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The Taylor-Couette Disc Contactor, a novel gas-liquid multiphase contactor

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Abstract

Industrial separation and reaction processes mostly require more than one phase. Defined phase contact of solids (S), liquids (L), and gases (G) forms the physical backbone regarding process intensification and optimization. Novel reactor and contactor design for liquid-liquid operations in the Taylor-Couette Disc Contactor (TCDC) serve in optimizing the contact of two phases as for example in bubble columns or liquid-liquid extraction columns [1]. The Taylor-Couette Disc Contactor combines the advantages of a Taylor-Couette reactor (TCR) and a Rotating disc contactor (RDC). The toroidal Taylor vortexes are stabilized with rotor discs. This geometric design was optimized by CFD simulation and resulted in TCDC design recommendations [2]. The main differences between the RDC and the TCDC are that the TCDC does not need stator rings. The increased rotor disc and shaft diameter combined with optimal compartment height is sufficient to decrease axial backmixing in a stable flow regime without the presence of stator rings. The prevention of hydraulic deadzones due to missing static internals provides ideal conditions to process additional phases like solids or gases. In this work, stable and continuous operation up to four phases has been performed in a TCDC column and proofs the suitability for defined, stable multiphase contact in the TCDC.

Introduction

Gas phase feed into a TCDC column requires an improvement of the original design concept [2]. Visual observations of G/L flow showed that the gas phase tends to form a stable gas layer around the shaft (hydrocycloning) and accumulating below the rotor discs. This results in completely blocked compartments by the gaseous phase. The gas phase in a single compartment accumulates up to a critical gas fraction, when exceeding maximum compartment load the gas layer abruptly rises to the next compartment and inhibits continuous stable G/L phase contact. To overcome this problem and to ensure proper phase contact, the rotor discs of the TCDC need to be perforated. For this reason, the effect on the flow behavior of different perforation patterns in the rotor discs of the TCDC was examined. This work is focused on the G/L flow provided by different perforation patterns. Literature shows a very limited selection of well investigated and suited apparatus designs that can be used for G/L or G/L/S phase contact like bubble columns, stirred vessels or loop reactors [3]. Defined G/L phase contact in a TCDC column is possible to be established by design measures and appropriate operation. The TCDC rotor discs are perforated to allow continuous gas rise along the column height. Different perforation patterns result in a specific volumetric holdup for the gas phase in the active mixing part of the column. Two different perforation patterns were investigated.

Experimental setup

Continuous G/L and G/L/S flow was implemented in a TCDC column with a column diameter of 50 mm and 700 mm active mixing height. Table 1 shows the geometric data for the TCDC DN50 column. For investigations of hydrodynamics, deionized water as continuous phase, compressed air as gas phase and the solid catalyst Amberlyst 15® was used as solid phase.

Table 1:-Dimensions TCDC DN50 column

	Abbreviation	Value	Unit
Column Diameter	D_C	50	[mm]
Shaft Diameter	d_{Sh}	25	[mm]
Column height	H	700	[mm]
Compartment height	H_c	25	[mm]
Rotor disc diameter	D_R	43	[mm]
Number of compartments	N_c	23	[-]

The solid phase was continuously added to the continuous liquid phase on top of the column. The solid phase sediments towards the collector pin at the bottom of the column. Peristaltic pumps were used for transporting the continuous phase as well as the solids suspension. The gas phase (air) was added at the bottom of the column. The effect of varying rotational speed (0-1000 rpm) and hydraulic load of the continuous water phase (10-18 $m^3\ m^{-2}h^{-1}$) on the volumetric holdup of the dispersed gas and solid phase was recorded. The gas flow was controlled by a Bronkhorst mass flow controller (F-201CV) and was fed through a porous sinter metal pin at the bottom of the column. The used sinter metal pin is a common silencer for compressed air with a porosity of 40%. The gas flowrate was varied from 0 to 6.9 ln/min (liters per minute at standard conditions: 273.15 K and 1013.25 hectopascal). Two different perforation patterns were tested. Figure 1 shows the two rotor disc designs. The disc on the left side (HOLE #1) has a perforated area of 0,92% related to the whole rotor disc area, with five 1 mm holes to ensure the gas phase to raise up continuously. The second rotor disc design is shown in figure. 1 (SLOT #1) the perforated area being increased from 0.92% to 17.32% using slots instead of holes.

