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Liu Yang[a]; Liang-Yin Chu[a]; Wen-Mei Chen[a]
[a] School of Chemical Engineering, Sichuan University, Chengdu, Sichuan, China

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Study on the Flow Field inside the Microfiltration Separator with Rotary Tubular Membrane

Liu Yang, Liang-Yin Chu, and Wen-Mei Chen
School of Chemical Engineering, Sichuan University,
Chengdu, Sichuan, China

Abstract: By using a new type of laser surveying instrument named particle image velocimetry (PIV), the flow field inside a rotary tubular membrane separator with a rotating inner tubular microfiltration membrane and a transparent outer cylinder was measured experimentally, and from which some new observations were resulted. Pairs of stable Taylor vortices with similar dimensions and opposite flowing directions were directly visualized by the measured streamlines and vorticity of flow field in the annular gap of the membrane separator. No matter how the axial Reynolds number, radial Reynolds number and Taylor number changed, the dimensions of the Taylor vortices and the distances between the centers of adjacent Taylor vortices were almost the same, but the shapes of the Taylor vortices at lower Taylor numbers were more regular than those at higher Taylor numbers. The Taylor vortices disappeared because of the turbulence when the Taylor number was too high. The maximum axial velocity near the membrane surface was about 20 times larger than the mean velocity of axial flow inside the annular gap, and the maximum outward radial velocity near the membrane surface was even about 3000 times larger than the average velocity of the radial permeating flow through the tubular microfiltration membrane. The large velocities near the membrane surface, which were due to the Taylor vortices, could prevent solid fine particles from depositing onto the membrane surface and/or entering into the membrane pores and therefore result in reduced concentration polarization and reduced membrane fouling. The results in

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Address correspondence to Liang-Yin Chu, School of Chemical Engineering, Sichuan University, Chengdu, Sichuan, 610065, China. Fax: +86-28-8540-4976; E-mail: chuly@scu.edu.cn

this study provided some valuable guidelines on the hydrodynamic way to reduce membrane fouling.

Keywords: Microfiltration, rotary tubular membrane, flow field, Taylor vortex, membrane fouling, particle image velocimetry (PIV)

INTRODUCTION

Microfiltration is an efficient method for solid-liquid separation when the dimension of solid particulates is as fine as micron, and concentration of micron-sized solid particulates by microfiltration is a usual pretreatment process for the thermal drying of these particles. For the microfiltration, dynamic separators with rotary membrane have been widely applied in various industries in the last decade because of their advantages such as low concentration polarization and low membrane fouling (1–5). The rotary tubular membrane separators are mainly composed of two concentric cylinders, with the inner one rotating and the outer one stationary. Usually the inner cylinder is perforated and covered with a microfiltration membrane and the outer one is a solid wall. Although the geometric structure of the rotary tubular membrane separator is simple, the fluid flow field inside the rotary tubular membrane separator is very complicated. To understand the separation behavior inside rotary tubular membrane separators and to obtain theoretical foundations for structure optimization and efficiency improvement of the rotary tubular membrane separators, it is essential to make the flow field inside the membrane separator as clear as possible. More importantly, the vortex generated inside the rotary tubular membrane separator would result in significant shear stress near the membrane surface, and then reduce the concentration polarization and membrane fouling. That is, to get valuable guidelines for reducing membrane fouling by the hydrodynamic way, it is essential and important to quantitatively understand the vortex formation and vortex characteristics inside the rotary tubular membrane separator.

Up to now, many investigations have been made on the flow field in rotary tubular membrane separators however, almost all previous investigations on the flow field inside the rotary tubular membrane separators have focused on the theoretical analyses (6–9). Although experimental results should be the direct evidence to verify the theoretical analyses and could more factually describe the flow field, there have been few experimental studies on the flow field inside the rotary tubular membrane separators up to now because of a lack of proper measuring methods.

Recently a new type of laser surveying instrument named Particle Image Velocimetry (PIV) has become available. It can be used to measure the velocity vectors, streamlines, vorticity, and velocity distribution of fluid flow simultaneously and instantly. It is a good instrument for experimental research on the flow field inside the rotary tubular membrane separators.

