# Beneficial Effect of Particle Adsorption in UF/MF Outside-In Hollow Fiber Filters

Yuriy Polyakov

USPolyResearch, New Jersey Institute of Technology

*RESEARCH DIRECTION*:

**LEARN FROM NATURE**


*PRINCIPLE OF NATURE APPLIED IN THE STUDY*:

**SYNERGETIC AND COMPLEMENTARY**

**COMBINATION OF PROCESSES**


*EXAMPLE IN NATURE:*

CYCLES OF MATTER (WATER, NITROGEN, OXYGEN)


*EXAMPLE OF THE PRINCIPLE IN MEMBRANE TECHNOLOGY*:

MEMBRANE BIOREACTORS

Key UF/MF disadvantage: membrane fouling (cake deposition)
Key mechanism of depth filtration: particle deposition on collectors

How to combine UF/MF and depth filtration *in a synergetic and complimentary way*?
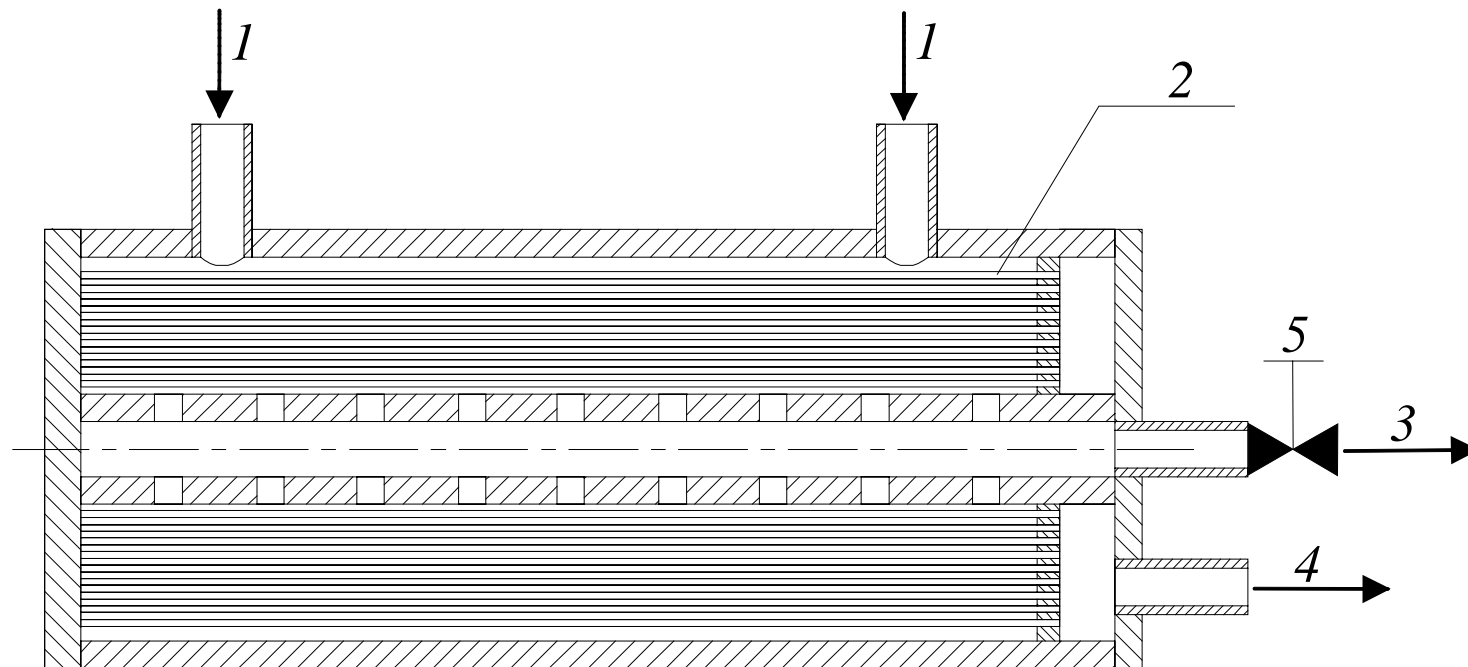Use an outside-in hollow fiber filter:

