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Fascinating Two-Phase Taylor-Couette Flow

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Abstract

Taylor-Couette flow, a gap phenomenon, has been discussed in literature over nearly one hundred years meanwhile. When balancing industrial implementation of Taylor-Couette reactors we rather resume scarce applications in photochemistry and similar fields, although we already learn in school that Taylor-Couette flow may provide as many as 74 different flow patterns, ready to make use of in liquid-liquid extraction. The mass transfer unit operation liquid-liquid extraction is widely applied and well established. Although plenty of different extraction equipment, covering stage wise and continuous phase contact, is offered on the market, equipment design and optimisation is still on the research agenda. Two-phase Taylor-Couette flow just needs rotation of an inner cylinder in an outer cylinder. With the huge variety of flow patterns and the simple apparatus design and construction in mind, our group has launched a project targeting detailed investigation of two-phase Taylor-Couette flow applications in liquid-liquid extraction. Two-phase Taylor-Couette flow opens access to problem-oriented design of phase contact, addressing several physical properties of constituents and phases.

Keywords: Liquid-Liquid Extraction, Two Phase Taylor-Couette Flow, Extractor Design, Process Design

Introduction

Although applied since hundreds of years, liquid-liquid extraction is still subject of intensive research activities. Whenever applicable liquid-liquid extraction contributes to process- and energy efficiency. Beside state of the art applications of liquid-liquid extraction, new challenges evolve from implementation in the biorefinery and recycling. Representatively the isolation of low molecular weight carboxylic acids from black liquor thickening condensates [1] and the still unsolved recycling of Li-ion batteries [2] may be mentioned. In both applications the process industry is faced with multicomponent mixtures with low load of target constituents. Although applied since decades the Bayer process is still state of the art in aluminum production, leaving millions of tons of hazardous red mud in dumps [3]. Depending on the origin of clay red mud may contain several rare earth elements in traces. In summing up these examples from different areas we still need to improve our technical and technological skills in processing low grade multicomponent resources. Facing these emerging challenges, future equipment in liquid-liquid extraction must provide high operation flexibility and it must withstand harsh operation conditions.

Dating back to the late 19th century and early 20th century, the Taylor-Couette contactor, primarily developed for the monitoring of liquid phase viscosity by Couette, got into the focus of research in academia and in the industry when Taylor investigated the flow patterns of later named Taylor-Couette flow. About 74 different flow patterns were identified, with several flow patterns attracting the applied research activities in chemical process engineering [4]. However industrial application has been limited to few fields in photochemistry, the nuclear industry and related areas. The main reason for limited application is dating back to Taylor-Couette flow being classified a gap phenomenon due to very limited free cross sectional area because of recommended minimum ratio of the inner cylinder diameter to the column cylinder diameter $D_i/D_C > 0.75$ [5, 6]. This design recommentation limits the free cross sectional area to a fraction of less than 44% of the overall cross sectional area. Based on the idea of increasing the hydraulic load of the Taylor-Coutte reactor by decreasing the diameter of the inner cylinder, a CFD investigation was started, with the aim to maintain the Taylor-Couette vortexes in the column. The CFD results show a minimum ratio of $D_i/D_C = 0.5$ to induce two-phase Taylor-Couette flow with a maximum hydraulic load. Thus, the hydraulics of a pilot scale Taylor-Couette reactor with a shaft ratio of $D_i/D_C = 0.5$ was investigated in detail.

Materials and methods

Materials

Hydraulics and operation performance of a Two Phase Taylor-Couette contactor with 0.1 m diameter and 1 m height and a cylinder ratio of $D_i/D_C = 0.5$ was investigated. Residence time distribution (RTD) was measured in single phase as well as dual phase operation, with the test system ShellSol-T (SST)/Water, with SST being the dispersed phase and water the continuous phase in counter-current operation. The total load of solvent phase and aqueous phase and the rate of rotation was varied. The dispersed phase holdup was deduced from RTD records too. The physical properties of the test system are summarized in table 1.