The objective of this study is to experimentally visualize and characterize the flow field inside the rotary tubular membrane separator and then provide some valuable guidelines for reducing membrane fouling by the hydrodynamic way. An experimental study on the flow field in a rotary tubular membrane separator by using a PIV is described in this paper, and the visualization and characterization of the Taylor vortices in the annular gap of the membrane separator were carried out by measuring the streamlines, vorticity, and two-dimensional velocity distributions, and from which some new observations were experimentally resulted.

EXPERIMENTAL

Instrument and Apparatus

The experimental apparatus was composed of a Particle Image Velocimetry (PIV) laser system (Dantec, Denmark) and a rotary tubular membrane separator system, as shown in Fig. 1. The PIV laser system was mainly composed of an optical system, a light orientation system, an image record system, an image analysis processing system, and a software system. The slice laser light was formed by penetrating a green laser beam through a polygonal optical lens. The flow field was lightened by the slice laser and the lightened particle image of flow field was recorded by a CCD camera system. The images in the CCD camera system were transmitted to the PIV processor immediately, and then images showing the velocity vector, streamlines, and vorticity inside the flow field were obtained.

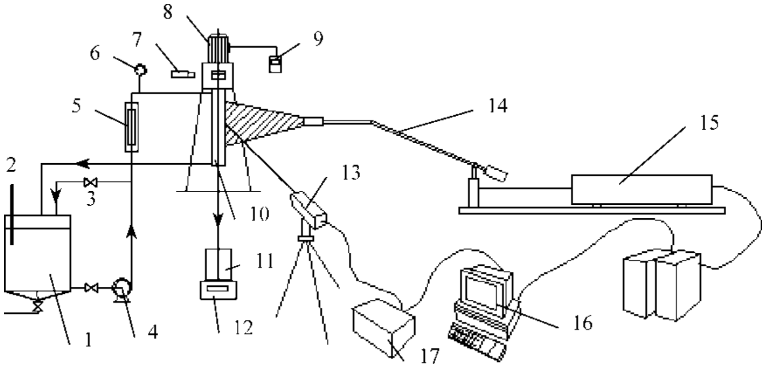

Figure 1. The experimental system for measuring the flow field inside the microfiltration separator with rotary tubular membrane. 1 – water tank; 2 – thermometer; 3 – valve; 4 – pump; 5 – flowmeter; 6 – pressure gauge; 7 – tachometer; 8 – electromotor; 9 – frequency modulator; 10 – rotary tubular membrane separator; 11 – filtrate beaker; 12 – balance; 13 – CCD camera; 14 – laser guiding beam; 15 – laser emitter; 16 – computer; 17 – PIV processor.

The membrane separator system was composed of a fluid flow circulating system and a rotary tubular membrane separator as shown in Fig. 2(a). The temperature of the fluids was maintained constantly at 20°C during the experiments. The rotary speed of the electromotor was adjusted by a frequency modulator. The outer cylinder of the membrane separator was made of transparent glass with inner radius of 37 mm, and the inner cylinder was polypropylene tubular microfiltration membrane with outer radius of 23 mm. The length of the tubular microfiltration membrane was 450 mm, and the mean diameter of the microfiltration membrane pores was about 7.5 μm.

Experimental Program

Certain amount of hollow glass microspheres with mean diameter of 10 μm was put into the water as tracer particles. The measured flow field was in the meridian plane of the membrane separator, as shown in Fig. 2(b) by the hatched part. To assure the meridian plane of the membrane separator was just lightened, the position of the slice laser source could be adjusted. The lens of the camera was just perpendicular to the plane of the slice laser beam. In the measurements, an optical compensating box was fixed around

