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Numerical and experimental investigation on integrated flocculation-membrane filtration process for the reactor configuration design and operational parameter optimization

Jie Wang [a,b,*], Yi Wu [b], Hongwei Zhang [a], Hui Jia [a]

[a] State Key Laboratory of Hollow Fiber Membrane Materials and Processes, Tianjin Polytechnic University, Tianjin 300387, China
[b] School of Environmental and Chemical Engineering, Tianjin Polytechnic University, Tianjin 300387, China

HIGHLIGHTS

- Micro-vortex scale is introduced to analyze the state of flow field.
- The characteristics of flow field are validated by real-time image technology.
- Configuration of "partial flocculation" accompanies with the best hydraulic conditions.

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ABSTRACT

According to the flocculation kinetics theory, micro-vortex scale was introduced to analyze the state of flow field in integrated flocculation-membrane filtration process. Combining numerical simulation with experimental investigation based on real-time image analysis, it was investigated that the characteristics of flow field in various reactor configurations and flocculation operational parameters. For numerical simulation, the results reveal that the best operational performance of integrated process can be achieved in the configuration of partial flocculation (PF) which occurs in the tank with a partition settled between flocculation area and membrane filtration area. When volume ratio of flocculation unit and membrane filtration unit is 2 to 1, which also means that the retention time of flocculation unit lasts longer than that of membrane filtration unit, in this work 27 min and 13 min respectively, Combining numerical simulation with experimental flocs of which size is similar to micro-scale vortex form larger-size ones that benefit forming loose cake layer through relative motion and collision, which can mitigate membrane fouling.

Nomenclature

λ_0	the size of micro-vortex (m)
υ	movement viscidity coefficient of water ($m^2 \cdot s^{-1}$)
ε	energy dissipation rate in unit time and unit volume of water ($m^2 \cdot s^{-3}$).
r_c	the resistance of filter cake (m^{-2})
d_0	the diameter of floc (m)
η	the porosity of cake layer.
P	the density (kg/m^3)
$\vec{v}$	the velocity (m/s)
$\bar{\bar{\tau}}$	the stress tensor (Pa)
P	the pressure (Pa)
τ	the stress tensor (Pa)
g	the gravitational force (N)

Abbreviations: CFD, Computational Fluid Dynamics; PF, partial flocculation; FF, full flocculation; MRF, multiple reference frame.

* Corresponding author at: State Key Laboratory of Hollow Fiber Membrane Materials and Processes, Tianjin Polytechnic University, Tianjin 300387, China. Tel.: +86 22 8395 5673; fax: +86 22 8395 5451.
E-mail address: wangjiemailbox@163.com (J. Wang).

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1. Introduction

The application of flocculation in water treatment has dramatically increased in the past decade [1–4]. Membrane filtration enabling excellent solid/liquid separation and biodegradation of organic matter achieved in a single tank has been studied for the treatments of both wastewater and drinking water, and already applied to municipal wastewater treatment at full scale [5–8]. Applying a flocculation step before membrane can remarkably improve the permeate quality in terms of organic matter. The flux was greatly enhanced for membrane filtration when a flocculation was added for treating water [9]. Therefore, the integrated process composed of pre-flocculation and membrane filtration has become particularly attractive since it is expected to display preferable operation efficiencies. Flocculation and membrane filtration have gained an unprecedented popularity in drinking water production, which had been confirmed by previous studies [10–12]. Integrated flocculation–membrane filtration, namely the combination of flocculation and membrane filtration directly, simultaneously simplify sedimentation tank. Additionally, single membrane filtration tank can replace the sand filtration units of a conventional water treatment plant. And flocculation has a considerable influence on the follow-up membrane fouling and the water quality after the whole treatment process. A number of researches have reported that good hydraulic condition plays an important role in mitigating membrane fouling due to its benefits to form flocs of larger size. Bridgemana [13], Rosângela [14] and Pikkarainen et al. [15] considered that suitable hydraulic condition could effectively improve the distribution of flow turbulence kinetic energy, dramatically increase the collision frequency of flocs, and effectively promote flocculation reaction. Different flocculation conditions (such as coagulant types and dosages, mix strategy and so on) cause diverse impacts on flocculation-membrane processes. Liu et al. [16] observed that quick stirring intensity and stirring time had different impacts on floc size, suggesting that various hydraulic conditions might lead to distinct floc sizes. Besides, based on the analysis of the removal of different pollutants in flocculation pretreatment, Howe et al. [17] found that the creation of large-size flocs caused the increase of sludge cake's porosity on membrane surface; meanwhile, dissolved organic pollutants were entrapped in the microbial flocs during the course of flocculation. Thus, flocs' size which determines the porosity of cake layer plays a key role in integrated flocculation–membrane filtration process. And in the integrated flocculation-membrane unit, Flocs' distribution has a significant effect on membrane fouling potential.

