Prediction of Holdup and Drop Size Distribution in a Disc-Doughnut Pulsed Column with Tenova Kinetics Internals for the Water-Alamine 336 System

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Abstract:

Tenova Pulsed Column Kinetics Internals (TPC-KIs) are a newly designed type of pulsed column internals with a novel structure that is expected to achieve less back-mixing, higher holdup and improved mass transfer. This study compared the hydrodynamic performance of TPC-KIs with standard disc and doughnut internals in a 2 m high 76 mm diameter pulsed solvent extraction column with the water-Alamine 336-Shellsol 2046 system. The effects of the wettability of column internals have also been considered. Dispersed phase holdup and Sauter mean droplet diameter were measured under various pulsation intensity and velocities of both phases, and empirical correlations for holdup and drop size have been refitted within absolute average relative errors within 15%. Tenova kinetics internals has lower holdup and larger Sauter-mean drop size compared to standard disc and doughnut internals, and these hydrodynamic parameters are predictable using the developed correlation in this study.

Key words:

Solvent extraction, pulsed column, TPC-KIs, Dispersed phase holdup, Sauter mean diameter, wettability, correlation

1. Introduction

Pulsed solvent extraction columns are an efficient liquid-liquid contactor design and have been studied with various types of column internals, such as Kühni column, pulsed packed column, pulsed perforated column and pulsed disc and doughnut column. As fixed components inside the pulsed column, the column internals can be produced at a low cost and operated with minimal ongoing maintenance. However, the design of these internals can significantly impact column performance and hence optimising their design is important. Additionally, when compared to other liquid-liquid separation apparatus such as mixer-settlers, pulsed columns can reduce evaporation loss, entrainment and solvent inventory to a large extent.

This study aims to compare the hydrodynamic performance of pulsed columns with Tenova Pulsed Column – Kinetics Internals (TPC-KIs) and standard disc and doughnut internals using water – Alamine 336 in Shellsol 2046 liquid-liquid system (either with aqueous continuous or organic continuous operation). Wang et al.^[2] has recently reported the hydrodynamic performance of a 1 m high 72.5 mm diameter pulsed solvent extraction column with Teflon standard disc and doughnut internals using tap water – Alamine 336 in Shellsol 2046. The study found the increase in dispersed phase holdup with dispersed phase flowrate and high pulsation intensity. However, there is very limited study on the performance of pulsed columns with TPC-KIs internals. As novel column internals with improved structure, TPC-KIs are expected to improve overall mass transfer performance by producing a larger dispersed phase holdup and less axial dispersion under comparable operating conditions^[1]. Due to the presence of a sawtooth edging of Tenova kinetics internals, its flood point is expected to be higher than for standard disc and doughnut internals, thus a much higher throughput can be achieved.

In the present study, polyvinylidene fluoride (PVDF) was used for both standard disc and doughnut internals and the TPC-KIs, but the surface roughness of the PVDF sheets was different for the two types of internals resulting in variation in surface wettability^[3]. The wettability of these internals indicates that liquid-liquid systems can be efficiently operated under both organic continuous and aqueous continuous. The present study investigates both the influence of which phase is continuous and the internal structures on the hydrodynamic performance of a pulsed solvent extraction column.

2. Background

Hydrodynamics is crucial for the assessment of solvent extraction column performance as it directly influences the interfacial area available for mass transfer. A larger liquid-liquid interfacial area results in higher mass transfer

fluxes according to the two-film theory^[4]. In the present study, two significant hydrodynamics parameters, dispersed phase holdup and Sauter mean diameter are investigated. The dispersed phase holdup can be easily calculated as the ratio of the dispersed phase volume in the active section of column to the total column volume. The Sauter mean diameter indicates the average dimension of the dispersed phase droplets. This is a dynamic parameter and changes with operating conditions and column geometry. The dispersed phase enters the column and forms droplets as it passes through the column internals until an equilibrium spread of droplet sizes is reached. Additionally the droplet size and shape can be influenced by the wettability and contact of the dispersed phase with the column internals^[5].

A number of researchers have reported studies on pulsed solvent extraction columns and proposed empirical correlations for predicting the hydrodynamic performance of pulsed solvent extraction columns with different types of column internals and liquid – liquid systems (see Table 1 and Table 2). However, there is limited study using the Tenova pulsed column – kinetics internals (TPC-KIs).

Table 1 Correlations from literature for the prediction of dispersed phase holdup in pulsed Solvent extraction columns

