Membrane Fouling at the *Service* of UF/MF: Hollow Fiber Membrane Adsorber

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Membrane fouling in UF/MF is a problem that has been attracting considerable intellectual and engineering resources over almost 40 years. A lot of efforts, such as high tangential flows, vibration, air sparging and the like, have been taken to minimize its negative impact on the performance of UF/MF filters [1]. All these efforts are associated with increased operating and maintenance costs, and, as a result, UF/MF is still not competitive with conventional technologies for most applications in water and wastewater treatment.

At the same time, particle deposition, or collection, on adsorbents and bed grains has been successfully used in water treatment for many decades [2, 3]. Membrane surface plays the role of a particle collector in a UF/MF water treatment filter, but, in contrast to adsorbents and bed grains, the formation of cake in the existing UF/MF filters has a negative effect on their production rate. Therefore, the idea of harnessing membrane fouling, instead of struggling against it, in order to produce an additional (to permeate) amount of clarified water in UF/MF filters looks very attractive.

Consider a hollow fiber (HF) filter in which the feed suspension is supplied to the HF shells (Fig. 1). The distinctive feature of such a hollow fiber membrane (HFM) adsorber will be an additional product stream, filtrate *3*, produced due to the particle collection on the HF surfaces. Let us assess this design from physical considerations.

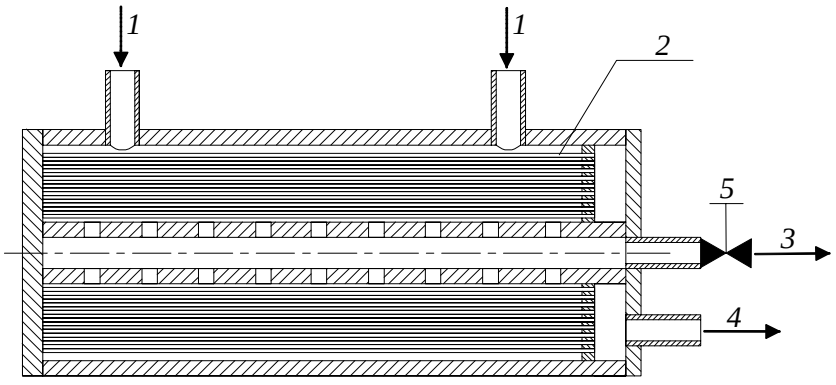

Fig. 1. Radial hollow fiber membrane adsorber: (*1*) feed, (*2*) hollow fiber, (*3*) filtrate, (*4*) permeate, (*5*) control valve

First, the HF packing densities in the existing filters are up to 0.5–0.6, which is close to those of adsorbent columns and filtration beds. HF filters show a highly developed membrane surface and very low flow velocities of slurry tangential to membrane surface.

The collection efficiency of such an adsorber can be enhanced by the permeation drag, which brings the suspended particles to the membrane surface.

Second, it is common knowledge that suspended particles (SP) in adsorbent columns are initially collected by the entrance layers of grains, and the deposition front moves on to the deep layers. The operation is terminated when a breakthrough takes place. So, the same process will take place in the HFM adsorber: the outer hollow fibers collect the suspended particles while the inner ones remain almost clean, keeping their permeate velocity at a high level. Clearly, during the initial period the SP concentration in the filtrate will be low, so the filtrate can be withdrawn, increasing the yield of clarified water in the filter. Potentially, this gives us a chance to build an outside-in HFM filter providing a constant product flow rate at constant transmembrane pressure (TMP), with a power consumption close to that of the deadend filter.

Third, the filtrate leaving an HFM adsorber can be used as a feed to another HFM adsorber, which allows us to achieve very high SP retentions and water recoveries. At the same time, conventional crossflow UF/MF devices have a retentate stream, in which the SP concentration is higher than that in the feed. It is well known that the higher the SP concentration in the feed, the higher the rate of cake deposition and the lower the permeate velocity. This limitation of conventional crossflow UF/MF plants makes it impossible to achieve high enough values of particle retention and water recovery.

Fourth, a wide range of polymers and other materials (hydrophobic polyethersulfons, polyvinylidene fluorides, and the like) that do not possess low adsorptive capabilities and, according to the modern theory, should not be used to manufacture UF/MF membranes [4, 5] could find a way to the market of HFM adsorbers. As a result, membrane technologists would get a chance to build processes manufacturing more effective and strong hollow fibers.