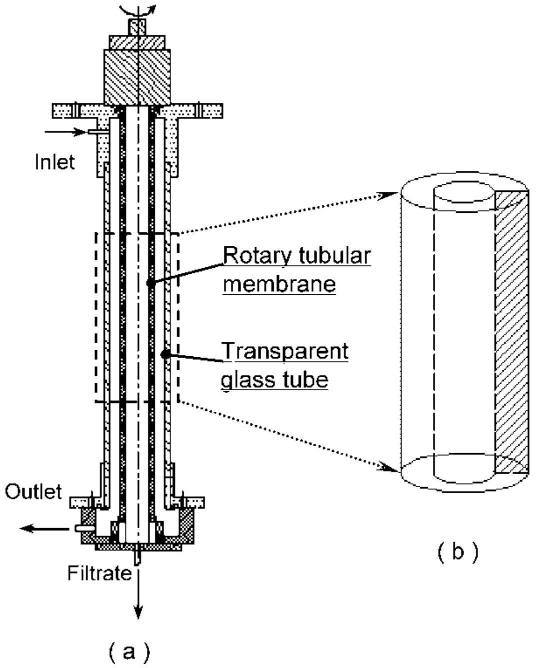

Figure 2. Schematic illustration of (a) the microfiltration separator with rotary tubular membrane and (b) the measurement position of the flow field.

the membrane separator. The optical compensating box was made of transparent glass with rectangular cross section and filled with water.

Definition of Dimensionless Numbers for the Membrane Process

To describe the membrane process more simply, several dimensionless numbers are defined for the rotary tubular microfiltration-membrane separators.

Axial Reynolds Number (Re_a)

Axial Reynolds number Re_a, which is the Reynolds number of the axial flow inside the annular gap of the membrane separator, is defined by the following equation:

$$Re_a = \frac{2\rho\delta V_a}{\mu} \tag{1}$$

where, δ is the width of the annular gap between the inner rotary tubular membrane and the outer glass cylinder, ρ is the liquid density, μ is the kinetic viscosity of liquid, and V_a is the mean velocity of axial flow inside the annular gap of the membrane separator.

Radial Reynolds Number (Re_r)

Radial Reynolds number Re_r, which is the Reynolds number of the radial permeating flow through the rotary tubular membrane, is defined as:

$$Re_r = \frac{\rho\delta V_{ri}}{\mu} \tag{2}$$

where, V_{ri} is the average velocity of the radial permeating flow through the tubular microfiltration membrane, which could be estimated by the following equation:

$$V_{ri} = \frac{Q}{A_m t} \tag{3}$$

where, Q is the total volume of the fluid that pass through the microfiltration membrane, A_m is the membrane area, and t is the time.

Taylor Number (Ta)

Taylor number Ta, which is introduced to describe the rotating flow inside the annular gap of the membrane separator, is defined by the following equation:

$$Ta = \frac{\rho\delta(r_i\omega)}{\mu} \tag{4}$$

where, r_i is inner radius of the annular gap, *i.e.*, the outer radius of the rotary tubular microfiltration membrane, ω is the angular velocity of the rotary tubular membrane. The definition of Taylor number is obviously similar to the definition of Reynolds number, and thus the Taylor number is also called rotary Reynolds number.

RESULTS AND DISCUSSION

Visualized Flow Field inside the Rotary Tubular Membrane Separator

The flow fields inside the rotary tubular membrane separators were systematically investigated by introducing different axial Reynolds numbers, different radial Reynolds numbers, and different Taylor numbers. In most experimental conditions, Taylor vortices were observed in the flow field inside the rotary tubular membrane separator. The experimental results of the flow fields are summarized in Table 1, and the streamlines and vorticity of some typical Taylor vortices are illustrated in Figs. 3 to 6, According to the geometry of the membrane separator, the width of the annular gap was 14 mm. Because the data-processing software could not illustrate the boundary sign of the actual flow field in the windows for presenting the streamlines and vorticity, by considering the refraction of the water in the annular gap and in the transparent optical compensating box around the membrane separator, the widths of the windows for illustrating the flow fields in Figs. 3 to 6 were a little bit larger than 14 mm.

In Figs. 3 to 6 pairs of stable Taylor vortices with similar dimensions and opposite flowing directions were obviously observed along the axial direction of the membrane separator. The blue and red areas represented the vortices

Table 1. Characteristics of the flow fields inside the rotary tubular membrane separators

		Characteristics of the flow field					
Re_a	Re_r	$Ta =$ 3497	$Ta =$ 5575	$Ta =$ 6074	$Ta =$ 6565	$Ta =$ 7535	$Ta =$ 8535
177.3	2.549	○[a]	○	–	○ (Fig. 3)	○	○
203.9	2.745	–	○	○ (Fig. 4)	○	○	×
292.6	3.345	–	○ (Fig. 5)	–	–	–	×
332.5	4.654	–	–	–	○ (Fig. 6)	○	–
363.6	4.654	–	×	–	×	×	–

[a]*Note:* "○" means Taylor vortices were observed, "(Fig. 3)" means typical Taylor vortices were illustrated in Figure 3, "×" means no Taylor vortices were observed, and "–" means no test.