Fig. 1. Radial hollow fiber membrane (HFM) adsorber: (*1*) feed, (*2*) hollow fiber, (*3*) filtrate, (*4*) permeate, (*5*) control valve

## WHY WOULD IT WORK?

- HF packing densities are up to 0.5-0.6
- low flow velocities tangential to membrane surface
- enhanced collection efficiency due to permeation drag
- adsorptive properties of the body of specially prepared MF and UF membranes are already successfully used in affinity filtration and membrane chromatography
- even if the HF were impermeable and made of a high-adsorption material, such a unit would work as a depth filter

## FEATURES OF THE PROCESS

- can be used in a process in which the product (permeate plus filtrate) flow rate and transmembrane pressure (TMP) are kept constant (by adjusting the control valve)
- filtrate leaving an HFM adsorber can be used as a feed to another HFM adsorber (multistage plants with high particle retentions and water recoveries)
- needs hollow fibers made of polymers with a high-adsorptive capability with respect to suspended particles (SP)

## MATHEMATICAL MODEL

1) Differential law of mass conservation:

$$\frac{\partial c}{\partial t} - \frac{1}{r}\frac{\partial(rwc)}{\partial r} = -s\frac{\partial \Gamma}{\partial t}.$$

2) Linear equation of reversible adsorption governing the growth of cake layer on the membrane surface:

$$\frac{\partial \Gamma}{\partial t} = \beta c - \alpha \Gamma .$$

3) Liquid continuity equation (integral form):

$$w = \frac{w_0 r_0}{r}\left[1 - \frac{1}{w_0 r_0}\int_r^{r_0} sV_p\, r\, dr\right],$$

4) Darcy's law governing the permeate velocity of a cake-covered membrane:

$$V_p = P/\left[\mu\left(R_m + r_c \Gamma\right)\right],$$

Here $c$ is the concentration of suspended particles; $t$ is the time; $w$ is the liquid velocity in the channels between hollow fibers; $r$ is the radial filter depth coordinate; $s$ is the ratio of HFM shell area to liquid volume inside the filter; $\Gamma$ is the cake mass per square meter of HFM shell area; $\beta, \alpha$ are the coefficients of adsorption and peptization, respectively; $V_p$ is the permeate velocity; P is the transmembrane pressure (TMP); $\mu$ is the liquid viscosity; $R_m = P/\left(\mu V_0\right)$ is the clean membrane resistance; $r_c$ is the specific cake resistance.

## SUMMARY OF THEORETICAL STUDY

- Numerical, approximate, and asymptotic solutions were obtained both for the HFM adsorber and deadend HFM filter.

- Mathematical model was used to describe existing experimental data for deadend HFM filters. The maximum error was within 5%, much lower than that for the classical cake filtration model, in which the growth of cake layer is taken directly proportional to the permeate velocity.

- With the empirical values of the adsorption and peptization coefficients determined by fitting the data of the deadend experiments, the mathematical model was used to evaluate the performance of an outside-in HFM adsorber.

- Modified mathematical model taking into account the particle adsorption on the inner pore surface was used to estimate the efficiency of using pores with sizes significantly exceeding the average size of particles in deadend HFM filters.

- To assess the effect of the permeate velocity on the coefficients of adsorption and peptization, a theoretical model based on the Carman-Kozeny equation and Smoluchowski stationary approximation (Interface Boundary Layer theory) for spherical Brownian particles was developed.