Fifth, the adsorptive properties of the body of specially prepared MF and UF membranes are already successfully used in affinity filtration and membrane chromatography, where a wide network of immobilized ligands, or incorporated ion-exchange particles, which is formed owing to extremely high porosity of the semipermeable membranes, accomplishes substance-specific treatment in the purification of protein solutions.

To evaluate the above physical considerations into numbers and relations, we carried out a special study [6–10].

To simulate the operation of an outside-in HFM filter, we used the conventional mathematical model developed for adsorbent columns and granular beds [2, 3, 11]. The governing equations based on the mechanism of reversible adsorption were modified to take into account the withdrawal of permeate as the suspension moves from the outer to inner hollow fibers, as well as the dependence of permeate velocity on the thickness of cake layer [6–10]. The initial condition of clean filter was assumed.

The ranges of values of unknown coefficients involved in the model were determined by approximating the data of two experimental studies with deadend outside-in HFM filters treating activated sludge. The first experiment was run on a laboratory HF

module with an initial permeate velocity of 250 l/(m^2 h) [12]. The second study included pilot experiments at three different TMP values: 20, 40 and 60 kPa [13]. The semiempirical values of the coefficients were determined by fitting the theoretical curve to the experimental data obtained for 20 kPa. The values of coefficients for 40 and 60 kPa were calculated by respectively increasing the value of the initial permeate velocity in their expressions.

The approximation of the deadend filter experimental kinetic curves showed that the mathematical model accurately describes the decline in permeate velocity, that is, the deposition of suspended particles on the outside surface of hollow fibers, for all four experiments [7, 10].

The mathematical model with the semiempirical coefficients obtained from the first experiment was then used to evaluate the performance of an outside-in HFM adsorber whose only difference from the deadend HF filter [12] is the presence of the second product stream: filtrate. In the flow diagram in Fig. 1, this operation corresponds to the open control valve *5* while the closed valve corresponds to the deadend operation. In our calculations, it was assumed that the feed flow rate is maintained constant at constant TMP, that is, the decline in permeate flow rate is compensated by the equal increase in filtrate flow rate adjusted by the control valve *5*.

Figure 2 presents the profiles of SP concentration and specific deposit in the adsorber when the constant feed flow rate is equal to the initial permeate flow rate. As expected, the profiles of SP concentration and specific deposit are much like the classical profiles in adsorbent columns and filtration beds. The suspended particles begin to deposit onto the outer layer of hollow fibers, with the deposit front moving on to the inner HF layer. As one can see, the filtrate can be withdrawn as clarified water for a quite long period, increasing the efficiency of the HF filter. In other words, the outside-in HFM adsorber can be a membrane filter providing a constant product (permeate plus filtrate) flow rate at constant TMP with a power consumption close to that for a deadend outside-in HF filter.