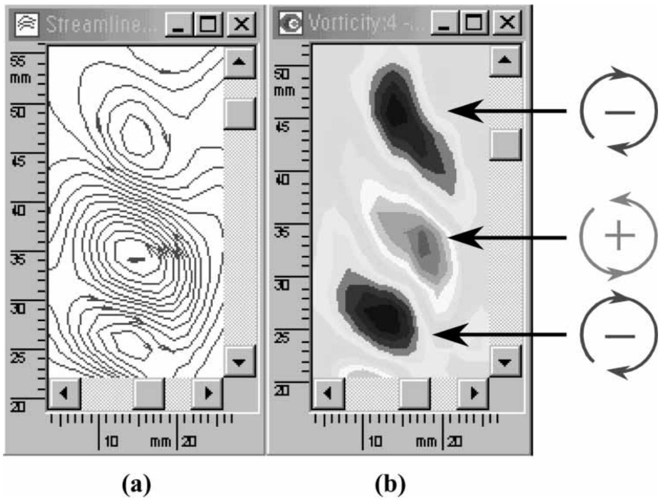

Figure 3. Streamlines (a) and vorticity (b) of flow field in the rotary tubular membrane separator with $Re_a = 177.3$, $Re_r = 2.549$ and $Ta = 6565$.

with opposite flowing directions. The flowing direction of the red vortex was anticlockwise, and its vorticity was positive; on the contrary, the flowing direction of the blue vortex was clockwise, and the vorticity was negative. The blue or red color change of the vortices presented that the vorticity became gradually larger from the boundary to the center of the vortices. In

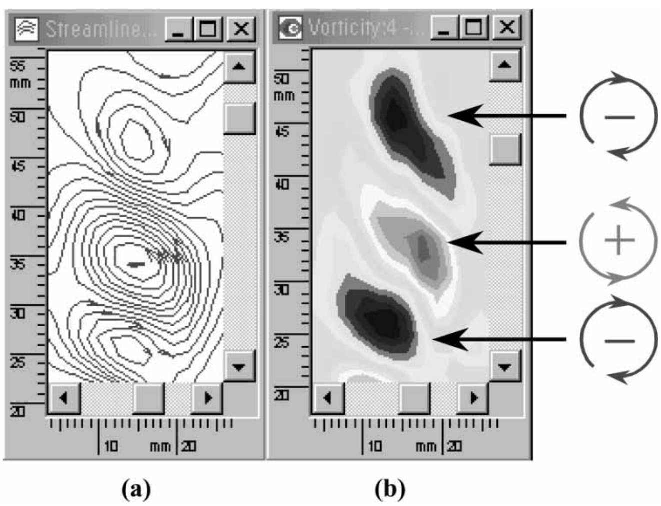

Figure 4. Streamlines (a) and vorticity (b) of flow field in the rotary tubular membrane separator with $Re_a = 203.9$, $Re_r = 2.745$ and $Ta = 6074$.

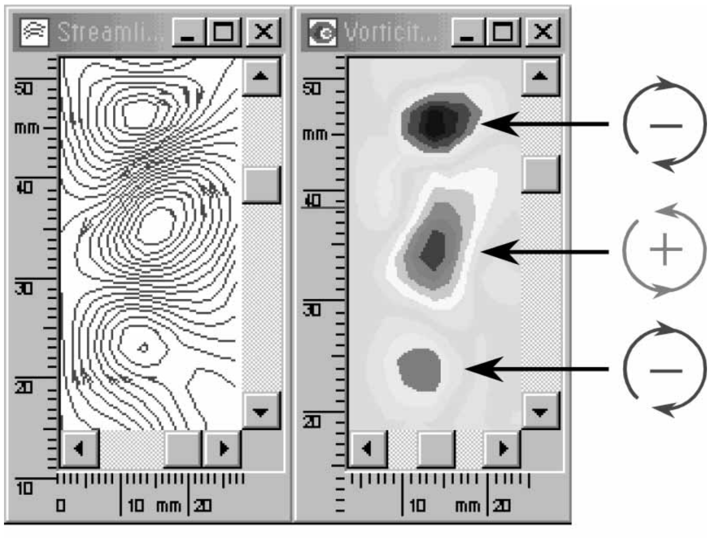

Figure 5. Streamlines (a) and vorticity (b) of flow field in the rotary tubular membrane separator with $Re_a = 292.6$, $Re_r = 3.345$ and $Ta = 5575$.

