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Effects of Design and Operating Parameters on Hydrodynamics of Circulating Bubble Columns with Open Channel Gas Separators

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Abstract. Hydrodynamics of two external loop circulating bubble columns with open channel gas separators were investigated experimentally. The hydrodynamics were studied under the effects of three operating parameters and one design parameter. The operating parameters were superficial gas velocity in the riser, U_{GR}, gas-liquid dispersion property, σ, and efficiency of gas separation, T_{VR}. The design parameter was the scale-up factor of the riser to downcomer cross-sectional area A_D/A_R. The gas-liquid dispersion property was varied by using various concentrations of additives like antifoam, alcohol and wettable suspended solids. All experiments were conducted using compressed air and tap water from the university main supply system. Time-dependent hydrodynamics variation related to air-water quality was minimized by using consistent air-water samples in order to satisfy experimental reproducibility. The results show that for any gas-liquid-additive system, there is an optimum volume of the liquid in the gas separator, T_{VRO}, that gives the minimum gas recirculation in the downcomer, ε_{GD}. At any A_D/A_R and T_{VR}, the effects of antifoam and suspended solids were found to reduce the gas holdup, while the alcohols were found to increase gas holdup. At T_{VRO}, the efficiency of the gas separator was improved significantly by increasing the scale-up factor, A_D/A_R. Liquid circulation was increased in the antifoam system, but reduced in the presence of wettable suspended solids. The results of this study indicate that the design and operating conditions were better at scale-up factor A_D/A_R=0.55 and volume ratio T_{VR}>20%, than that at A_D/A_R=0.25 for all the additives investigated.

Keywords.: Circulating bubble column, Hydrodynamics, Alcohol, Antifoam, Suspended solid, Gas separator, Scale-up.

1. Introduction

Circulating bubble columns (CBC) are widely used as multiphase contactors and reactors in processes involving oxidation, fermentation, food, waste treatment and biotechnology. They are characterized by their simple construction, ease of operation and maintenance, low capital and running costs and ability to handle shear sensitive

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systems. The characteristics feature of CBCs is the well defined bulk liquid circulation. In CBC, the content is pneumatically agitated by a gas stream, usually at the bottom. In addition to agitation, the gas stream has the important function of facilitating exchange of material between the gas phase and the liquid/solid phase. Gas separators play a significant role on the operation of CBCs, and affect the system hydrodynamics of gas holdup and the liquid circulation. The gas separators in external loop CBCs are either closed channel composed of a horizontal tube connecting the riser and downcomer, or open channel like a tank placed at the top of the riser and downcomer. The extent to which the gas disengages at the gas separator is determined by its design and operating conditions. The fraction of the gas that does not disengage, but entrapped by the descending liquid and taken into the downcomer, has a significant influence on the fluid dynamics and hence the overall system performance. The data published in the literature for hydrodynamics of CBCs overlooked the influence of the gas separator design. Indeed many of the researchers do not clearly describe the gas separator geometry or liquid height in it. Designs that allow for a gas residence time in the separator that is substantially longer than the time required for the bubbles to disengage will minimize the fraction of gas recirculation through the downcomer (Klein *et al.* [1], Merchuk [2], Al-Masry [3]).

There is a limited work in the literature directed towards studies of the role of gas separator on the hydrodynamics of external loop CBCs. Some of the papers published on this subject are focused on closed channel configuration (Al-Masry and Dukkan [4], Bentifraouine *et al.* [5], Al-Masry and Abasaeed [6]) and few others directed towards open channel gas separators (Ghirardini *et al.* [7], Bentifraouine *et al.* [5], Benyahia and Jones [8], Jin *et al.* [9], Al-Masry [3, 10]). Figure 1 shows variations of the gas separators used in the literature for external loop CBCs. The gas separator design given by Al-Masry and Dukkan [4] has shown in successive studies by Al-Masry [10] and Al-Masry [3] that it has promising features that need to be further explored in our multiphase laboratory. In particular, there is a need for more work on the effects of design and operating parameters on the hydrodynamics of external loop CBCs with open channel gas separators in the presence of surface active substances and suspended wettable solid particles. The need to study such systems arises from the increasing usage of CBCs in biotechnology and fermentation industries where the physical properties of the liquid medium affect significantly the system performance. Thus, this work aimed to study the hydrodynamics of external loop CBCs with open channel gas separators, as well as the effects of scale-up A_D/A_R, gas separation efficiency T_{VR}, in the presence of common additives usually found in gas-liquid dispersions.

