = \frac{67 \mu w_{\text{in}} l}{d_{eq}^2} - \frac{133 \cdot \frac{\mu G d_{od} l^2 n_{HF}}{D^2 - d_{od}^2 n_{HF}}}{d_{eq}^2 (D^2 - d_{od}^2 n_{HF})}$$

where:
- $\Delta P_a$ - hydraulic resistance of the HPC, Pa;
- $d_{eq}$ - equivalent diameter of the HPC, m;
- $\mu$ - viscosity of the liquid, Pa s.

Similarly, when integrating the Darcy equation, an expression is derived for calculating the hydraulic resistance of the drainage channel $\Delta P_d$ (Pa):

$$\Delta P_d = 64 \cdot \mu \cdot G \cdot l^2 \frac{d_{id}^2}{d_{id}}$$

where:
- $d_{id}$ - internal diameter of the fiber, m;

The velocity can be calculated as the ratio of the permeate flux to the cross section of the fiber:

$$w = \frac{P}{S} = \frac{G F}{S} = \frac{4G l}{d_{id}}$$

where:
- $P$ - flux of permeate, m$^3$/s;
- $S$ - cross-sectional area of the drainage channel, m$^2$;
- $F$ - surface area of the drainage channel, m$^2$.

3. Results and discussion

According to the relationships obtained, the dependence of the HPC hydraulic resistance on the membranes operational area and the optimum range of geometric dimensions (diameters) of HF membranes were established (fig.1). Relationship between of the drainage channel’s hydraulic resistance $\Delta P_d$ and the packing density of membrane in module for different HF diameters (from 0.8 to 1.6 mm) is shown on fig.2.

The obtained dependences allow to determine the driving force of the separation process (pressure drop on both sides of the membrane), which could be related to exploitation costs. For comparison, the pressure channel’s hydraulic resistance of SW modules is comparable or slightly lower than this.
value for HF. However, the drainage grid significantly increases the hydraulic resistance in the drainage channel, which leads to a decrease in the driving force of the process (increase in operating costs). To sum up, these relationships allow developers to choose the optimal construction and parameters of membrane module.

![Figure 1. Relationship between the HPC hydraulic resistance $\Delta P_a$ and the packing density of membrane module ($m^2 / m^3$).](image1)

![Figure 2. Relationship between the drainage channel’s hydraulic resistance $\Delta P_d$ and the packing density of membrane module for different HF diameters.](image2)

Based on the results of the calculation and analysis of industrial experience, the advantages of hollow fiber reverse osmosis membranes and modules are:
- **High packing density of membranes** \((m^2 / m^3)\). With the same hydraulic resistance and operating pressure for SW and HF membranes, the packing density of HF is higher, which makes it possible to increase productivity in the same overall module dimensions by 1.5-2 times compared to the SW or to reduce the module dimensions while maintaining productivity.

- **Hydrodynamics in the HPC.** The hydrodynamic regime in the HPC of the HF module is turbulent, the transition region. Thus, Reynolds number value for HF remains approximately constant for different fiber diameters and is equal to 500. According to the paper [7], the critical value of the Reynolds number for a cramped channel at which the hydraulic regime becomes turbulent, is 100. HF module is the self-supporting construction and is not complicated by separating and drainage grids, liquid mixing occurs due to the flow around the fibers and their own oscillations. Thus, in the HPC of the HF module, the turbulence degree of the flow increases compared with SW one, hence an increase in the mass-transfer coefficient and a decrease in the concentration-polarization (CP) value could be achieved.

- **High resistance to contamination and economical washing stages.** Due to better hydrodynamics in HPC, the requirements for the feed water are less rigid for HF elements, compared with SW one - the layer of impurities forming on the fiber surface breaks down easily. As a consequence, the consumption of reagents and water for washing decreases. Comparative characteristics of SW and HF modules is shown in tab.1.

| Parameter                         | SW            | HF            |
|-----------------------------------|---------------|---------------|
| Permeate productivity, m³/h       | Up to 2       | 3 - 4         |
| Operational surface, m² (packing density, m² / m³) | 35 – 40       | 60 – 90       |
| Fluid hydrodynamic mode in HPC    | laminar       | turbulent, transition area |

### 4. Conclusions

The optimal geometric dimensions of the hollow fibers and the packing densities of them are discussed. Analysis of the manufacturing of HF and flat composite membranes and modules [2] and operational characteristics shows the perspectives of HF modules. The ability to reduce the size of hollow fiber modules while maintaining high performance makes them promising to use especially in limited spaces: compact desalination plants on sea vessels and submarines; mobile water treatment plants; water treatment plants for the aerospace industry.

### References

[1] Zheng X, Zhang Z, Yu D, Chen X, Cheng R, Min S, Wang J, Xiao Q, Wang J 2015 *Resources, Conservation and Recycling* **105** 1–10

[2] Lee K P, Arnott T C, Mattia D 2011 *Journal of Membrane Science* **370** 1–22

[3] Kucera J 2010 Reverse Osmosis, Design, Process, and Applications for Engineers Wiley-Scrivener p 416

[4] Gorenflo A, Redondo J A, Reverberi F 2005 *Desalination* **178** 247-260

[5] Chatterjee A, Ahluwalia A, Chatterjee A, Senthilmurugan S, Gupta Sh K 2004 *Journal of Membrane Science* **236** 1–16

[6] Ukai T, Nimura Y, Ukai T, Hamada T, Matsui H 1980 *Desalination* **32** 169 – 178

[7] Happel J, Brenner H 1965 *Reynolds number hydrodynamics Published by Prentice Hall, Englewood Cliffs, N.J.* p 630