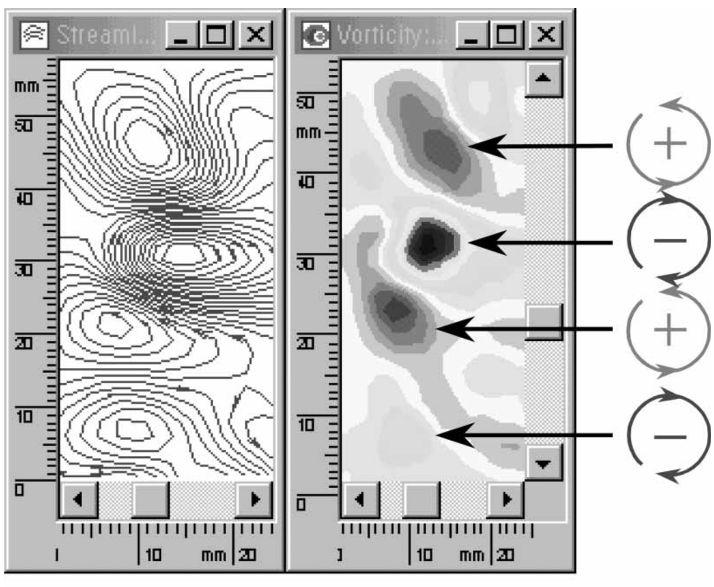

Figure 6. Streamlines (a) and vorticity (b) of flow field in the rotary tubular membrane separator with $Re_a = 332.5$, $Re_r = 4.654$ and $Ta = 6565$.

Figs. 3 to 6, only some typical Taylor vortices were illustrated, in fact there were more stable Taylor vortices along the whole axial length of the membrane separator. No matter how the axial Reynolds number, the radial Reynolds number and the Taylor number changed, the dimensions of the Taylor vortices and the distances between the centers of adjacent Taylor vortices were almost the same. However, the shapes of the Taylor vortices at lower Taylor numbers (e.g., 5575, and 6074) were more regular than those at higher Taylor numbers (e.g., 6565 and larger).

At certain axial Reynolds numbers and radial Reynolds numbers, if the Taylor number was very high (e.g., $Ta = 8535$ at $Re_a = 203.9$ and $Re_r = 2.745$, or at $Re_a = 292.6$ and $Re_r = 3.345$), the Taylor vortices disappeared because of the turbulence. That is, the experimental results verified that there was an upper critical Taylor number for the Taylor vortices existed stably in the rotary tubular membrane separator. When the axial Reynolds number and/or the radial Reynolds number increased, the upper critical Taylor number decreased. For example, when $Re_a = 363.6$ and $Re_r = 4.654$, no Taylor vortices were observed in the experiments, i.e., the critical Taylor number should be lower than 5575. Therefore, to ensure stable Taylor vortices existed in the rotary tubular membrane separator, a proper combination of the axial Reynolds number, the radial Reynolds number and the Taylor number is essential in the operation.

Velocity Distribution of Fluid Flow inside the Rotary Tubular Membrane Separator

The velocity distributions of the flow fields were obtained according to the PIV measurement results by using the software called Flowman that was provided by the PIV instrument. The axial and radial velocity distributions in the meridian plane of the annular gap could be numerically presented. The cylindrical coordinates for describing the position inside the membrane separator, and the directions of the radial velocity and axial velocity are defined as shown in Fig. 7. For the radial velocity, positive value stands for that the direction is from the rotating tubular membrane to the outer transparent cylinder, and *vice versa*. For the axial velocity, positive value means that the direction is from the bottom to the top, and *vice versa*.