2. Materials and Methods

Two external loop circulating bubble columns made from transparent acrylic resin were used in this study. Both columns had open channel gas liquid separator, with columns dimensions given in Fig. 2. Gas holdups were inferred from manometric methods and liquid circulation velocity by electromagnetic meters (Bernier and Brennen [11]). Various types of additives like silicone based antifoam, hexanol, pentanol and suspended wettable solids of paper fibers (500 μm rod like) were added to air-tap water system, with various concentrations (Table 1). The volumes of the gas-liquid separators in both columns were changed by changing the volume of the liquid level in them at zero gas input (Table 2). Schematic diagram of the experimental setup is shown in Fig. 2.

The time-dependent gas hydrodynamics variation could be related to the quality of the liquid or gas used in the experimental runs. Tap water is the most widely used liquid in two-phase studies. It is a complex mixture consisting of many components. Most o the components exist in very small concentrations, some of which are too small to detect with common measurement devices. Surfactants may also leach into tap water during storage and/or transportation. For air-tap water system, it has been reported that the gas holdup variation with time could be attributed to coalescence-inhibiting volatile substances, which exists in the tap water at very low concentrations, or to traces of impurities such as oils from compressed air. As the volatile substances evaporate from water, the coalescence-inhibiting ability of the water is continuously reduced, consequently the gas holdup will change continuously with time (Maruyama *et al.* [12], Tang and Heindel [13], Kantarci [14]). To reduce these possible effects of tap water quality and impurities in compressed air on the hydrodynamics of this work, consistent samples of tap water and filtered air were used. Reproducibility of the experimental data of the present work is tested and satisfied by taking three very close results for each run and averaging them. This issue is very serious as scattered experiments in our laboratory revealed significant discrepancy in the results, and need to be considered carefully, especially in large research labs and universities that have many possible uncontrollable daily impurities in the air and water supply systems.

3. Results and Discussion

The hydrodynamics of the air-water and the air-water with additives in the small and large CBCs are presented as a function of the volume ratio, T_{VR}, scale-up factor, A_D/A_R, and additives concentrations, x. The initial liquid level in the gas separator at zero gas throughput is used to calculate the volume ratio T_{VR}:

$$T_{VR} = \frac{Z_L \; W \; L}{V_R} \tag{1}$$

For each experimental run, seven different volume ratios were used. In plotting the independent hydrodynamics parameter ε_{GR}, ε_{GD} or U_{LR} as a function of U_{GR} and T_{VR}, there are seven resulting curves behave in three different groups. The first group at T_{VR}=0 and this resembles one T_{VR} curve. The second group at $T_{VR}=T_{VRC}$ and this resembles also one T_{VR} curve. The third group at $T_{VR}=T_{VRO}$ and this resembles five T_{VR} curves, usually in top of each other. Also, there are two scale-up factors, A_D/A_R, four additives types, and three concentrations for each additive, were used in this work. All of these give enormous amounts of data need to be presented graphically in a clear and precise style. For the sake of clarity and space, the changes of the independent hydrodynamics parameters with T_{VR} are shown at the highest additive concentration, as the trend in behavior at the lower concentrations is the same.