- Effects of process and membrane characteristics on the filter performance were evaluated and technological recommendations were formulated both for HFM adsorbers and deadend HFM filters.
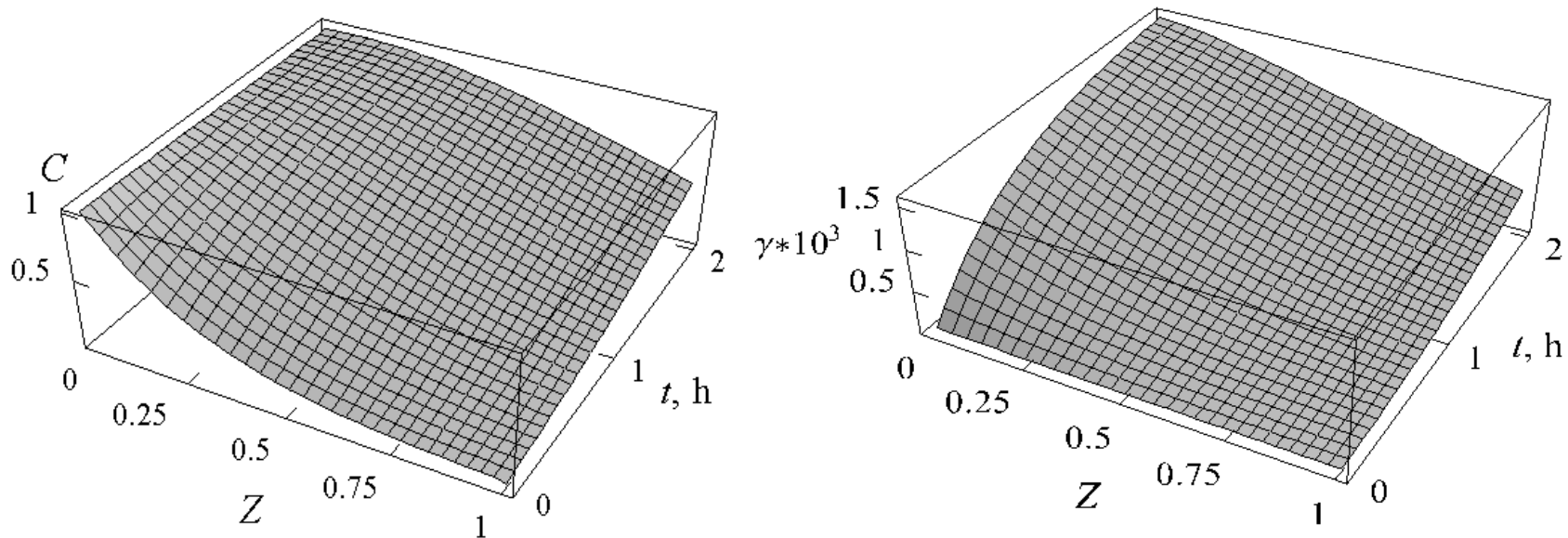
RESULTS OF THE THEORETICAL STUDY FOR HFM ADSORBERS



Fig. 2. Profiles of (a) dimensionless SP concentration $C$ and (b) dimensionless specific deposit $\gamma$ (mass of adsorbed particles per unit membrane surface area) in an outside-in HFM adsorber ($Z = \left(r_0^2 - r^2\right)/\left(r_0^2 - r_{in}^2\right)$ is the dimensionless depth coordinate)

Table 1. Performance of HFM adsorber at various TMP in continuous flow and batch operations ($V_0 = 6.94 \times 10^{-5}$ m/s corresponds to the experimental data for a deadend filter)

| $w_0 \times 10^3$, m/s | $V_0 \times 10^5$, m/s | $\xi_0$ | Continuous flow | | Batch | |
|---|---|---|---|---|---|---|
| | | | $t_{op}$, s | $\xi_0 V_{av}/V_0$ | $t_{op}$, s | $\xi_0 V_{av}/V_0$ |
| 4.48 | 1.16 | 0.50 | 9316 | 0.239 | 14865 | 0.176 |
| 2.98 | 1.16 | 0.75 | 18870 | 0.347 | 27637 | 0.256 |
| 2.26 | 1.16 | 0.99 | 30267 | 0.455 | 41445 | 0.339 |
| 8.97 | 2.31 | 0.50 | 2656 | 0.267 | 4557 | 0.206 |
| 5.96 | 2.31 | 0.75 | 6634 | 0.355 | 10454 | 0.265 |
| 4.53 | 2.31 | 0.99 | 11518 | 0.451 | 16897 | 0.335 |
| 13.45 | 3.47 | 0.50 | 910 | 0.322 | 1542 | 0.267 |
| 8.95 | 3.47 | 0.75 | 3176 | 0.378 | 5164 | 0.292 |
| 6.80 | 3.47 | 0.99 | 6055 | 0.461 | 9216 | 0.348 |
| 26.91 | 6.94 | 0.50 | – | – | – | – |
| 17.89 | 6.94 | 0.75 | 502 | 0.524 | 729 | 0.469 |
| 13.59 | 6.94 | 0.99 | 1562 | 0.542 | 2359 | 0.447 |