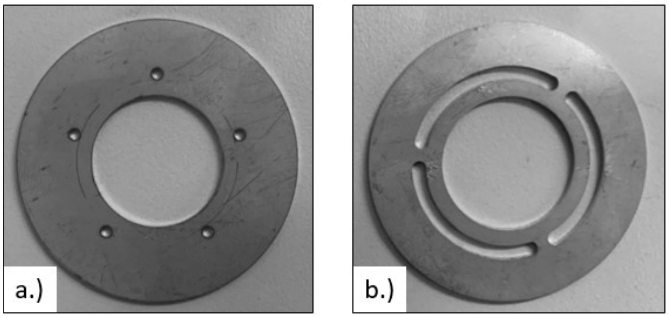

Figure 1: a.) Perforated rotor discs with five holes and 0.92% perforated area (HOLE #1); b.) Perforated rotor discs with slots and 17.32% perforated area (SLOT #1).

Measurement Methods

The volumetric gas holdup was determined by measuring the height of the water level at the top of the column with and without aeration. The holdup of the gas phase is defined in equation 1.

$$\varphi_g = \frac{V_g}{V_g + V_l} \tag{1}$$

Constant column diameter simplifies equation 1 to equation 2.

$$\varphi_g = \frac{H_1 - H_0}{H_1} \tag{2}$$

The heights (H0, H1) used for calculation of the proportional gas holdup in equation 2 are shown in figure 2.

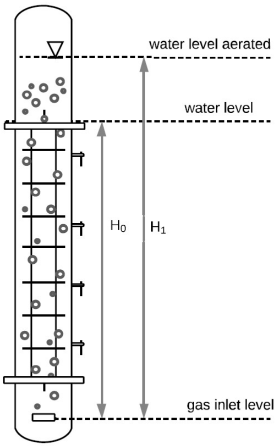

Figure 2: Aerated Taylor-Couette Disc Contactor with definition of heights, used for volumetric gas holdup determination.

The hydraulic load B_C [$m^3\ m^{-2}h^{-}1$] is defined in equation 3 and relates the volumetric flow rate of the continuous water phase to the free cross-sectional area. The free cross-sectional area in aTCDC is defined as column diameter minus shaft diameter (D_C-d_{Sh}).

$$B = \frac{\dot{V}_{water}}{A_{free}} \tag{3}$$

The solids phase holdup in the active mixing area of the column is also determined volumetrically by measuring the height change of the solid phase in the collector pin at the bottom of the column. The gas distributor design has a major influence on the flow regime in standard G/L contactors like stirred vessels [5]. The gas distributor design in a TCDC column has minor effect on operation, since each compartment acts like an individual mixer and the gas phase is uniformly distributed along the column height. The flow regime and gas distribution in a single compartment at a specific operating point is representative for the whole column height. Figure 3 gives an example of two different G/L flow patterns in a single compartment of the TCDC for two different operation conditions using the rotor disc design HOLE #1, as shown in figure. 1a.

In general, three different flow regimes are observed. The rising bubbles can take their way up mainly at the outside of the rotor disc, as happens at lower rotation speed, which is called "outside pass". A so called "mixed flow" (figure 3b) is possible when the bubbles either pass the discs on the outside or through the perforation. At high rotational speed the centrifugal force dominates and the whole gas fraction is pressed through the holes in the discs ("inside pass") as shown in figure 3a.