Researchers	Column type	Liquid-liquid systems	Direction	Applicable region	Correlations
Griffith et al. ^[6]	Unknown	unknown		mixer-settler region	$x_d = \frac{v_d}{fH}$ (1)
Miyauchi and Oya ^[7]	Pulsed perforated plate column with height of 0.37, 0.78, 0.86 m and diameter of 32 and 54 mm	water - MIBK liquid-liquid systems	aqueous continuous	NA	$\text{for } \chi < 0.0031 \frac{m^{11}}{s}, x_d = 4.93 \times 10^2 \chi^{0.84} v_d^{\frac{2}{3}} \quad (2)$ $\text{for } \chi > 0.0031 \frac{m^{11}}{s}, x_d = 4.93 \times 10^2 \chi^{0.84} v_d^{\frac{2}{3}} \quad (3)$ $\chi = \frac{Af}{(\beta H)^{\frac{1}{3}}} \left(\frac{\mu_d^2}{\gamma \Delta \rho} \right)^{\frac{1}{4}} \quad (4)$
Kumar and Hartland ^[8]	Pulsed perforated-plate column	23 different liquid-liquid systems	both	All regions	$x_d = k_1 \exp [k_2 Af - (Af)_m] v_d^{0.86} (v_c + v_d)^{0.28} \Delta \rho^{-0.3} \rho_d^{-0.93} \mu_d^{0.77} \varepsilon^{-0.56} H^{-0.56} \quad (5)$ $\text{in which } (Af)_m = 9.69 \times 10^{-3} \left(\frac{\gamma \Delta \rho^{1/4} \varepsilon}{\mu_d^{3/4}} \right)^{0.33} \quad (6)$
Wang et al. ^[2]	Pulsed disc and doughnut column with height of 1 m and diameter of 72.5 mm	water – Alamine 336	organic continuous	All regions	$x_d = k_1 \exp [k_2 Af - (Af)_m] \left(\frac{v_d^4 \rho_c}{g \gamma} \right)^{0.27} \left(\frac{v_c + v_d}{v_d} \right)^{0.32} \left(\frac{\Delta \rho}{\rho_c} \right)^{-0.98} \left(\frac{\mu_d}{\mu_c} \right)^{0.18} \quad (7)$

Table 2 Correlations from literature for the prediction of dispersed phase drop size in pulsed solvent extraction columns

Researchers	Column type	Correlations
Hinze^[9] and Shinnar and Church ^[10]	Agitation dispersions in stirred tanks	$d_{32} = k \left(\frac{\gamma}{\rho_c} \right)^{-0.6} \psi^{-0.4} \quad (8)$
Kumar and Hartland^[11]	Pulsed and Karr columns	$\frac{d_{32}}{H} = \frac{C_\Psi \varepsilon^{0.32}}{\frac{1}{1.55 \left(\frac{\gamma}{\Delta \rho g h^2} \right)^{1/2}} + \frac{1}{0.42 \left[\left(\frac{\psi}{g} \right) \left(\frac{\Delta \rho}{g \gamma} \right)^{1/4} \right]^{-0.35} \left[h \left(\frac{\Delta \rho g}{\gamma} \right)^{1/2} \right]^{-1.15}}} \quad (9)$
Van Delden et al.^[12, 13]	Pulsed disc and doughnut columns	$\frac{d_{32}}{\sqrt{\frac{\gamma}{\Delta \rho g}}} = C_1 \varepsilon^{n_1} \left(h \frac{\sqrt{\rho_* g}}{\gamma_*} \right)^{n_2} \left(\frac{\mu_d g^{1/4}}{\rho_*^{1/4} \gamma_*^{3/4}} \right)^{n_3} \left(\frac{\gamma}{\gamma_*} \right)^{n_4} [C_2 + \exp \left\{ C_3 \frac{Af}{\varepsilon \left(\frac{\gamma_* g}{\rho_*} \right)^{1/4}} \right\}] \quad (10)$
Torab-Mostaedi et al.^[14]	Pulsed disc and doughnut column	$\frac{d_{32}}{\sqrt{\frac{\gamma}{\Delta \rho g}}} = 33.53 \times 10^{-3} \left(\frac{Af^4 \rho_c}{g \gamma} \right)^{-0.283} \left(\frac{d_a \rho_c \gamma}{\mu_c^2} \right)^{0.29} \left(\frac{\rho_c \gamma^4}{\psi \mu_c} \right)^{-0.13} \left(\frac{\Delta \rho}{\rho_c} \right)^{2.86} \left(\frac{\mu_d}{\mu_c} \right)^{0.085} \left(\frac{h}{d_a} \right)^{-0.734} (1 + L)^{0.34} \quad (11)$
Wang et al.^[15]	Pulsed disc and doughnut column	$\frac{d_{32}}{\sqrt{\frac{\gamma}{\Delta \rho g}}} = 31.7 \varepsilon^{1.6} \left(\frac{v_c \mu_c}{\gamma} \right)^{0.116} \left(\frac{v_d}{v_c} \right)^{0.118} [0.324 + \exp \left\{ \frac{-6.27 Af}{\varepsilon \left(\frac{\gamma_* g}{\rho_*} \right)^{0.25}} \right\}] \quad (12)$

3. Experimental

3.1. Liquid-liquid system

The liquid-liquid system used in this study was tap water as the aqueous phase and 3 v/v % Alamine® 336 (tri-octyl/decyl amine, BASF), and 1 v/v % Isodecanol (ExxonMobil), diluted with Shellsol® 2046 (Shell) as the organic phase. No mass transfer of the solute occurred in this hydrodynamic study. The physical properties of each phase including density, ρ , viscosity, μ , and interfacial tensions γ_{q-org} were measured and results are shown in Table 3. Densities of aqueous and organic phases were measured three times to obtain average values using 25 mL density bottles. A Cannon portable viscometer was used to measure the viscosity of each phase. Interfacial tension was measured with a Theta Attension Tensiometer.