$w_0$ is the feed velocity, $V_0$ is the initial permeate velocity, $\xi_0$ is the ratio of initial permeate to feed flow rates, $t_{op}$ is the separation cycle duration, and $\xi_0 V_{av}/V_0$ is the proportion of permeate in product (permeate plus filtrate)

Table 2. Performance of HFM adsorber at various adsorptive capabilities of HF membranes with respect to suspended particles ($\beta = 1.81 \times 10^{-4}$ m/s is the value obtained from the deadend experiment)

| $\beta \times 10^4$ | Continuous flow | | Batch | |
|---|---|---|---|---|
| m/s | $t_{op}$, s | $V_{av}/V_0$ | $t_{op}$, s | $V_{av}/V_0$ |
| 1.81 | 1562 | 0.542 | 2359 | 0.447 |
| 3.61 | 5318 | 0.367 | 8350 | 0.262 |
| 5.42 | 9895 | 0.317 | 15142 | 0.217 |

- the lower is the coefficient of peptization, the higher is the performance
- coefficient of adsorption rises with an increase in permeate velocity
- coefficient of peptization declines with increasing permeate velocity
- adsorption and peptization coefficients almost linearly depend on the permeate velocity

## THREE-STAGE PROCESS FLOW DIAGRAM
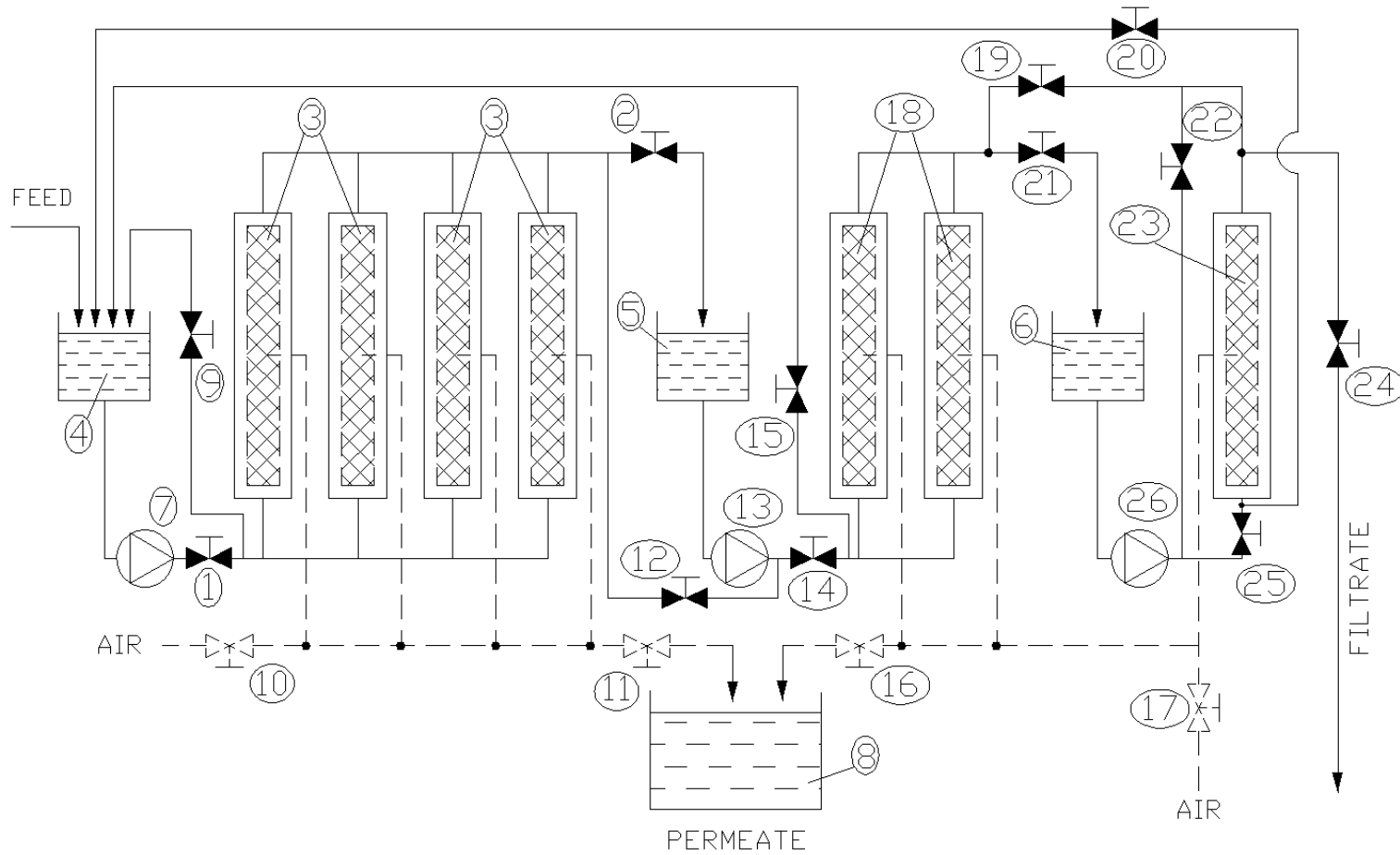


*1, 9–12, 14–17, 19, 20, 22, 25* – shutoff valve; *2, 21, 24* – control valve; *3* – first-stage HFM module; *4* – feed tank; *5* – first-stage filtrate tank; *6* – second-stage filtrate tank; *7* – first-stage pump; *8* – permeate tank, *13* – second-stage pump; *18* – second-stage HFM module; *23* – third-stage HFM module; *26* – third-stage pump.

## RESULTS OF THE THEORETICAL STUDY FOR DEADEND HFM FILTERS

- the larger is the coefficient of adsorption, the higher is the performance because the particle deposition dominates in the entrance region of the filter while the inner area of the filter continues to operate at a high permeation velocity (same effect as observed in HFM adsorbers)