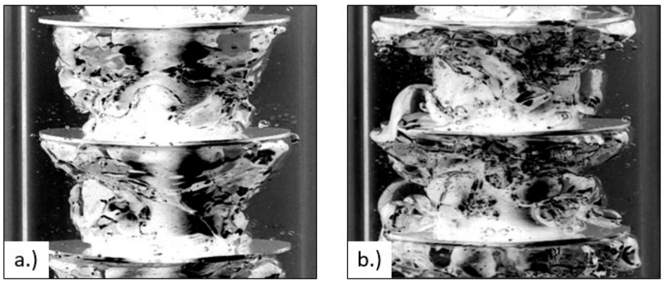

Figure 3: G/L flow regime for 0.92% perforated area (HOLE #1) in two compartments a.): at 1000 rpm, 5.13 ln/min and B=10 $m^3\ m^{-2}h^{-1}$ ("inside pass") b.): at 600 rpm, 3.84 ln min^{-1} and B=10 $m^3\ m^{-2}h^{-1}$("mixed flow")

Exemplarily, the limiting rotational speed for the change of the flow regimes is shown in table 2. The observed flow regimes for the given gas and water flow rate change in dependency of the rotational speed. Variation of the air or water flowrate will change the region of the rotational speed for the specific flow regime.

Table 2: Flow regimes for 3.84 $lnmin^{-1}$ of air and hydraulic load of B_C=10 $m^3\ m^{-2}h^{-1}$

Flow regime	rpm [1/min]
Outside pass	0-400
Mixed	400-600
Inside pass	700-1000

Visual categorization of the varying flow regimes was performed by evaluation of slow motion videos using a FDR-AX700 4K HDR camcorder. This slow motion videos clearly indicate the changing flow regime with increasing rotational speed.

Results

Characterization of the gas phase holdup in the column was performed by changing the rotational speed in steps of 100rpm in the range of 0rpm up to 1000rpm. These gas holdup measurements were done for 17 different air flow rates in the range of 0 to 6,8 ln/min, resulting in 170 data points for fixed volumetric flowrate of the continuous phase. This experiments were carried out for three different hydraulic loads of the continuous phase (B_C = 10, 14, 18 $m^3/m^{-2}h^{-1}$) and two different rotor disc designs (figure 1). Maximal gas holdup of approximately 20% was achieved in the TCDC DN50 column. Figure 4 shows the effect of three different rotational speeds and increasing air flow rate on the gas holdup for the rotor disc design HOLE #1 with 0.92 % perforated disc area.

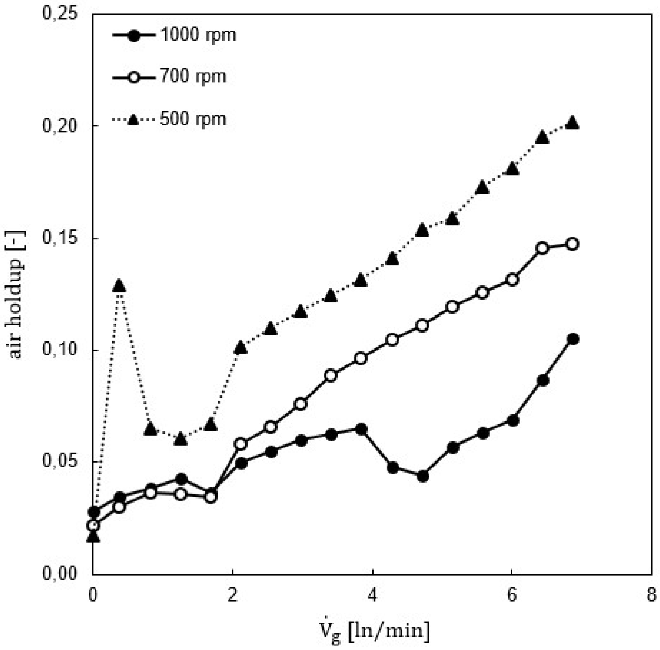

Figure 4: Effect of varying rotational speed and gas flow rate on the gas holdup for the rotor disc design HOLE #1 with 0.92% perforated area (figure 1a) at the hydraulic load of B_C=18.14 m^3 $m^{-2}h^{-1}$