Table 1: Physical properties of the test system

	Kinematic Viscosity [$m^2 s^{-1}$]	Density [$kg\ m^{-3}$]
ShellSol-T (dispersed)	$1.85*10^{-6}$	756.8
Deionized water (continuous)	$1.102*10^{-6}$	998.1

Methods

Residence time distribution (RTD) was determined with a pulse signal by injecting 2 ml of saturated sodium chloride solution into the continuous phase (deionized water) at the top of the column. The electric conductivity was measured on four positions along the active column height via non-commercial probes [7, 8] with minimum invasive impact to avoid disruptions of the flow pattern. For this purpose, electrodes with tip sensors made of stainless steel wire (d_{Tip} = 0.6 mm) were used.

The results of the RTD were interpreted with the dispersion model as well as the tank-in-series model. For the evaluation with the dispersion model, open-open boundary conditions (large deviation from plug flow $D_{ax}/uL > 0.01$) [9] was applied:

$$E_{\theta,oo} = \frac{1}{2}\sqrt{\frac{\bar{t}}{\pi\, t*\left(\frac{Dax}{uL}\right)}}\ \exp\left[-\frac{\bar{t}\left(1-\frac{t}{\bar{t}}\right)^2}{4\, t*\left(\frac{Dax}{uL}\right)}\right] \qquad (1)$$

In equation 1, t represents the time, $\bar{t}$ the mean residence time and D_{ax}/uL the vessel dispersion number with D_{ax} as axial dispersion coefficient. For comparison with the dispersion model, the number of corresponding vessels in series N was calculated via the maximum of the dimensionless exit age distribution $E_{\theta,\,max}$ according to Levenspiel [9]:

$$E_{\theta,max} = \frac{N*(N-1)^{N-1}}{(N-1)!} * e^{-(N-1)} \qquad (2)$$

Results and discussion

Results

As already indicated by CFD analysis the Taylor-Couette contactor can manage intensive phase contact in counter current two-phase flow mode for small ratio of $D_i/D_C = 0.5$. Primarily the flow rate of both phases and consequently the hydraulic load may be varied in a very wide operation window. Drop size distribution and dispersed phase holdup are controlled by the speed of rotation. Compared with two-phase Taylor-Couette contactors of small gap (D_i/D_C = 0.8) the experimental setup for large gap $D_i/D_C = 0.5$ shows a broad operation range of so called cork screw flow pattern to finally switch into stapled toroidal flow. Small gap contactors ($D_i/D_C = 0.8$) pretty soon form banded flow of pearl necklace like droplet arrangement, which finally merges (coalesces) to homogeneous banded flow. Figure 1 shows representative results obtained from CFD simulation of two-phase Taylor-Couette flow for $D_i/D_C = 0.5$.