The integrated flocculation–membrane filtration is a single-stage instantaneous water treatment process, that is, a short process. As a consequence of rapid filtering, the inadequate flocculation occurs, which leads to the phenomenon of "Deferred flocculation", influencing the water quality discharged. Different reactor configurations and flocculation controlling parameters cause different impact on hydraulic conditions within the reactor, thus influencing the flocs' size. Generally, two types of reactor configurations have been focused on, full flocculation (FF) and PF. FF means that two processes, flocculation and membrane filtration, are conducted in one tank, and while PF takes place in the tank with a partition settled between flocculation unit and membrane filtration unit.

This research tries to investigate the problem on how to combine flocculation operational parameters with membrane filtration in integrated flocculation–membrane filtration. This work aims to guide the design and optimization of integrated flocculation–membrane filtration process. The design and optimization of integrated flocculation–membrane filtration requires knowledge of membrane fouling, mixing, flocculation kinetics. However, integrated flocculation–membrane filtration design is mainly based on the flocculation kinetics and membrane fouling considerations even though the hydrodynamics with an integrated flocculation–membrane filtration system is critical importance to the performance of the system. Current design methods cannot directly predict how vessel design affects hydrodynamics, hence overall performance. Computational fluid dynamics (CFD) provides a method for the prediction of the effect of design feature on the hydrodynamics from a fundamental level [18]. From the perspective of hydraulics, the CFD were adopted to analyze the fluid flow through the different reactor configurations (include the "FF" and "PF") and flocculation operational parameters (flocculation retention time). It mainly focused on evaluating the effects of different reactor configurations and flocculation operational parameters on membrane fouling mitigation.

2. Materials and methods

2.1. Micro-vortex theory of flocculation

According to the micro-vortex theory of flocculation theory, Wang [19] analyzed the inertia effects in the dynamics of flocculation. He found that collisions and relative movements exist among particles in the vortexes, closing to their sizes. This kind of vortexes is called micro-vortex which can be expressed as:

$$\lambda_0 = \left(\frac{\upsilon^3}{\varepsilon}\right)^{\frac{1}{4}} \tag{1}$$

where, λ_0 (m) stands for the size of micro-vortex; υ ($m^2 \cdot s^{-1}$) means the movement viscidity coefficient of water; ε ($m^2 \cdot s^{-3}$) represents energy dissipation rate in unit time and unit volume of water.

Turbulent motion can be regarded as the result of a variety of vortexes in different scales superposing on the laminar flow. The greater the size of vortex is, the stronger the inertia of vortex behaves, and the smaller the viscosity and velocity gradient performs. The velocity gradient (G) of vortex peaks when the vortex size equals to the minimum characteristic vortex size λ_0. Therefore, particles smaller than the impeller-region Kolmogoro1 microscale may erode at a critical velocity related to the local energy dissipation rate, while those larger than the impeller-region Kolmogoro1 microscale may fragment at a critical velocity related to the impeller tip speed. As flocs' size approximates the micro-vortex, due to strong centrifugal effect, the micro-vortex can enhance the flocs' collision for bonding into large-scale flocs that lead to the increase of cake layer's porosity on membrane surface to prevent membrane fouling.

2.2. Kozeny–Carman theory

Flocculation plays an important role in water treatment process since the effluent water quality is mainly governed by the flocs' size in flocculation process. Furthermore, the size of flocs directly restricts the development of membrane fouling. Schrader et al. [20] studied the relationship between floc size and membrane fouling in both raw water and mixed solution. According to the Kozeny–Carman theory, they found that the resistance of filter cakes could be expressed as (2):

$$r_c = \frac{(1\text{-}\eta)^2}{d_0^2 \eta^3} \tag{2}$$

where, r_c (m^{-2}) means the resistance of filter cake; d_0 (m) stands for the diameter of floc; η represents the porosity of cake.

The greater the particle size is, the weaker the resistance of filter cake conducts. Membrane fouling is mitigated with the increase of particle size. Hydraulic condition governs the dynamics of flocs' aggregation, erosion, and rupture. Particles' aggregation and breakup in the flocculation stage limit the increase of flocs' size. When aggregation reaches equilibrium with erosion under certain hydraulic condition, the flocs can obtain minimal disruption. Thus it can be seen that appropriate vortex size not only provides motion space for flocs' collision, but also offers velocity gradient for their aggregation. The appropriate vortex size plays significant role in flocs' growth. The creation of large floc size is beneficial to postponing membrane fouling in integrated flocculation–membrane filtration process.

2.3. Modeling methods

From the perspective of hydraulics, characteristics of fluid flow formed in different reactors with various operational parameters and reactor configurations were investigated to analyze their effects on the flocs' formation. The designed reactor includes two configurations, FF and PF. The model is simplified as shown in Fig. 1. The reaction period