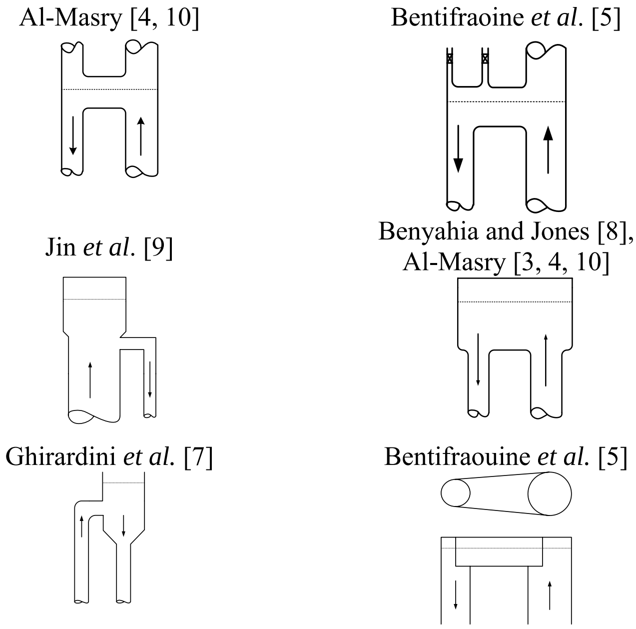
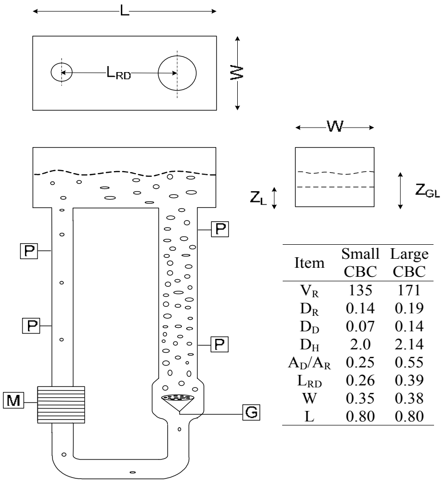


Fig. 1. Variations of external loop CBC gas separators.



Item	Small CBC	Large CBC
V_R	135	171
D_R	0.14	0.19
D_D	0.07	0.14
D_H	2.0	2.14
A_D/A_R	0.25	0.55
L_{RD}	0.26	0.39
W	0.35	0.38
L	0.80	0.80

Fig. 2. Schematic diagram of the experimental setup: G: gas input, P: pressure tappings, M: magnetic flowmeter.

Table 1. Concentration of additives used

System	Additive	x, ppm	σ, mN/m
Air-tap water	Nil	-	72
Air-tap water	Antifoam	10	54.7
		50	45.2
		100	39.2
Air-tap water	Hexanol	10	60
		50	51.1
		100	46.7
Air-tap water	n-pentanol	10	57
		50	52.7
		100	44.3
Air-tap water	Paper fibers	0.05 wt%	49.4
		0.1 wt%	45.7
		0.2 wt%	44

Table 2. Volume ratios used

Z_L, m	T_{VR} %, small CBC	T_{VR} %, large CBC
0.0	0	0
0.05	7	18
0.1	11	30
0.15	19	40
0.20	23	47
0.25	32	52
0.30	37	57

3.1. Air-water system

Riser and downcomer gas holdups data are shown in Figs. 3 and 4, respectively. Generally, gas holdup increases with superficial gas velocity, and decreases with T_{VR} and A_D/A_R. It is clear that the gas holdups, at $A_D/A_R=0.55$, for all the seven changes made in the liquid height Z_L, have lower values than those shown at $A_D/A_R=0.25$. The same behavior is repeated for the downcomer gas holdup, with almost complete gas separation at $A_D/A_R=0.55$, giving indication of better scale-up factor. Effect of T_{VR} on liquid circulation velocity is shown in Fig. 5. Generally, liquid circulation increases with superficial gas velocity and T_{VR}, while it decreases with A_D/A_R. The effect of T_{VR} on liquid circulation velocity resulted in similar trends to those given by the gas holdup except the order is reversed; i.e. starting with $T_{VR}=0$ and increasing to $T_{VR}= T_{VRO}$. At $T_{VR}=0$, the CBC operates in two modes. Firstly, the liquid velocity is zero in the downcomer, because the level in the gas separator is not high enough to establish continuity and circulation, therefore the CBC operates in a mode similar to bubble columns with the downcomer leg not functioning. When the superficial gas velocity