Table 3 Physical properties of liquid-liquid system

Aqueous Phase	Organic Phase	ρ_{aq} (kg/m ³)	ρ_{org} (kg/m ³)	μ_{aq} (Pa·s)	μ_{org} (Pa·s)	γ_{aq-org} (N/m)
Tap water	3 v/v % Alamine 336 & 1 v/v % isodecanol in Shellsol 2046	998	801.2	1.02×10^{-3}	2.30×10^{-3}	0.011
Tap water	8 v/v % Lix 84 in Shellsol 2046	998	810.3	1.02×10^{-3}	2.08×10^{-3}	0.022

3.2. Equipment

A 2 m high 76 mm diameter pulsed solvent extraction pilot-scale column was used to collect experimental data. The column set-up has been reported in previous study^[3]. The main column consists of a concentric reducer, two 1 m long cylinder components and a tee piece, which was connected to the inlet from aqueous feed solution tank and the outlet of the loaded organic tank. All four column parts were made of QVF precision borosilicate glassware and connected with relevant couplings and seals. Pulsing was powered with a three-phase induction motor and connected to a zero-max gearbox from Naismith with a piston unit linked to the bottom distributor of the organic phase^[3].

The standard disc and doughnut internals and Tenova pulsed column – kinetics internals (TPC-KIs) (see Figure 1) were placed inside the pulsed column separately in order to assess their enhancement in the breakage of dispersed phase droplets and improve the interfacial area between the two immiscible phases to enable better mass transfer performance. Seventy seven disc and seventy six doughnut plates, which were made of PVDF

(polyvinylidene fluoride), were alternatively connected by three 10 mm diameter SS rods with 9.8 mm spacing apart. The open free area for both internals is 22.4%. Pilot scale experiments were conducted at room temperature.

Figure 1. Schematic drawings for standard disc and doughnut internals (left) and Tenova kinetics internals (right)

3.3. Column Operation

The dispersed phase holdup under a wide range of operating conditions was measured using the drainage technique, which was detailed by Torab-Mostaedi (2011) ^[14]. At a defined pulsing amplitude and frequency and stable phase flowrates, column operation under steady state conditions was stopped by simultaneously closing the inlets and outlets for both aqueous and organic phase and turning the pulsing unit's power off. After labelling the interface level, the dispersed phase droplets remaining inside the main section of pulsed column were allowed to settle/rise to the interface level. The volume of the dispersed phase droplets present under steady state conditions were then measured with a volumetric flask via the difference between the two interface levels. The dispersed phase holdup, which is defined as the ratio of the volume of dispersed phase droplets at steady state over the total volume of the column main section, could then be calculated.

Photographs of the dispersed phase droplets were also taken at equilibrium using a Canon G16 camera with fixed focus and external speedlite at the middle of the column using a Perspex cubical viewing box. Dozens of digital photographs at each defined operating condition were taken and drop size analysed using Nano Measurer 1.2 software for a minimum 150 droplets diameter data.

The pulsation intensity was varied from 0 m/s to 0.03 m/s, and the dispersed phase and continuous phase velocities were changed between 3.68×10^{-4} to 1.84×10^{-3} m/s and 2.39×10^{-4} to 1.84×10^{-3} m/s, respectively.

4. Results and discussion

4.1. Dispersed phase holdup

For the newly designed TPC-KIs, the effect of pulsation intensity on the dispersed phase holdup was studied and the results are plotted on Figure 3 for both aqueous continuous and organic continuous operation. To enable comparison between the standard disc and doughnut internals and TPC-KIs, the effect of pulsation intensity on the dispersed phase holdup with organic continuous for both internals is shown in Figure 4. The aqueous phase flow rates were varied from 7.35×10^{-4} to 1.47×10^{-3} m/s and 6.62×10^{-4} to 1.43×10^{-3} m/s for the continuous phase flow rates.

Figure 3 shows that the dispersed phase holdup, under all five A/O ratios, always decreases with increasing pulsation intensity to a minimum value ($(Af)_{\min} = 0.01 \pm 0.002$ m/s for aqueous continuous series and $(Af)_{\min} = 0.02 \pm 0.002$ m/s for organic continuous series, respectively). Following this, the volume of dispersed phase droplets generally increases with pulsation intensity. At the pulsation intensity of $(Af)_{\min}$, the lowest volume of dispersed phase is kept inside the column and therefore may limit the mass transfer rate. For the same values of dispersed phase velocity for both aqueous continuous ($v_d = 7.35 \times 10^{-4}$ m/s) and organic continuous ($v_d = 6.62 \times 10^{-4}$ m/s), the data series are in good agreement with each other^[3]. Holdup results at $v_d = 7.35 \times 10^{-4}$ m/s for the organic continuous system were higher than that at $v_d = 6.62 \times 10^{-4}$ m/s for aqueous continuous system. Similarly, holdup data at $v_d = 1.43 \times 10^{-3}$ m/s for the aqueous continuous system was lower than the holdup at $v_d = 1.47 \times 10^{-3}$ m/s for the organic continuous system. To have improved overall mass transfer performance, it is beneficial to maintain a higher dispersed phase holdup in the working section of the column as it results in a larger interfacial area between the two immiscible phases. Hence, choosing the organic continuous system would be a wise option for PVDF Tenova Pulsed Column – Kinetics Internals.