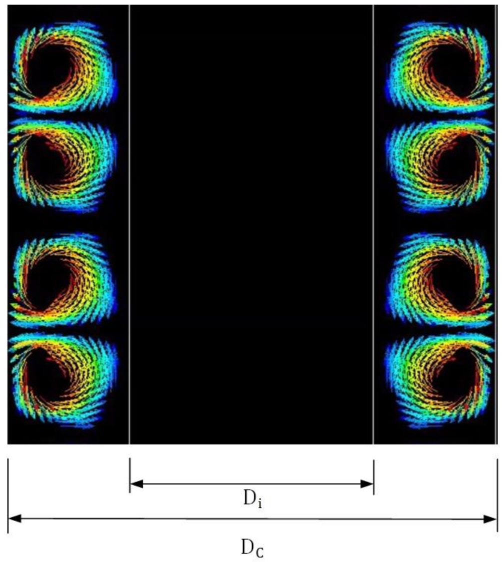
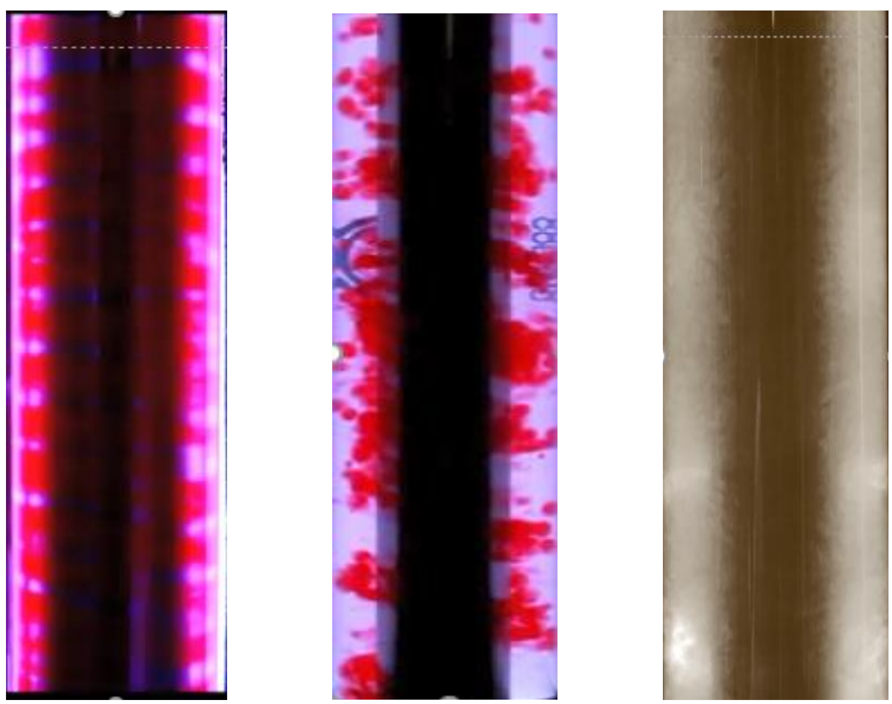


Figure 1: Flow pattern from CFD simulation of two-phase Taylor-Couette flow for $D_i/D_C = 0.5$

Figure 2 shows the comparison of banded flow for $D_i/D_C = 0.8$, cork screw flow as well as banded two phase flow for $D_i/D_C= 0.5$. The hydraulic load B was adjusted at $B = 14\ m^3m^{-2}h^{-1}$.



a) b) c)

Figure 2: Comparison of two-phase Taylor-Couette flow for $B = 14\ m^3m^{-2}h^{-1}$; a) $D_i/D_C = 0.8$, n = 950 rpm b) $D_i/D_C = 0.5$, n = 1000 rpm and c) $D_i/D_C = 0.5$, n = 1200 rpm; Continuous phase: water, dispersed phase: Shellsol-T; Temperature: ambient

Figure 2a shows the characteristic banded flow of the dispersed phase, with the bandwidth reflecting the gap width. Figure 2b shows cork screw formation of the dispersed phase at moderate solvent holdup of $\varphi < 5\%$. Figure 2c shows banded two-phase flow at high dispersed phase holdup of $\varphi > 20\%$. In any of the figures, the black center bar shows the shaft. In Figure 2c the band width corresponds with the gap width (actually the quality of the photograph 2c is not sufficient for clear indication of the band width).

Conclusion

CFD simulation and experimental validation of simulation results confirm that it is possible to induce two-phase Taylor-Couette flow for large gap ($D_i/D_C = 0.5$) experimental Taylor-Couette set up. This hydraulic specification of two-phase Taylor-Couette flow opens an engineering window for applications in liquid-liquid extraction under extreme (harsh) process conditions. The two-phase Taylor-Couette contactor just needs a rotating shaft for tuning operation to the process needs, is easy to construct and does not provide any dead zone for crud accumulation. To sum up, it offers a wide operation window.

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