- the higher is the transmembrane pressure, the faster is the decline in the dimensionless product flow rate

- using pore sizes much larger than the average particle size can be beneficial only when the separation cycle does not exceed 30 minutes

- adsorption on the exterior interporous membrane surface taking place while the pores with sizes larger than the particle size are narrowed due to the adsorption of particles on their inner surfaces can result in a sharp decrease in permeate flow rate due to the accelerated filling of the cake "craters" over the pores with cake once the effective size of the pores drops to the critical value

## CONCLUSIONS

- Hollow fiber membrane adsorber benefits from cake formation on the membrane surface and produces an additional volume of clarified water – filtrate. Such an adsorber may be more cost-effective than the existing deadend and crossflow membrane filters.
- Increasing the adsorptive capability of hollow fiber membranes with respect to suspended particles will improve the performance of outside-in hollow fiber membrane adsorbers and deadend filters.

## WHAT TO DO NEXT

- build and test experimental and pilot HFM adsorbers
- improve existing deadend HFM filters by using HF membranes with a high adsorptive capability
- improve the mathematical model by using the experimental results
- develop simple engineering algorithms for HFM adsorber design

## PROPOSED PROJECT

Combine the efforts of universities and membrane companies under the umbrella of the North American Membrane Society to carry out experimental and theoretical studies in order to implement the HFM adsorber technology.