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Taylor-Couette Column for Emulsion Liquid Membrane System: Characterisation Study

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Abstract

Study on the application of Taylor-Couette column for emulsion liquid membrane system has been done. To optimise extraction process under TCC, a research to investigate effect of viscosity and cylinders rotation is of important. Fluid viscosity was examined by varying volume ratio of kerosene to water. TCC was characterised to determine flow regimes, shear stress, and energy loss distribution. Volume ratio of oil to water was varied at 1:1, 1:3, 1:5, and 1:6 while inner and outer cylinders speed were maintained constant at 300 and 200 rpm, respectively. Investigation on the effect of volume ratio of oil to water towards flow regime ended to same flow regime of Featureless Turbulent. There was degradation of wall shear stress from 8.57×10^{-2} Pa to 7.42×10^{-2} Pa.

INTRODUCTION

Emulsion liquid membrane (ELM) was invented to overcome the limitation of liquid-liquid extraction (LLE). The conventional LLE requires separated compartment for extraction and stripping processes. Besides, the need of high volume of solvent as well as further treatment process make this process uneconomical for low solute concentration.

ELM offers simpler system in terms of both equipment and solvent usage. Combination of extraction and stripping in a single step significantly contributes to time and equipment saving (Ahmad et al., 2014; Andereck et al., 1986). ELM has been applied in the removal of many impurities from wastewater (Boogar et al., 2013, Dou et al., 2007; Dou et al., 2008). However, ELM is facing problem of emulsion instability (Furukawa & Fukano, 2001). Regarding to this problem, some efforts have been done. Some researchers studied emulsification process to get optimally stable emulsion (Sarip, 2012; Tsukahara et al., 2013; Van Gils et al., 2012). Emulsion formulation related to the consideration of chemical type and concentration while emulsification method refers to operating parameters in emulsification include time, speed, frequency, and tool. It is believed that smaller emulsion provides larger contact area and better stability. Ultrasound emulsification produced tiny emulsion as revealed by some researchers (Sarip, 2012; Tsukahara et al., 2013; Van Gils et al., 2012). However too stable emulsion could lower extraction efficiency and rate (Wu & Andereck, 1992). Among the available method to overcome the emulsion instability problem is the application of TCC for extraction process. TCC consists of two cylinders, rotate in same or opposite direction. In TCC, solution is flowed in the gap of two cylinders. TCC provides higher extraction efficiency since mass transfer occurs along the cylinder. Moreover, this system has about 45 times lower shear stress than that of conventional stirred tank that almost

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nullify membrane breakage and emulsion swelling which in turn increase extraction efficiency. Another advantage of TCC is shorter process time.

Some studies related to application of Taylor-Couette flow have been done, i.e. turbulence flow, dilute polymer solution, and mixing process. Taylor-Couette flow have also been applied to increase the performances of plasma filtration, extraction, bioreactor for animal cell culture, vortex bioreactor and ELM process. Application of TCC for extraction process is affected by liquid viscosity, as ELM employs emulsion in the process. Fluid viscosity could determine the resistance to shear stress. Moreover, cylinders rotation also determines Reynolds number. To optimise extraction process under TCC, a study to investigate effect of viscosity and cylinders rotation was done. Fluid viscosity was examined by varying volume ratio of kerosene to water. TCC was characterised to determine flow regimes, shear stress, and energy loss distribution.

THEORY

Characterisation of flow regimes in TCC was done by Andereck et al. (1986) by mapping out flow patterns of the inner and outer cylinders in different rotation rates. The mapping of flow patterns was carried out based on Reynolds number of outer and inner cylinders. There were 18 principles regimes of flow pattern between independently rotating cylinders, as given in Figure 1.

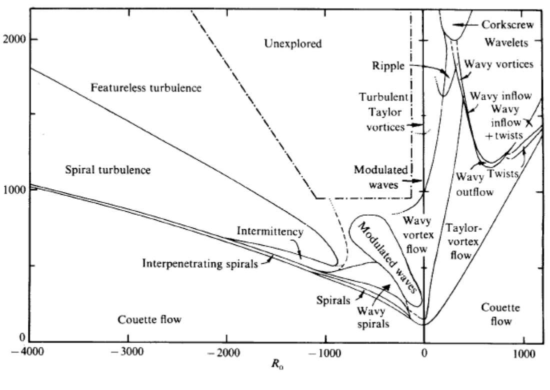

Figure 1. Regimes observed in flow between independently rotating cylinders.