Figure 3. Effect of pulsation intensity and dispersed phase velocity on the dispersed phase holdup x_d for Tenova pulsed column kinetics internals

Figure 4 presents dispersed phase holdup as a function of pulsation intensity for the different internals at the same operating conditions. A slightly lower dispersed phase holdup was measured with TPC-KIs at low pulsation intensity ($Af \leq 0.015$ m/s) compared to the standard disc and doughnut internals, but higher holdup was measured when the pulsation intensity was increased above 0.015 m/s. For both sets of internals, the dispersed phase holdup dropped to a minimum value at a constant pulsation intensity (for standard disc and doughnut internals, $(Af)_{\min} = 0.02 \pm 0.002$ m/s; for TPC-KIs, $(Af)_{\min} = 0.015 \pm 0.002$ m/s). It was also found that there was little effect of the continuous phase velocity on the dispersed phase holdup but an obvious effect of the dispersed phase velocity.

Figure 4. Effect of pulsation intensity and continuous phase velocity on the dispersed phase holdup x_d for different column internals

Figure 5 and 6 shows how the dispersed phase velocity and continuous phase velocity influenced the dispersed phase holdup for the different internals at a constant pulsation intensity of 0.01 m/s. For the same continuous phase velocity of 6.62×10^{-4} m/s, the holdup for both standard disc and doughnut internals and Tenova kinetics internals keeps linearly with dispersed phase velocity. The dispersed phase holdup for both sets of internals also increases at a similar rate, although the standard disc and doughnut generally provided slightly higher holdup at these operating conditions (which is at a relatively low pulsation rate of 0.01 m/s).

The effect of continuous phase velocity on dispersed phase holdup with a dispersed phase velocity of 7.35×10^{-4} m/s is presented in Figure 6, and it can be concluded that varying the continuous phase velocity did not show an observable effect on holdup with either set of internals.

Figure 5. Effect of dispersed phase velocity on dispersed phase holdup at constant continuous phase velocity ($v_c = 6.62 \times 10^{-4}$ m/s) and pulsation intensity ($Af = 0.01$ m/s)

Figure 6. Effect of continuous phase velocity on dispersed phase holdup under same dispersed phase velocity ($v_d = 7.35 \times 10^{-4}$ m/s) and pulsation intensity ($Af = 0.01$ m/s)

4.2. Correlation for dispersed phase holdup

An empirical correlation for prediction of the dispersed phase holdup with standard disc and doughnut internals and Tenova Pulsed Column – Kinetics Internals was reported using a water – LIX 84 liquid-liquid system^[3] with an absolute average relative error (AARE) of 5.76%. The Average Absolute Relative Errors (AARE) caused by fitting the experimental data for water – Alamine® 336 system into the original correlation^[3] was found to be 48.65%. In this study, all the experimental data collected for the two types of internals and operations (aqueous continuous or organic continuous) were fitted to equation 13 (see Figure 7) with correlations constants k_1 and k_2 (in Table 4) dependent on the operating regime (mixer-settler region at pulsation intensity of 0 ~ 0.015 m/s; transition and emulsion region at pulsation intensity of 0.015 ~ 0.03 m/s). k_1 and k_2 here in Table 4 are also applicable to predict the holdup for previous system^[3] and resulting in AAREs of 14.58% and 7.40% for Tenova kinetics internals and standard disc and doughnut internals, respectively.

$$x_d = k_1 \exp [k_2 |Af - (Af)_m| (\frac{v_d^4 \rho_c}{g\gamma})^{0.31} (\frac{v_c + v_d}{v_d})^{0.32} (\frac{\Delta \rho}{\rho_c})^{-0.98} (\frac{\mu_d}{\mu_c})^{0.18}] \quad (13)$$

On this basis equation 13 can be used to predict the dispersed phase holdup in pulsed columns fitted with both standard disc and doughnut internals and TPC-KIs operating with either aqueous continuous or organic continuous. The overall AARE between the experimental data and correlation results for the three operating regimes and two different liquid-liquid systems is 15.56%. Hence, the dispersed phase holdup for standard disc and doughnut internals and Tenova kinetics internals are predictable for both water – Alamine® 336 and water – LIX 84 systems.

Table 4 Regressed parameters for the correlation of dispersed phase holdup shown by equation (13)

Internals	Operation	Operating regime	k_1	k_2	AARE
Standard disc and doughnut internals	Organic continuous system	mixer-settler	7.65	77.30	15.45%
		transition & emulsion	6.34	39.17	
Tenova kinetics internals	Organic continuous system	mixer-settler	7.71	6.49	21.67%
		transition & emulsion	6.11	21.97	
	Aqueous continuous system	mixer-settler	3.75	91.48	12.03%
		transition & emulsion	1.64	43.80

Figure 7. Comparison of the experimental dispersed phase holdup and predicted holdup with Eq. 13

4.3. Drop size - Sauter mean diameter d_{32}

Another significant hydrodynamic parameter used to determine the interfacial area between two immiscible phases is dispersed phase drop size which can be represented by the Sauter mean diameter (d_{32}). Up to 300 individual droplet sizes under each particular A_f , V_c and V_d were recorded under a range of pulsation intensities and phase velocities using photographs taken in the Perspex cubical viewing boxes located in the middle of the column (Figure 8). The diameters of dispersed phase droplets were measured manually via Measurer 1.2 software, using the known distance between each internal plate as the reference scale. All the Sauter mean diameter data were obtained at the same operating conditions as the dispersed phase holdup. Results are presented in Figure 9 and Figure 10.