Increasing rotational speed at fixed gas and liquid flowrate results in a decreasing gas holdup. The gas holdup decreases due to increasing centrifugal forces that compress the gas to the area of the shaft where it partly accumulates and forms a continuous stratified layer. A rotational speed of 1000 rpm complies to a centrifugation number of Z=24. The significant decrease of the gas holdup at 3.8 ln/min and 1000rpm was observed for 900rpm and 1000rpm, independent of the hydraulic load. Analysis of slow motion videos showed that at this point the rising gas phase is no longer dispersed after passing the holes but flows through the holes as a constant film. The peak at the 500rpm line in figure 4 is explained by the backpressure of the rising gas bubbles caused by the continuous liquid phase flow in countercurrent direction. At this operation point the gas phase forms a stable doughnut-shaped layer below the rotor discs which intermittently climb up from one compartment to the next, as shown in figure 5. This effect decreases with decreasing hydraulic load and was not observed when B_C was below 18.14 $m^3/m^{-2}h^{-1}$

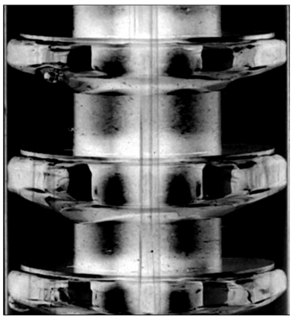

Figure 5: Doughnut shaped gas layer below the rotor discs (0.92% perforated area) at a hydraulic load of B=18.14 m^3 $m^{-2}h^{-1}$, 500rpm and 0.38 ln/min

The comparison of the two different rotor disc designs (figure 1) for Bc=10 $m^3m^{-2}h^{-1}$ and varying gas flow rate on the gas holdup is illustrated in figure 6. The solid line with full dots (1000 rpm HOLE #1) shows the same trend as the 1000 rpm line in figure 4, with the difference that experiments in figure 6 were done at a lower hydraulic load of B=10 instead of B=18,14. The HOLE #1 rotor disc design ensures a significantly higher holdup at elevated gas flow rates compared to the SLOT #1 design. This is caused by the small holes limiting the amount of rising gas from one compartment to the next. There is nearly no difference in the gas holdup when comparing 500rpm to 1000 rpm using the SLOT #1 rotor disc design. Investigation of slow motion videos showed that 17.32% perforation is sufficient to allow for an unhindered rise of the gas phase.

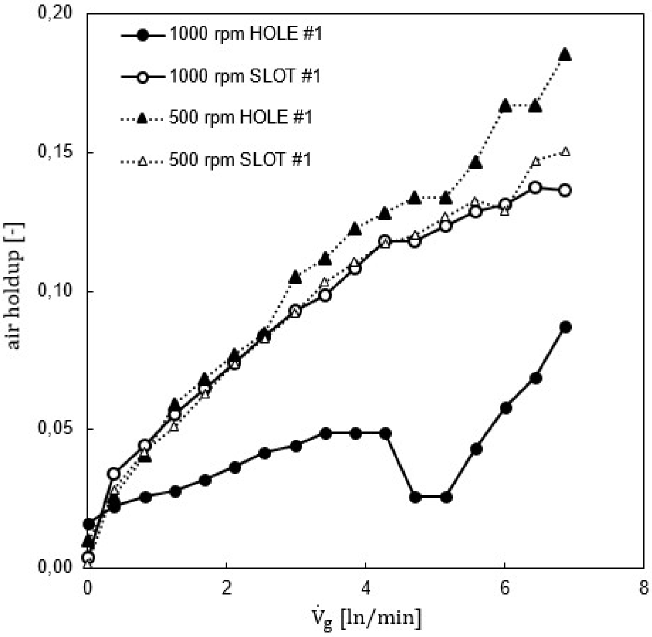

Figure 6: Experimental data for the influence of rotor disc design on the gas holdup for fixed hydraulic load of B=10 m^3 $m^{-2}h^{-1}$ and increasing gas flowrate. HOLE #1 indicates the 0.92% perforated area (figure 1a) and the 17.32% perforated disc ist abreviated with SLOT #1 (figure 1b).

The effect of the transition of the three flow regimes on the gas holdup is shown in figure 7. Independent of the rotor disc design, the “s”-shaped curve slope indicates the on-set rotational speed of the three flow regimes. At the beginning the gas passes the rotor discs on the outside. After overcoming the mixed flow region the complete gas flow passes the discs through the perforated area. A smaller perforated area increases the limits of the mixed flow region.