Some control parameters was taken into account for TCC characterisation with two rotating cylinders as described below (Andereck et al., 1986, Ahmad et al., 2014). Radius ratio, η is determined by using Eq. (1).

$$\eta = \frac{r_i}{r_o} \qquad (1)$$

r_i and r_o are radius of inner and outer cylinder, respectively. Aspect ratio, Γ can be defined by using Eq. (2).

$$\Gamma = \frac{L}{d_G} \qquad (2)$$

L is the length of fluid column, while d_G is gap width, can be calculated as $r_o - r_i$. Reynolds numbers of inner and outer cylinder are shown in Eq. (3).

$$Re_i = \frac{(r_i \omega_i d_G)}{\nu} \qquad (3)$$

$$Re_o = \frac{r_o \omega_o d_G)}{\nu} \qquad (4)$$

Where, Re_i and Re_o are Reynolds number of inner and outer cylinder, respectively, ω_i and ω_o are angular velocity of inner and outer cylinder, respectively and υ is kinematic viscosity

The angular velocity of inner cylinder (ω_i) is always defined as positive, whereas the angular velocity of outer cylinder (ω_o) can be either positive (for co rotating system) or negative (for counter rotating system). Another dimensionless control parameter of the system is the ratio of angular velocities, as shown in Eq. (5)

$$\Psi = -\frac{\omega_o}{\omega_i} \qquad (5)$$

Taylor number is also dimensionless number used to characterise this system. Later stability of Taylor-Couette flow can be described using this number. Taylor number can be defined as (van Gils et al., 2012) shown in Eq. (6).

$$Ta = \frac{1}{4}\sigma(r_o - r_i)^2(r_o + r_i)^2(\omega_i - \omega_o)^2\nu^{-2} \qquad (6)$$

Where σ is

$$\sigma = \left(\left((1+\eta)/2\right)/\sqrt{\eta}\right)^4 \qquad (7)$$

To represent profile of velocity along the cylinder gap, Vt is defined by using Eq. (8).

$$Vt = Ar + \frac{B}{r} \quad (8)$$

r varies from r_i to r_o, while A and B can be calculated by using Eq. (9) and (10) respectively.

$$A = \omega_i \frac{(\eta^2 - \Psi)}{\eta^2 - 1} \quad (9)$$

$$B = \omega_i r_i^2 \frac{(1 - \Psi)}{1 - \eta^2} \quad (10)$$

Estimation for wall shear stress can be done by using Eq. (11).

$$\tau = -2\mu \frac{B}{r_i^2} \quad (11)$$

The energy loss along the gap width under counter rotating of inner and outer cylinders can be determined as Dou et al. (2008) shown in Eq. (12).

$$\frac{dH}{ds} = 4\mu \frac{\omega_i r_i}{h^2} \frac{r_i^4}{r^4} \frac{(1-\eta)^2}{\eta^2} \frac{(1-\Psi)^2}{(1-\eta^2)^2} \left[\frac{\eta^2 - \Psi}{\eta^2 - 1} \frac{r}{r_i} + \frac{r_i}{r} \frac{1-\Psi}{1-\eta^2} \right]^{-1} \quad (12)$$

EXPERIMENTAL STUDY

Deionised water was used for all of the solutions preparation. Commercial grade kerosene was employed. Kerosene and deionised water was mixed at volume ratio of 1:1, 1:3, 1:5, and 1:6. Study on the effect of speed rotation was done at outer cylinder and inner cylinder speed of 0 and 31.4 rad/s, respectively. For each variation, fluid viscosity was measured (Ahmad et al., 2014) and flow pattern was visualised. Characterisation of Taylor-Couette flow was carried out by calculating Reynolds number, Taylor number, shear stress, and energy loss distribution.

RESULTS AND DISCUSSION

Characterisation

The developed TCC system has Ri, Ro and L of 2.4 cm, 4.0 cm and 15 cm, respectively, thus result in η and Γ to be 0.6 and 9.375, respectively. This dimension provides total gap volume that can be used for extraction process of about 482.5 mL. Reynolds number of both outer and inner cylinders could be determined by measuring fluid kinematic viscosity.

Varying volume ratio of oil to water resulted in kinematic viscosity of 9.8×10^{-7}, 8.4×10^{-7}, 8×10^{-7}, and $7.9 \times 10^{-7} m^2/s$, respectively. In all experiments investigated, the outer and inner cylinders were rotated at a constant speed of 200 and 300 rpm. The negative sign indicated that the outer cylinder rotated at opposite direction of inner cylinder rotation (counter rotation).