U_{GR} is increased in the riser to a transitional superficial gas velocity U_{GRT}, the two-phase volume in the riser increases leading to the increase of the two-phase volume in the gas separator, and the liquid continuity re-establishes and circulation begins. At zero liquid level in the gas separator (T_{VR}=0), the gas separator gives the lowest gas separation. When the liquid level is increased to intermediate critical value, the gas separator operates at its critical state (T_{VR}=T_{VRC}) giving improvement in gas separation, yet not the optimum. Finally, when the liquid level increases to its optimum value, the gas separator acts at its full capacity (T_{VR}=T_{VRO}) giving the maximum separation efficiency at that particular geometry. Thus, the optimum operating parameters are T_{VRO}=11% at Z_L=0.1 m at A_D/A_R=0.25, and T_{VRO}=30% at Z_L=0.1 m at A_D/A_R=0.55. The trends obtained here were similarly reported for Newtonian viscous air-glycerol systems in external loop CBCs by Al-Masry [3, 10]. The reported optimum operating parameters for foaming air-glycerol systems were then, T_{VRO}=23% at Z_L=0.2 m at A_D/A_R=0.25, and T_{VRO}=52% at Z_L=0.32 m at A_D/A_R=0.55. Jin *et al.* [9] reported effect of A_D/A_R on external loop CBCs hydrodynamics. The authors found that D_D/D_R of 0.7 (A_D/A_R=0.5) and height of liquid in the gas separator of Z_L=0.2 m to be the best geometry and operating parameters to achieve high aeration and mixing efficiency for high viscous broth system in cultivation of filamentous fungi. Although the results reported by Jin *et al.* [9] were for 13 dm^3 small bench scale CBC, they agree very well with the results of this work.

3.2. Surface active agents

The results of the additives will be presented only at Z_L=0, Z_L=Z_{LC} and Z_L=Z_{LO} for clarity of graphical presentations. Effect of T_{VR} on the riser gas holdup in the presence of additives is shown in Fig. 6. Figure 6A shows riser gas holdup in the presence of 100 ppm antifoam, Fig. 6B shows riser gas holdup in the presence of 100 ppm hexanol, and Fig. 6C shows riser gas holdup in presence of 100 ppm pentanol. Generally, increasing A_D/A_R and T_{VR} reduces the gas holdup in the riser. The amount of gas holdup produced using hexanol and pentanol additives are higher than the gas holdup resulted from antifoam addition. For the small CBC (A_D/A_R=0.25) and large CBC (A_D/A_R=0.55), the general trend of the effect of T_{VR} on the hydrodynamics of air-water system is repeated here in Fig. 6. This means that when the liquid volume in the gas separator reaches its optimum value T_{VRO}, increasing it any further produces no more positive effects. Therefore, at T_{VRO} and any additive concentration, all the five T_{VR} curves are averaged, and plotted in Fig. 7 for each concentration, to show the effect of additives concentrations on riser gas holdup. Figure 7A shows the effect of antifoam concentration in the small and large CBC. There is no significant influence of concentration of the antifoam agent is observed. Antifoam agents tend to enhance the bubble coalescence, and therefore, bubble size. As a result, gas holdup is lowered due to the higher slip velocity of large bubbles in the presence of an antifoam agent compared with that in its absence. Alcohols addition showed different behavior than the antifoam.

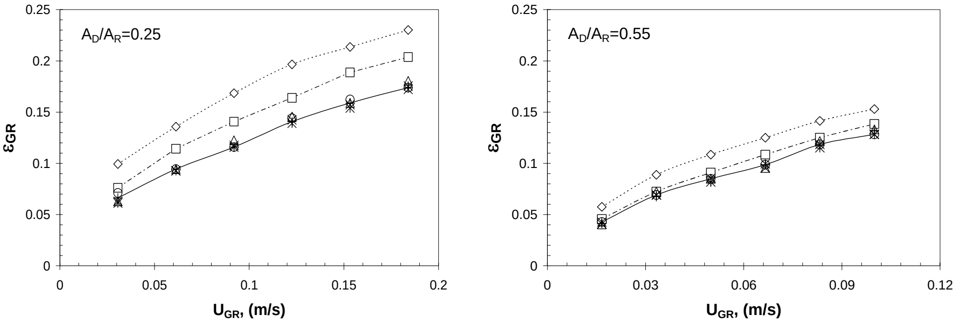


Fig. 3. Effect of T_{VR} on riser gas holdup with tap water, ◊: Z_{L1}, □: Z_{L2}, Δ: Z_{L3}, ×: Z_{L4}, *: Z_{L5}, O: Z_{L6}, +: Z_{L7}.