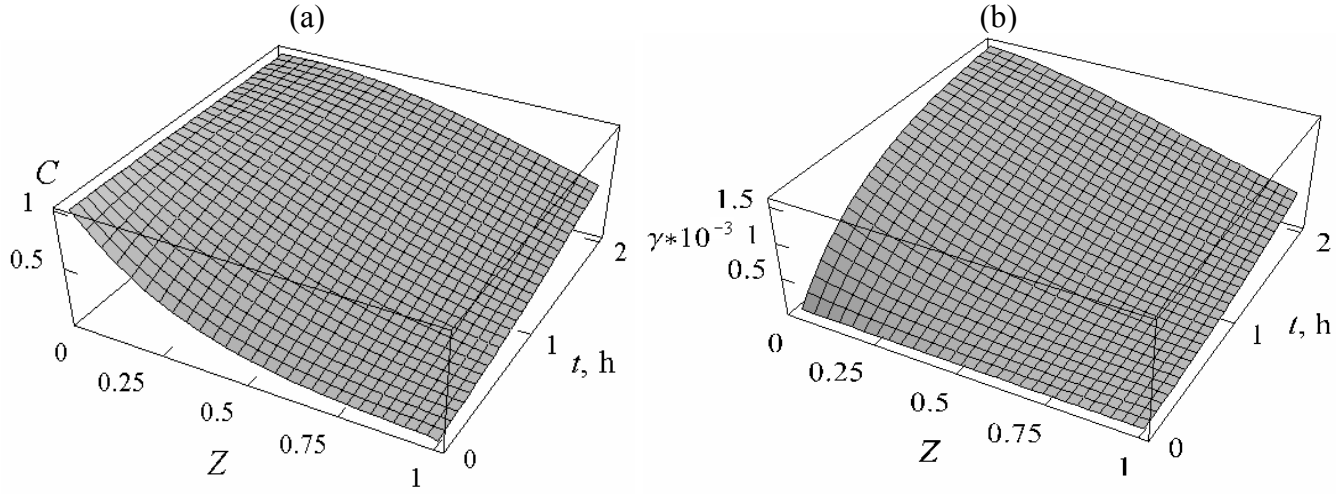

Fig. 2. Profiles of (a) dimensionless SP concentration C and (b) dimensionless specific deposit γ (mass of adsorbed particles per unit membrane surface area) in an outside-in HFM adsorber (Z is the dimensionless depth coordinate)

As it follows from Table 1, in which the separation cycle is terminated for backflushing when the product SP concentration reaches 10% of the feed concentration, the adsorber achieves a maximum efficiency (longest duration of separation cycle) when the constant feed flow rate is equal to the initial permeate flow rate. This is true for continuous flow and batch operations. In Table 1, w_0 is the feed velocity, V_0 is the initial permeate velocity, ξ_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; the product consists of both the filtrate and permeate and the ratio of average permeate velocity to initial permeate velocity multiplied by the ratio of initial permeate to feed flow rates is equal to the fraction of permeate in the product. The data in Table 1 also demonstrate that the greatest product volume, which is equal to the product of linear feed velocity (remaining constant in each separation cycle), filter cross section area (being the same in all calculations), and separation cycle duration, can be achieved at the lowest TMP. For example, the volume at the lowest TMP is about 30% higher than that for the double TMP. It also implies that, given the same constant product flow rate, the separation cycle duration of two adsorbers will be about three times longer than that of one adsorber operated under double TMP. This fact may be of great importance in optimizing the design of multistage plants of HFM adsorbers. Finally, it can be seen from Table 1 that, owing to the filtrate stream, an HFM adsorber would be able to produce approximately twice as much clarified water as a deadend filter with the same characteristics.

Table 1. Performance of HFM adsorber at various TMP in continuous flow and batch operations ($V_0 = 6.94\times10^{-5}$ m/s corresponds to the experimental data of [12])

$w_0\times10^3$, m/s	$V_0\times10^5$, m/s	ξ_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

Table 2 (ξ_0 = 1) demonstrates that an increase in the adsorptive capability of hollow fiber membranes with respect to suspended particles, given the same all other process parameters, can cause a considerable improvement in the HFM adsorber performance. For

example, as the coefficient of adsorption increases twice, the product volume increases about 3.3 times. This results from the fact that the higher the coefficient of adsorption, the higher the rate of particle deposition on the outer hollow fibers and the cleaner the rest of the adsorber. The latter causes a higher averaged permeate flow rate and a lower SP concentration in the filtrate. It should be noted that the separation cycle duration of almost half an hour, which was obtained for the HFM adsorber equipped with a bunch of hollow fibers made of a low-adsorption polymer as were used in [12], would be good enough for modern commercial membrane systems. At the same time, increasing the adsorption coefficient, which can be effected by using high-adsorption materials for membranes, varying the ionic strength and pH of the slurry and so on, could provide us with a great potential for improving the performance of outside-in HFM filters.

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 [12])

$\beta \times 10^4$ m/s	Continuous flow		Batch	
	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

If we build a multistage plant consisting of HFM adsorbers, in which the filtrate leaving the first-stage adsorber is used as the feed to the second stage adsorber and so on, we can achieve very high particle retentions in this plant: after the second stage it could be about 99%. Obviously, the values of water recovery that could be reached in HFM adsorbers would be close to those of deadend HFM filters.

It should be noted that the positive effect of increasing the value of the adsorption coefficient must be also observed for the existing deadend outside-in HF filters due to the fact that particle deposition would dominate in the entrance region of the filter while the inner area of the filter would continue to operate at a high permeation velocity [7].

SUMMARY

(1) 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.

(2) 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.

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