Flow Regime

In this study, flow regime was investigated as the effect of volume ratio of oil to water. It was found that decreasing volume ratio of oil to water from 1:1 to 1:6 gave a decrease in kinematic viscosity thus lowering the flow resistance. Investigation on the effect of volume ratio of oil to water towards flow regime ended to same flow regime of featureless turbulent. It was due to insignificant difference of kinematic viscosity for each volume ratio. Mathematically, the increase of fluid viscosity will linearly decrease Reynolds number. Some studies showed that flow pattern of fluids were significantly affected by fluid viscosity (Furukawa and Fukano, 2001, Boogar et al., 2013).

Flow pattern of laminar Couette in a Taylor-Couette flow system will run into transition to Taylor vortex flow when cylinder rotation is increase to certain number (Sarip, 2012). The obtained Reynolds numbers of outer and inner cylinders were converted into graph by mapping flow pattern as given by Andereck et al. (1986) in Figure 2.

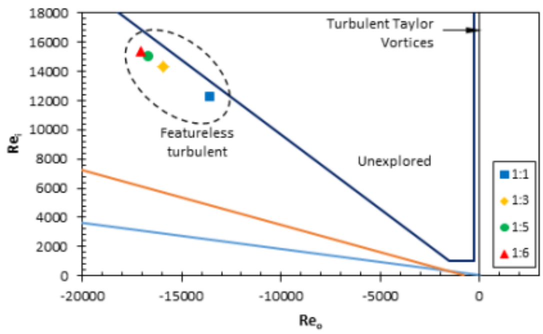

Figure 1. Flow regime in Taylor-Couette column (outer cylinder rotation: 200 rpm; inner cylinder rotation: 300 rpm; volume ratio of oil to water: 1:1, 1:3, 1:5, 1:6).

Study of Ahmad et al. (2014) supported this finding. Using radius ratio η = 0,571, the study underwent TUR (Featureless Turbulent Flow) and TTV (turbulent taylor vortices). While this current study applying radius ratio of 0.6 provided TTV (turbulent Taylor vortices). Some researchers found this flow pattern in their studies. Wu & Andereck (1992) revealed that the phase dynamics of the coherent structure were described by a diffusion model with a diffusion coefficient an order of magnitude larger than for the laminar Taylor vortex flow. Tsukahara et al. (2013) observed the presence of TTV in the flow field and in the cases of rib-roughened inner cylinders. For more details, data from each flow type mapping is given in Table 1.

Table 1. Flow regime of each volume ratio of oil to water (O/W)

ω_o(rpm)	ω_i (rpm)	Volume Ratio			
		1:1	1:3	1:5	1:6
200	300	TUR	TUR	TUR	TUR

Using different volume ratio, it was found that volume ratio gave no effect to the flow regime. However, the same flow regime given by different volume ratio caused various turbulent flows due to the difference of bubbles spread. This is due to the boundary of kerosene and water was located in different level thus the rotation resulted in different forces. Figure 3 shows the flow pattern of each volume ratio produced by camera setting of ISO-6400, 1/500 exposure time, +5 exposure bias, and f/5.3 F-Stop.

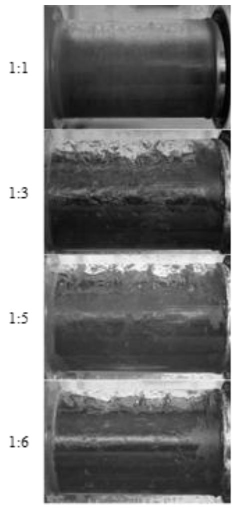

Figure 2. Flow pattern in each volume ratio (outer cylinder rotation: 200 rpm; inner cylinder rotation: 300 rpm; volume ratio of oil to water: 1:1, 1:3, 1:5, 1:6).

Taylor Number and Shear Stress

Ahmad et al. (2014) revealed the increment of Taylor number by the increase of counter rotated cylinders speed compared to that of co rotated cylinders. Counter rotation cylinders provide higher Taylor number by using lower rotation speed. Taylor number is non-dimensional number that determines Taylor-Couette flow pattern by characterising the importance of centrifugal force by fluid rotation, relative to viscous force. Taylor number for each volume ratio of oil to water is given in Figure 4. It can be observed that Taylor number increase as the decrease of volume ratio of oil to water. The increment was due to the decrease of fluid viscosity.