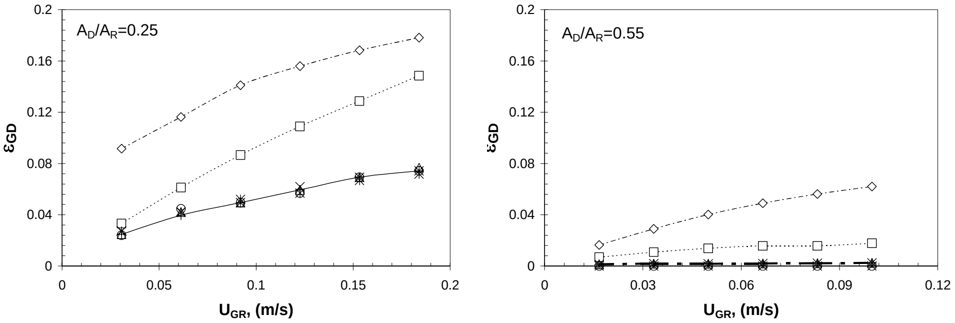


Fig. 4. Effect of T_{VR} on downcomer gas holdup with tap water, ◊: Z_{L1}, □: Z_{L2}, Δ: Z_{L3}, ×: Z_{L4}, *: Z_{L5}, O: Z_{L6}, +: Z_{L7}.

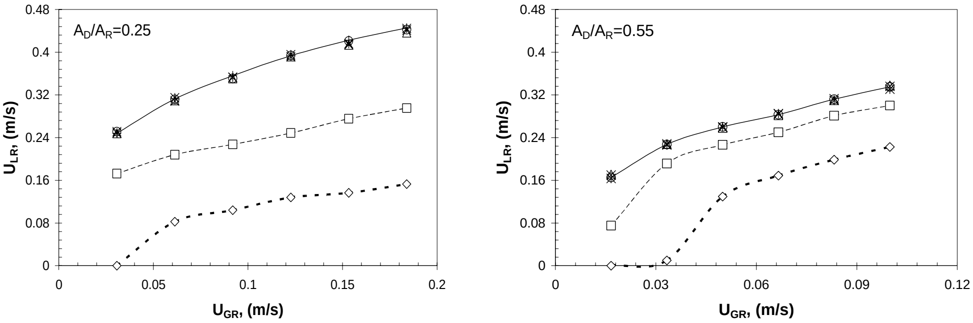


Fig. 5. Effect of T_{VR} on liquid circulation velocity with tap water, ◊: Z_{L1}, □: Z_{L2}, Δ: Z_{L3}, ×: Z_{L4}, *: Z_{L5}, O: Z_{L6}, +: Z_{L7}.