Figure 8 shows the radial and axial velocity distributions of the fluid flow at different axial positions in the annular gap of the membrane separator with $Re_a = 203.9$, $Re_r = 2.745$ and $Ta = 6074$, which is the same situation as that shown in Fig. 4. That is, the radial and axial velocity distributions here represent the numeric data of the lower vortex that illustrated in Fig. 4. The radial velocity distributions shown in Figs. 8(a) and 8(d) were approximately single-peak curves, i.e., the fluid at the bottom of the vortex simply flowed outwards from the rotating tubular membrane to the outer transparent cylinder, but the fluid at the top of the vortex simply flowed inwards. For the

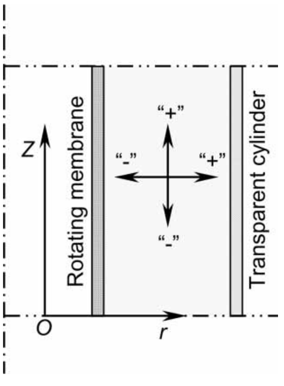

Figure 7. Definitions of the positional coordinates and the directions of the radial velocity and axial velocity in the annular gap of the rotary tubular membrane separator.

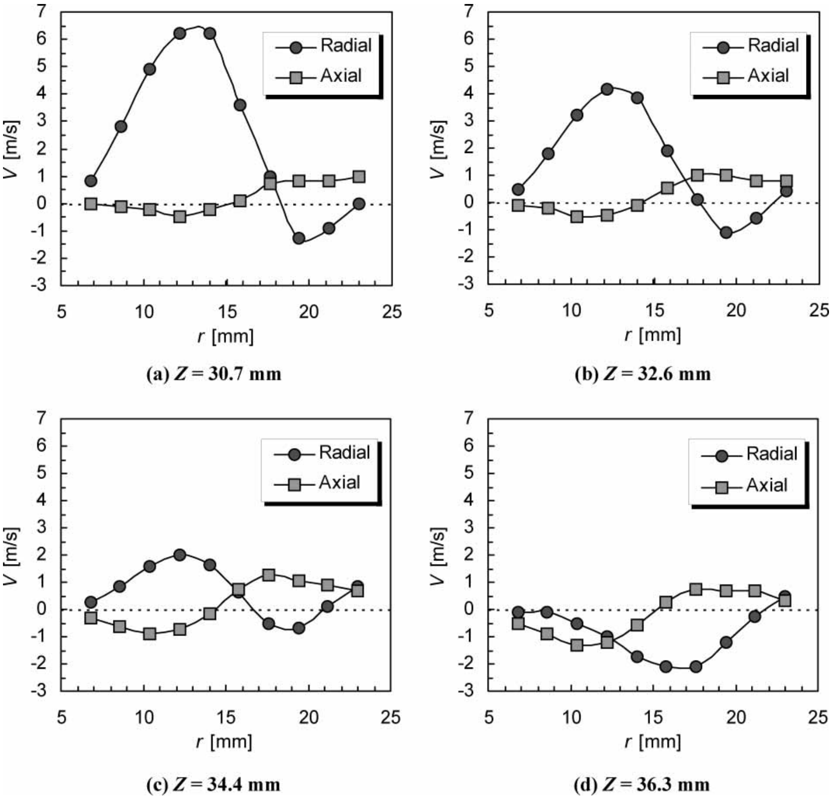

Figure 8. Radial and axial velocity distributions of the fluid flow at different axial positions in the annular gap of the rotary tubular membrane separator with $Re_a = 203.9$, $Re_r = 2.745$ and $Ta = 6074$ (numeric data for the lower vortex shown in Figure 4).

axial velocity distributions, the situation was quite different. In the inner part (e.g., $r < 15$ mm or so), the fluid in the vortex always flowed downwards; on the contrary, in the outer part (e.g., $r > 15$ mm or so), the fluid in the vortex always flowed upwards. The velocity directions presented here were just consistent with the directions of the streamlines of the lower vortex shown in Fig. 4(a).