Figure 8. Apparatus and software for measurement of dispersed phase droplets

In Figure 9, the Sauter mean diameter of the dispersed phase droplets using the TPC-KIs with aqueous continuous (open points) and organic continuous (closed points) is shown under various pulsation intensity and phase velocities. It is clearly shown that d_{32} decreases as pulsation intensity increases from 0.005 m/s up to 0.03 m/s. At low pulsing rate ($Af \leq 0.015$ m/s), d_{32} experimental points for aqueous continuous system do not vary much with variation in A/O ratios compared to that with organic continuous system. At high pulsing rate conditions ($Af \geq 0.02$ m/s), the Sauter mean diameters for both the aqueous continuous and organic continuous systems are very similar due to excess mechanical energy from the pulsing unit and less impact from the wettability of the internals.

Figure 9. Effect of pulsation intensity on the Sauter mean diameter d_{32} with different aqueous to organic phase ratio

In this water – Alamine 336 system (faster kinetics liquid-liquid system compared to water – LIX 84 system), the Sauter mean diameters d_{32} for both internals decrease with higher pulsation intensity and approaches a minimum value of ~ 0.0015 m (see Figure 10). It is compatible with results observed in the previous study^[3] of the pulsed column with standard disc and doughnut internals and TPC-KIs by using water – Lix 84 liquid-liquid system. The effect of continuous phase velocity and dispersed phase velocity on d_{32} with standard disc and doughnut internals was found to be small. The experimental data for different A/O ratios for TPC-KIs were scattered over a wider range of d_{32} , especially at low pulsing rates. Therefore it may be concluded that the inner structure and surface properties of the column internals has a larger impact on the dimensions of the dispersed phase droplets at low pulsation rates.

Figure 10. Effect of pulsation intensity on the Sauter mean diameter d_{32} with different aqueous to organic phase ratio

4.4. Prediction of Sauter mean diameter and cumulative volume distribution

The original correlation^[3] in literature did not fit both liquid-liquid systems, and the average absolute relative error is 19.40% for water – Alamine 336 system. Therefore, an advanced empirical correlation based on the equation developed by van Deldan et al.^[12, 13] is used (see equation 14) with refitted parameters C_1 and C_2 shown in Table 5..

$$d_{32} = C_1 \varepsilon^{0.3} \left(\frac{\gamma}{\Delta \rho g} \right)^{0.5} \left(h \frac{\sqrt{\rho_* g}}{\gamma_*} \right)^{0.18} \left(\frac{\mu_d g^{0.25}}{\rho_*^{0.25} \gamma_*^{0.75}} \right)^{0.14} \left(\frac{\gamma}{\gamma_*} \right)^{0.06} \left[C_2 + \exp \left\{ (-2.59) \times \frac{Af}{\varepsilon \left(\frac{\gamma_* g}{\rho_*} \right)^{0.25}} \right\} \right] \left(\frac{v_d}{v_c} \right)^{0.05} \quad (14)$$

Table 5 Refitted constants for the correlation of Sauter mean diameter d_{32}

Constants	Operation	C_1	C_2	AARE
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Standard disc and doughnut internals	Organic continuous system	0.0105	0.2368	9.44%
Tenova kinetics internals	Organic continuous system	0.0243	0.0215	10.46%
	Aqueous continuous system	0.02	0	11.30%

Figure 11. Comparison between the experimental Sauter mean diameter and predicted data

The correlation is well predicted the Sauter mean diameter (Figure 11) and the AARE of refitted constants are 9.44% and 10.46% for the standard disc and doughnut internals and the Tenova kinetics internals, and 11.30% AARE for aqueous continuous system with TPC-KIs. Additionally, equation 14 can also be applied for the prediction of the dispersed phase Sauter mean diameter for the water-Lix 84 system^[3]. This results in AARE of 12.19% and 13.80% for TPC-KIs and standard disc and doughnut internals, respectively.

The droplet distribution is also studied by applying the Weibull distribution equation (equation 15). The parameters (a, b) of the cumulative distribution function is summarised in Table 6 and Figure 15.

$$F(d_i|a, b) = 1 - e^{-\left(\frac{d_i}{b}\right)^a} \quad (15)$$

Table 6 Regressed parameters a and b for Equation 15

Internals	Operation	Operating intensity (m/s)	a	b
Standard disc and doughnut internals	Organic continuous	0.01	6.07	3.44
		0.02	8.24	2.48
Tenova kinetics internals	Organic continuous	0.01	5.83	6.55
		0.02	4.59	2.53
	Aqueous continuous	0.01	4.88	6.08
		0.02	4.05	2.23

Under higher pulsing rates ($Af = 0.02$ m/s), a smaller distribution of droplet's diameter is evident. The prediction of the cumulative drop distribution in Figure 12 shows that the predicted values fit the experimental data well. Additionally, the cumulative drop distributions for standard disc and doughnut internals are narrowed compared to TPC-KIs with either aqueous continuous system or organic continuous system. Similar trends were seen in the previous investigations with the LIX 84 in Shellsol 2046 system^[3].