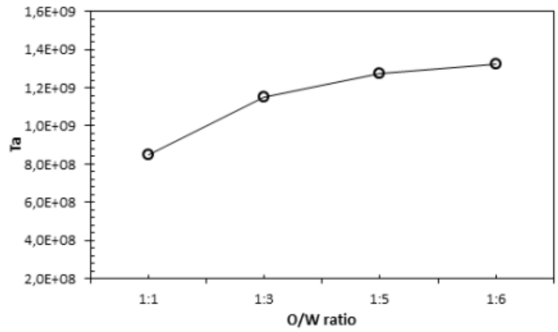

Figure 3. Taylor number for each volume ratio of oil to water (outer cylinder rotation: 200 rpm; inner cylinder rotation: 300 rpm; volume ratio of oil to water: 1:1, 1:3, 1:5, 1:6).

Further study in Taylor-Couette system characterisation was done to wall shear stress. It is known that wall shear stress is equal and opposite to that of fluid shear stress. Effect of volume ratio of oil to water on the wall shear stress is described in Figure 5. It is seen in Figure 5 that wall shear stress has negative value, showing that its direction was opposite to the fluid flow direction as the result of counter rotated cylinders. The figure reveals the decrease of wall shear stress with the reduction of volume ratio of oil to water. At volume ratio of oil to water of 1, the highest shear stress of 8.57×10^{-2} Pa was obtained. While at the lowest volume ratio of oil to water of 1/6, the lowest wall shear stress of 7.42×10^{-2} Pa was achieved. This result indicates the degradation of about 13% under the investigated conditions.

Figure 6 presents distribution of energy loss along the gap width for variation of volume ratio of oil to water under counter rotating of inner and outer cylinders. Investigation was carried out in the aspect and radius ratios of 9.375 and 0.6, respectively. In this study, inner cylinder rotated while the outer cylinder was at rest, it can be seen

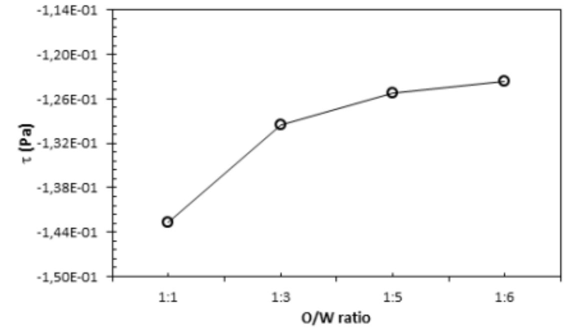

Figure 4. Wall shear stress for each volume ratio of oil to water (outer cylinder rotation: 200 rpm; inner cylinder rotation: 300 rpm; volume ratio of oil to water: 1:1, 1:3, 1:5, 1:6).

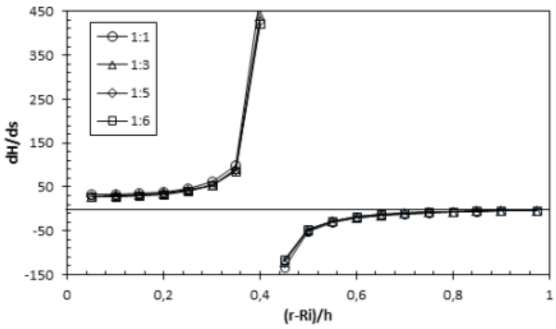

Figure 5. Energy loss ditribution (outer cylinder rotation: 200 rpm; inner cylinder rotation: 300 rpm; volume ratio of oil to water: 1:1, 1:3, 1:5, 1:6).

that the energy loss distribution for volume ratio of 1/3, 1/5, and 1/6 was almost the same. The highest energy loss distribution was achieved by the system with volume ratio of oil to water of 1. This is due to higher fluid viscosity leads to higher energy loss thus delay fluid instability. Fluid viscosity could determine energy loss in the flow thus affects the efficiency of the fluid transportation. But in some cases, flow stability could be enhanced by energy loss (Dou et al., 2007).

CONCLUSION

Investigation on the effect of rotational speed and volume ratio of oil to water have been done. Flow regimes, shear stress, tangential velocity as well as energy loss distribution along the gap of TCC were studied. Under the investigated conditions in term of rotation speed of the two counter-rotating cylinders, high fluid instability regimes were obtained thus provided turbulent flow regimes.

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