The peak values of the radial velocity in Figs. 8(a) to 8(d) were 6.255, 4.140, 1.996, and -2.118 m/s respectively. The peak values of the downward axial velocity in the inner part were -0.434, -0.545, -0.939, and -1.307 m/s respectively, and those of the upward axial velocity in the outer part were 0.770, 1.000, 1.235, and 0.746 m/s respectively. Obviously, the maximum radial velocity was always larger than the maximum axial velocity in the observed Taylor vortex. Both the radial and axial velocities near the membrane surface were much lower than the maximum values inside the vortex. The radial velocities near the membrane surface were 0.788, 0.487, 0.232, and -0.069 m/s respectively, and the axial velocities near the membrane surface were -0.055, -0.194, 0.347, and -0.490 m/s respectively.

In the experiments, when the membrane separator was operated with $Re_a = 203.9$, $Re_r = 2.745$ and $Ta = 6074$ (the condition for the flow filed shown in Fig. 4 and Fig. 8), the mean velocity of axial flow inside the annular gap of the membrane separator (V_a) was 0.02299 m/s, and the average velocity of the radial permeating flow through the tubular membrane (V_{ri}) was 0.00024 m/s. It was amazing that the maximum axial velocity in the Taylor vortex was about 50 times larger than the mean velocity of axial flow inside the annular gap of the membrane separator, and the maximum radial velocity in the Taylor vortex was even as high as 25,000 times larger than the average velocity of the radial permeating flow through the tubular membrane. The maximum axial velocity near the membrane surface was also about 20 times larger than the mean velocity of axial flow inside the annular gap, and the maximum outward radial velocity near the membrane surface was also about 3,000 times larger than the average velocity of the radial permeating flow through the tubular microfiltration membrane. The large velocities and the resultant large shear stresses in the main flow and near the microfiltration membrane surface, which were due to the Taylor vortices, could prevent solid fine particles from depositing onto the microfiltration membrane surface and/or entering into the microfiltration membrane pores. Therefore, both reduced concentration polarization and reduced fouling could be effectively achieved in the rotary tubular membrane separators by introducing the Taylor vortices.

CONCLUSIONS

A PIV has been successfully used to investigate the flow field inside the microfiltration separator with rotary tubular membrane. Pairs of stable Taylor vortices with similar dimensions and opposite flowing directions were directly observed in the flow field in the annular gap of the membrane separator. No matter how the axial Reynolds number, the radial Reynolds number, and the Taylor number changed, the dimensions of the Taylor vortices and the distances between the centers of adjacent Taylor vortices were almost the same. However, the shapes of the Taylor vortices at lower Taylor numbers were more regular than those at higher Taylor numbers. There was an upper critical Taylor number for the Taylor vortices existed stably in the rotary tubular membrane separator. At certain axial Reynolds numbers and radial Reynolds numbers, if the Taylor number was very high, the Taylor vortices disappeared because of the turbulence. When the axial Reynolds number and/or the radial Reynolds number increased, the upper critical Taylor number decreased. To ensure stable Taylor vortices existed in the rotary tubular membrane separator, a proper combination of the axial Reynolds number, the radial Reynolds number and the Taylor number is essential in the operation.

The maximum radial velocity was always larger than the maximum axial velocity in the observed Taylor vortex. The maximum axial velocity near the microfiltration membrane surface was about 20 times larger than the mean velocity of axial flow inside the annular gap, and the maximum outward radial velocity near the microfiltration membrane surface was even about 3000 times larger than the average velocity of the radial permeating flow through the tubular membrane. The large velocities and the resultant large shear stresses near the microfiltration membrane surface, which were due to the Taylor vortices, could prevent solid fine particles from depositing onto the microfiltration membrane surface and/or entering into the microfiltration membrane pores and therefore result in reduced concentration polarization and reduced membrane fouling.

NOMENCLATURE

A_m	membrane area [m^2]
Q	fluid volume passing through the membrane [m^3]
Re_a	Axial Reynolds number [$-$]
Re_r	Radial Reynolds number [$-$]
r_i	inner radius of the annular gap [m]
t	time [s]
Ta	Taylor number [$-$]
V_{ri}	mean velocity of the radial permeating flow through the tubular membrane [m/s]
V_z	mean velocity of axial flow inside the annular gap [m/s]
δ	width of the annular gap [m]
μ	kinetic viscosity of liquid [N $\cdot$ s/m^2]
ρ	liquid density [kg/m^3]
ω	rotary angular velocity [rad/s]

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