Figure 12. Prediction of drop size cumulative volume distribution with the cumulative probability function

5. Conclusions

1. Slightly higher dispersed phase holdup can be achieved with standard disc and doughnut internals compared with Tenova Pulsed Column – Kinetics Internals (TPC-KIs).
2. Due to the inner structure and surface property, the dispersed phase droplet diameters were scattered across a wide range at low pulsing intensity with the TPC-KIs. The internal edge and wettability of internal surface is key factor for the dispersed phase droplets formation. The Sauter mean diameter is likely independent of operating conditions at pulsation intensity higher than 0.02 m/s.
3. Correlations of both dispersed phase holdup and Sauter mean diameter for both the Tenova Pulsed Column – Kinetics Internals and the standard disc and doughnut internals and two different liquid-liquid systems are presented with the overall absolute average relative error of 15.56% and 11.44%, respectively. The dispersed phase holdup and Sauter mean diameter are predictable for standard disc and doughnut internals and TPC-KIs.

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7. Nomenclature

a	interfacial area, m^2
A	pulsation amplitude, m
d_{32}	Sauter-mean drop diameter, m
f	pulsation frequency, Hz
g	gravity acceleration, m/s^2
h	column height, m
A/O	flow ratio, viz velocity ratio of dispersed phase to continuous phase, dimensionless
v_d/v_c	dispersed phase velocity/continuous phase velocity, m/s
x_d	volume fraction holdup of dispersed phase, dimensionless
ε	the fractional free area, dimensionless
ϵ	drop distortion parameter, dimensionless
γ	interfacial tension, N/m
μ_d/μ_c	viscosity of dispersed phase/continuous phase, Pa·s
ρ_d/ρ_c	density of dispersed phase/continuous phase, $\text{kg/m}^{3[3]}$
$\Delta\rho$	density difference between phases, kg/m^3
ψ	mechanical power dissipation per unit mass, W/kg
Subscripts or superscripts	
c	continuous phase
d	dispersed phase

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Supporting materials:

Table S1. Experimental holdup and predicted value for
Tenova kinetics internals at organic continuous with water-Alamine 336 system

No.	A/O	Af (m/s)	Xd_exp	Xd_pred	d32_exp (m)	d32_pred (m)
1	1.11	0	0.0852	0.0343	NA	NA
2	0.68	0	0.1005	0.0411	NA	NA
3	0.51	0	0.1050	0.0461	NA	NA
4	1.64	0	0.1385	0.0716	NA	NA
5	2.22	0	0.2557	0.1079	NA	NA
6	1.11	0.005	0.0594	0.0332	0.0074	0.0077
7	0.68	0.005	0.0670	0.0398	0.0071	0.0074
8	0.51	0.005	0.0746	0.0446	0.0073	0.0073
9	1.64	0.005	0.0989	0.0693	0.0088	0.0080
10	2.22	0.005	0.1674	0.1045	0.0080	0.0082
11	1.11	0.01	0.0411	0.0322	0.0056	0.0055
12	0.68	0.01	0.0449	0.0385	0.0070	0.0053
13	0.51	0.01	0.0441	0.0432	0.0069	0.0052
14	1.64	0.01	0.0731	0.0671	0.0065	0.0057
15	2.22	0.01	0.1065	0.1011	0.0065	0.0058

16	1.11	0.015	0.0274	0.0273	0.0035	0.0039
17	0.68	0.015	0.0320	0.0327	0.0047	0.0038
18	0.51	0.015	0.0342	0.0367	0.0051	0.0037
19	1.64	0.015	0.0624	0.0570	0.0037	0.0041
20	2.22	0.015	0.0868	0.0858	0.0042	0.0041
21	1.11	0.02	0.0388	0.0305	0.0021	0.0028
22	0.68	0.02	0.0434	0.0365	0.0032	0.0027
23	0.51	0.02	0.0449	0.0409	0.0031	0.0027
24	1.64	0.02	0.0761	0.0636	0.0025	0.0029
25	2.22	0.02	0.0989	0.0958	0.0025	0.0030
26	1.11	0.025	0.0411	0.0340	0.0018	0.0021
27	0.68	0.025	0.0434	0.0407	0.0018	0.0020
28	0.51	0.025	0.0457	0.0457	0.0018	0.0019
29	1.64	0.025	0.0913	0.0710	0.0021	0.0021
30	2.22	0.025	0.1294	0.1069	0.0020	0.0022
31	1.11	0.03	0.0411	0.0380	0.0015	0.0015
32	0.68	0.03	0.0449	0.0454	0.0014	0.0015
33	0.51	0.03	0.0563	0.0510	0.0015	0.0014
34	1.64	0.03	0.0913	0.0792	0.0016	0.0016
35	2.22	0.03	0.1370	0.1194	0.0015	0.0016

Table S2. Experimental holdup and predicted value for standard disc and doughnut internals at organic continuous with water-Alamine 336 system