Perforation percentage of 0.92% (HOLE #1) ends up in a higher holdup at lower rotational speed and lower gas holdup at higher rotational speed for 17.32% (SLOT #1) perforated area. This transition point is located at 600rpm for a constant gas flowrate of 6.43 ln/min and decreases with decreasing gas flowrate (500rpm for 2.11 ln/min).

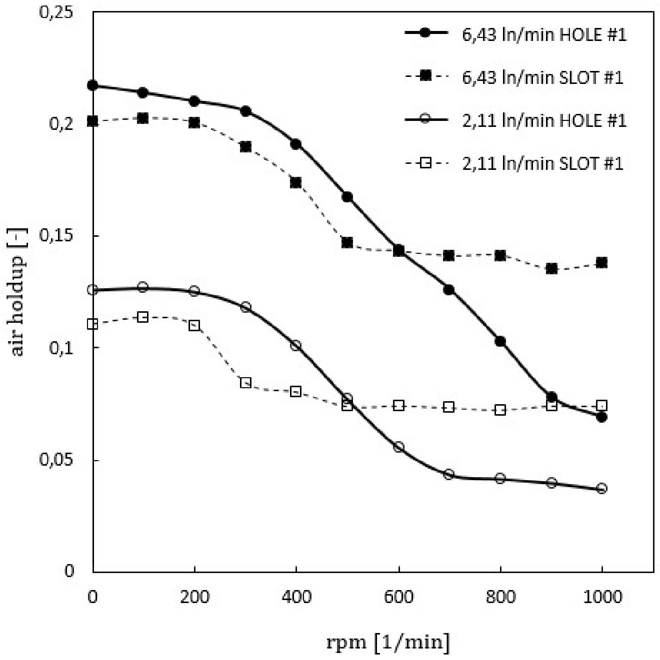

Figure 7: Experimental holdup data, comparing two different rotor disc designs HOLE #1 (figure 1a) and SLOT #1 (figure 1b) and two gas flow rates for a fixed hydraulic load of B=10 $m^3/m^{-2}h^{-1}$ and varying rotational speed.

The effect of air flow rate on the solid phase holdup for G/L/S three phase flow was investigated and recorded too. First results show that the solid phase holdup is mainly affected by the roatational speed, independend of the gas flow rate.

Conclusion and Outlook

Hydraulic investigations of continuous gas-liquid flow (G/L) in a Taylor-Couette Disc Contactor with 50mm column diameter (TCDC DN50) and 700mm active mixing height were performed. The influence of two different perforated rotor disc designs on flow pattern and gas phase hold up was investigated. The two rotor disc designs differ in the percentage of perforated disc area (0.92% and 17.32%) and the perforation pattern (five 1mm holes and three slots). Water was used as continuous liquid phase and compressed air as gas phase. The effect of varying rotational speed, hydraulic load and gas flowrate on the gas holdup was investigated for both rotor disc designs.

By increasing the rotational speed of the rotor discs, three different flow regimes were observed, strongly affecting the gas holdup in the active mixing height. Formation of different flow regimes was observed for both rotor disc designs. With increasing rotational speed, the gas holdup inside the active mixing height decreases. This is explained by the increasing centrifugal force that compresses the gas and forces it to remain at the area of the shaft. There the gas phase forms an accumulated layer around the shaft und thus the volumetric gas holdup decreases. A perforated rotor disc area of 17.32% is sufficient to allow nearly unhindered rise of the gas phase. Change of the flow regimes from outer pass over mixed flow to inner pass can be identified from the holdup data and was confirmed by slow motion videos.

To sum up, the aerated Taylor-Couette Disc Contactor shows defined and stable continuous gas-liquid phase contact. Due to the simple rotor design, combined with perforated rotor discs, this agitated column type can also be used for multiphase contact, as shown for continuous gas-liquid-solid flow. For both rotor disc designs the perforated area was located directly next to the shaft diameter. The effect of different locations on the hydraulics will be investigated too. Optical investigation of the available G/L contact area will be performed combined with measurement of kLa data for characterization of G/L contact in the TCDC column. Scale up experiments are in preparation.

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