No.	A/O	Af (m/s)	Xd_exp	Xd_pred	d32_exp (m)	d32_pred (m)
1	1.11	0	0.1903	0.1705	0.0048	0.0059
2	0.68	0	0.1674	0.1855	0.0051	0.0058
3	0.51	0	0.1659	0.1962	0.0048	0.0057
4	1.64	0	0.1918	0.2617	0.0049	0.0061
5	2.22	0	0.2100	0.3693	0.0051	0.0061
6	1.11	0.005	0.1598	0.1158	0.0039	0.0045
7	0.68	0.005	0.1263	0.1260	0.0041	0.0044
8	0.51	0.005	0.1545	0.1333	0.0045	0.0043
9	1.64	0.005	0.1735	0.1778	0.0046	0.0046
10	2.22	0.005	0.1933	0.2509	0.0043	0.0047
11	1.11	0.01	0.1050	0.0787	0.0033	0.0035
12	0.68	0.01	0.0997	0.0856	0.0036	0.0034
13	0.51	0.01	0.1111	0.0906	0.0032	0.0034
14	1.64	0.01	0.1339	0.1208	0.0036	0.0036
15	2.22	0.01	0.1621	0.1705	0.0036	0.0036

16	1.11	0.015	0.0845	0.0602	0.0026	0.0028
17	0.68	0.015	0.0852	0.0656	0.0027	0.0027
18	0.51	0.015	0.0822	0.0693	0.0029	0.0027
19	1.64	0.015	0.1027	0.0925	0.0031	0.0028
20	2.22	0.015	0.1202	0.1305	0.0028	0.0029
21	1.11	0.02	0.0670	0.0590	0.0024	0.0023
22	0.68	0.02	0.0670	0.0642	0.0023	0.0022
23	0.51	0.02	0.0685	0.0679	0.0025	0.0022
24	1.64	0.02	0.0906	0.0906	0.0027	0.0023
25	2.22	0.02	0.1172	0.1278	0.0024	0.0024
26	1.11	0.025	0.0837	0.0717	0.0019	0.0020
27	0.68	0.025	0.0738	0.0781	0.0019	0.0019
28	0.51	0.025	0.0700	0.0826	0.0021	0.0019
29	1.64	0.025	0.1005	0.1102	0.0020	0.0020
30	2.22	0.025	0.1218	0.1554	0.0021	0.0020
31	1.11	0.03	0.0883	0.0873	0.0017	0.0017
32	0.68	0.03	0.0807	0.0950	0.0018	0.0017
33	0.51	0.03	0.0791	0.1005	0.0018	0.0016
34	1.64	0.03	0.1210	0.1340	0.0016	0.0017
35	2.22	0.03	0.1568	0.1890	0.0018	0.0018

Table S3. Experimental holdup and predicted value for
Tenova kinetics internals at aqueous continuous with water-Alamine 336 system

No.	A/O	Af (m/s)	Xd_exp	Xd_pred	d32_exp (m)	d32_pred (m)
1	1.11	0	0.1096	0.1270	NA	NA
2	1.64	0	0.1172	0.1446	NA	NA
3	2.22	0	0.1598	0.1598	NA	NA
4	0.68	0	0.1872	0.2184	NA	NA
5	0.51	0	0.2770	0.2976	NA	NA
6	1.11	0.005	0.1202	0.1010	0.0069	0.0070
7	1.64	0.005	0.1446	0.1150	0.0070	0.0067
8	2.22	0.005	0.1842	0.1271	0.0070	0.0066
9	0.68	0.005	0.2055	0.1737	0.0071	0.0071
10	0.51	0.005	0.3486	0.2368	0.0072	0.0072
11	1.11	0.01	0.1050	0.0804	0.0060	0.0049
12	1.64	0.01	0.1126	0.0915	0.0063	0.0047
13	2.22	0.01	0.1339	0.1012	0.0063	0.0046
14	0.68	0.01	0.1720	0.1382	0.0067	0.0050
15	0.51	0.01	0.2511	0.1884	0.0067	0.0051

16	1.11	0.015	0.0639	0.0639	0.0038	0.0034
17	1.64	0.015	0.0708	0.0728	0.0042	0.0033
18	2.22	0.015	0.0769	0.0805	0.0042	0.0032
19	0.68	0.015	0.1081	0.1099	0.0042	0.0035
20	0.51	0.015	0.1492	0.1499	0.0044	0.0036
21	1.11	0.02	0.0381	0.0308	0.0022	0.0024
22	1.64	0.02	0.0411	0.0350	0.0019	0.0023
23	2.22	0.02	0.0441	0.0387	0.0022	0.0023
24	0.68	0.02	0.0708	0.0529	0.0023	0.0025
25	0.51	0.02	0.0928	0.0721	0.0023	0.0025
26	1.11	0.025	0.0396	0.0383	0.0015	0.0017
27	1.64	0.025	0.0426	0.0436	0.0015	0.0016
28	2.22	0.025	0.0449	0.0482	0.0015	0.0016
29	0.68	0.025	0.0639	0.0659	0.0017	0.0017
30	0.51	0.025	0.0898	0.0898	0.0017	0.0018
31	1.11	0.03	0.0472	0.0477	0.0012	0.0012
32	1.64	0.03	0.0502	0.0543	0.0012	0.0011
33	2.22	0.03	0.0533	0.0600	0.0012	0.0011
34	0.68	0.03	0.0807	0.0820	0.0013	0.0012
35	0.51	0.03	0.1096	0.1118	0.0014	0.0012

Table S4. Experimental holdup and predicted value for
Tenova kinetics internals at organic continuous with water-Lix 84 system

No.	A/O	Af (m/s)	Xd_exp	Xd_pred	d32_exp (m)	d32_pred (m)
1	1.11	0	0.0670	0.0639	NA	NA
2	0.68	0	0.0685	0.0696	NA	NA
3	0.51	0	0.0639	0.0736	NA	NA
4	1.64	0	0.1157	0.0982	NA	NA
5	2.22	0	0.1385	0.1385	NA	NA
6	1.11	0.005	0.0556	0.0619	0.0072	0.0084
7	0.68	0.005	0.0487	0.0674	0.0085	0.0079
8	0.51	0.005	0.0548	0.0713	0.0077	0.0077
9	1.64	0.005	0.0830	0.0950	0.0065	0.0088
10	2.22	0.005	0.1218	0.1341	0.0070	0.0091
11	1.11	0.01	0.0457	0.0599	0.0057	0.0060
12	0.68	0.01	0.0464	0.0652	0.0074	0.0056
13	0.51	0.01	0.0457	0.0690	0.0068	0.0054
14	1.64	0.01	0.0677	0.0920	0.0055	0.0063

15	2.22	0.01	0.0837	0.1298	0.0061	0.0065
16	1.11	0.015	0.0487	0.0469	0.0048	0.0043
17	0.68	0.015	0.0495	0.0511	0.0058	0.0040
18	0.51	0.015	0.0540	0.0540	0.0061	0.0039
19	1.64	0.015	0.0753	0.0721	0.0046	0.0045
20	2.22	0.015	0.0852	0.1017	0.0052	0.0046
21	1.11	0.02	0.0563	0.0524	0.0030	0.0031
22	0.68	0.02	0.0518	0.0570	0.0033	0.0029
23	0.51	0.02	0.0556	0.0603	0.0033	0.0028
24	1.64	0.02	0.0822	0.0804	0.0032	0.0032
25	2.22	0.02	0.1065	0.1135	0.0034	0.0033
26	1.11	0.025	0.0586	0.0585	0.0025	0.0022
27	0.68	0.025	0.0609	0.0636	0.0028	0.0021
28	0.51	0.025	0.0624	0.0673	0.0026	0.0020
29	1.64	0.025	0.0837	0.0898	0.0021	0.0023
30	2.22	0.025	0.1172	0.1267	0.0027	0.0024
31	1.11	0.03	0.0616	0.0653	0.0019	0.0016
32	0.68	0.03	0.0624	0.0710	0.0018	0.0015
33	0.51	0.03	0.0639	0.0751	0.0018	0.0015
34	1.64	0.03	0.0913	0.1002	0.0018	0.0017
35	2.22	0.03	0.1218	0.1414	0.0016	0.0018

Table S5. Experimental holdup and predicted value for
Standard disc and doughnut internals at organic continuous with water-Lix 84 system

No.	A/O	Af (m/s)	X_{d_exp}	X_{d_pred}	d_{32_exp} (m)	d_{32_pred} (m)
1	1.11	0	0.1705	0.1705	0.0066	0.0062
2	0.68	0	0.1849	0.1855	0.0067	0.0059
3	0.51	0	0.1979	0.1962	0.0075	0.0057
4	1.64	0	0.2420	0.2617	0.0061	0.0065
5	2.22	0	0.3280	0.3693	0.0069	0.0068
6	1.11	0.005	0.1339	0.1158	0.0055	0.0047
7	0.68	0.005	0.1370	0.1260	0.0060	0.0045
8	0.51	0.005	0.1476	0.1333	0.0063	0.0043
9	1.64	0.005	0.1910	0.1778	0.0055	0.0049
10	2.22	0.005	0.2861	0.2509	0.0059	0.0051
11	1.11	0.01	0.0715	0.0787	0.0034	0.0037
12	0.68	0.01	0.0845	0.0856	0.0037	0.0035
13	0.51	0.01	0.0883	0.0906	0.0044	0.0034
14	1.64	0.01	0.1111	0.1208	0.0031	0.0038

15	2.22	0.01	0.1621	0.1705	0.0031	0.0040
16	1.11	0.015	0.0586	0.0602	0.0028	0.0029
17	0.68	0.015	0.0654	0.0656	0.0025	0.0028
18	0.51	0.015	0.0647	0.0693	0.0029	0.0027
19	1.64	0.015	0.0883	0.0925	0.0028	0.0031
20	2.22	0.015	0.1256	0.1305	0.0026	0.0032
21	1.11	0.02	0.0624	0.0590	0.0024	0.0024
22	0.68	0.02	0.0677	0.0642	0.0029	0.0023
23	0.51	0.02	0.0624	0.0679	0.0028	0.0022
24	1.64	0.02	0.0913	0.0906	0.0025	0.0025
25	2.22	0.02	0.1263	0.1278	0.0026	0.0026
26	1.11	0.025	0.0913	0.0717	0.0020	0.0020
27	0.68	0.025	0.0898	0.0781	0.0024	0.0019
28	0.51	0.025	0.0791	0.0826	0.0024	0.0019
29	1.64	0.025	0.1263	0.1102	0.0019	0.0021
30	2.22	0.025	0.1804	0.1554	0.0019	0.0022
31	1.11	0.03	0.1126	0.0873	0.0017	0.0018
32	0.68	0.03	0.1050	0.0950	0.0017	0.0017
33	0.51	0.03	0.1005	0.1005	0.0018	0.0016
34	1.64	0.03	0.1537	0.1340	0.0014	0.0019
35	2.22	0.03	0.2055	0.1890	0.0015	0.0019

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