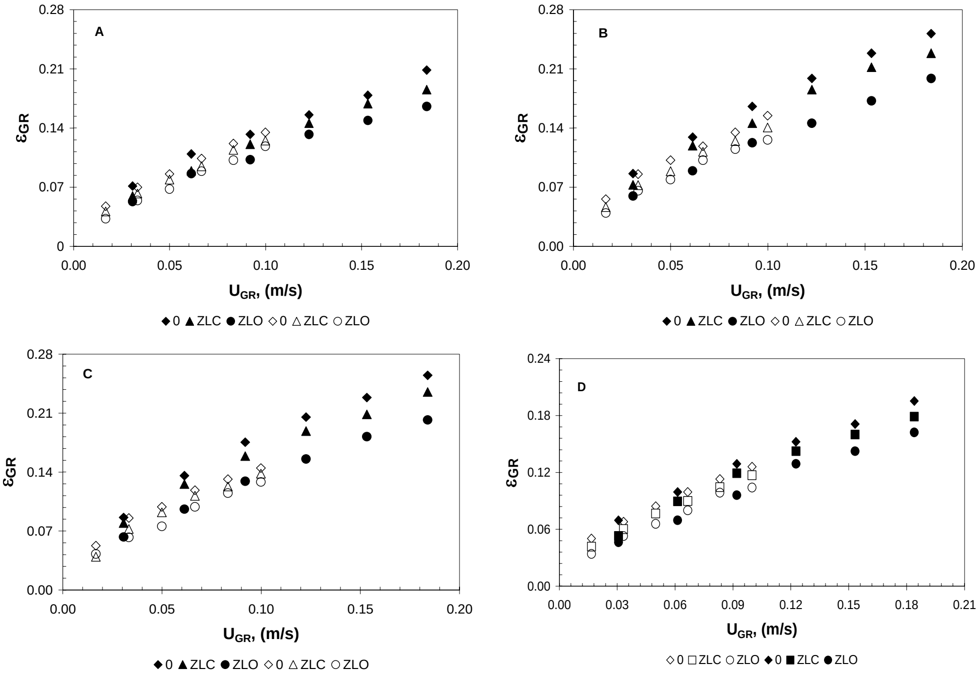


Fig. 6. Effect of T_{VR} on riser gas holdup. A antifoam, B hexanol, C pentanol, D paper fibers. A_D/A_R=0.25 filled symbols, A_D/A_R=0.55 unfilled symbols.

Figures 7B and 7C show the effect of hexanol and pentanol concentration on riser gas holdup. The effect of alcohols concentration on gas holdup is clear, leading to increase in gas holdup with the increase in the concentration. At A_D/A_R=0.25 and T_{VRO}, increasing U_{GR} leads to an increase in gas holdup. This is attributed to the excess of gas bubbles generated in the riser, as well as the increase of gas recirculation in the downcomer, which contributes to the total gas input in the riser. With pentanol there is a clear increase of riser gas holdup at A_D/A_R=0.25 compared to tap water as seen in Fig. 7C. At A_D/A_R=0.55 and T_{VRO} the gas holdup is higher than tap water for both alcohols used, as seen in Fig. 7B and Fig. 7C, with clear trend of gas holdup increase with concentration. The amount of riser gas holdup increase with alcohol addition is usually higher in bubble columns, internal loop CBC and external loop CBC with closed channel gas separators, than those generated in CBCs with open channel gas separators (Al-Masry and Dukkan [4], El Azher *et al.* [15]. In fact, the gas holdup increase or reduction due to antifoam or alcohols addition as well as variation with concentration cannot be satisfactorily explained by differences between characteristics physical properties of dispersions (surface tension) which was almost identical. This phenomenon could be possibly quantitatively explained by variables such as dynamic surface tension and/or surface viscosity. The surfactants tend to accumulate at the bubble surface and create surface tension gradient that cause tangential stresses along the bubble surface. These stresses retard surface motion, internal circulation within the bubble, and the rise velocity of the bubbles. The addition of surfactant increases the gas holdup due to enhancement of the non-coalescing tendency of the bubbles. [Koide *et al.* [16], Zahradnik *et al.* [17]]. Malysa *et al.* [18] conducted extensive studies on bubble motion in pure water and solutions of various surface active substances using square column with capillary at the bottom. The authors used high speed CCD cameras to monitor bubble motion within the column and during collision with the gas-liquid interface at top of the column. It has been shown that the presence of surface active substances, like n-butanol, n-octanoic acid and α-terpineol, has a profound influence on values of terminal velocity and local velocity. The bubble terminal velocity decreased rapidly at low surfactant concentration, but there can be found some characteristics concentrations above which the velocity almost stopped to decrease. Immobilization of the bubble surface resulting from adsorption of the surface active substances (surface tension gradient inducement) caused over twofold lowering of the bubble velocity. The findings by Malysa *et al.* [18] substantiate our results for the surfactants effects on gas holdup. Zahradink *et al.* [19] showed that the coalescence behavior in gas-liquid systems containing aliphatic alcohols C_1-C_8 can be appropriately characterized by the coalescence ratio, ψ. The coalescence ratio expresses the extent of coalescence in a given-liquid system and determined under model condition simulating contact of two isolated bubbles in a pseudo-infinite medium. In a coalescence cell, the coalescence ratio is obtained as the number of a coalescing bubble pair. Values of the transition concentration, c_t, defined as the concentration corresponding to 50% coalescence were determined for all alcohols from the graph ψ vs. c, showing dependence of coalescence ratio on the concentration of additives. The authors found for C_1-C_8 alcohols, that transition from 100% of the bubble pair coalescence to complete coalescence suppression was in all cases very sharp and occurred within a narrow concentration range. The transition concentration was found $2.5\text{x}10^{-4}$ and $5.5\text{x}10^{-5}$ kmol/m^3 for pentanol and hexanol, respectively. Values for transitional concentration exhibited significant decrease with increasing length of carbon chain, and well described by:

$$c_t = 31 n_c^{-7.2} \tag{2}$$

In the present work, the 10 ppm ($1.134\text{x}10^{-4}$ kmol/m^3) pentanol aqueous solution is less than the critical concentration, c_t, given by Eq. (2), while the other concentrations for pentanol and hexanol are larger than the critical concentrations for coalescence suppression. From the gas holdup graphs the trend in general is that at lower concentration of pentanol and hexanol, the gas holdup is closer to the coalescence of tap water, and then increases with increasing alcohol concentration.

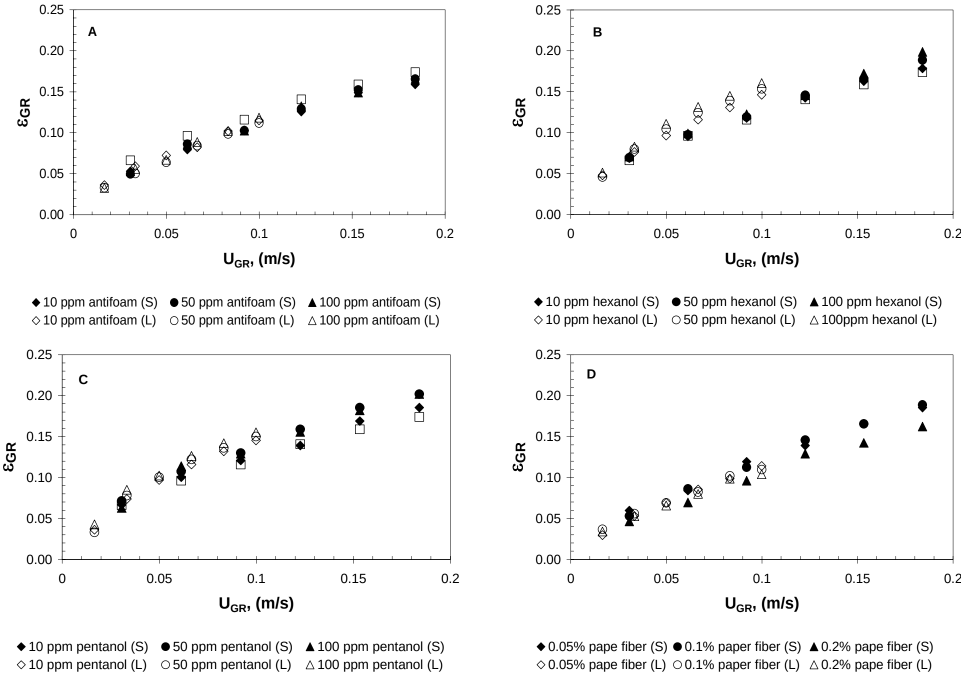


Fig. 7. Effect of additives concentration on riser gas holdup at T_{VRO}. A antifoam, B hexanol, C pentanol, D paper fibers. A_D/A_R=0.25 filled symbols, A_D/A_R=0.55 unfilled symbols.

Effects of T_{VR} on downcomer gas holdup are shown in Fig. 8. The trend is that increasing T_{VR} reduces downcomer gas holdup. Figure 8A shows the downcomer gas holdup with antifoam. The gas recirculation with antifoam at A_D/A_R=0.55 reduces almost to nil at T_{VRO}. Figures 8B and 8C show downcomer gas holdup with hexanol and n-pentanol, respectively. There is slight gas recirculation at T_{VRO} with these surfactant as expected, since the bubbles rise velocity are less than tap water. The trends of the curves are the same as the trends explained earlier for air-water system. It is clear that at A_D/A_R =0.55, the downcomer gas holdup has lower values than those shown at A_D/A_R =0.25, indicating a very good separation of gas bubbles at the top of the column in the presence of surface active agents with increasing downcomer to riser diameters ratio. The effects of surface active agents concentration on downcomer gas holdup are shown in Fig. 9. Downcomer gas holdup for alcohols has small but systematic increase with concentration of alcohols as seen in Figs. 9B and 9C. However, for the antifoam, the concentration effect is not clear.

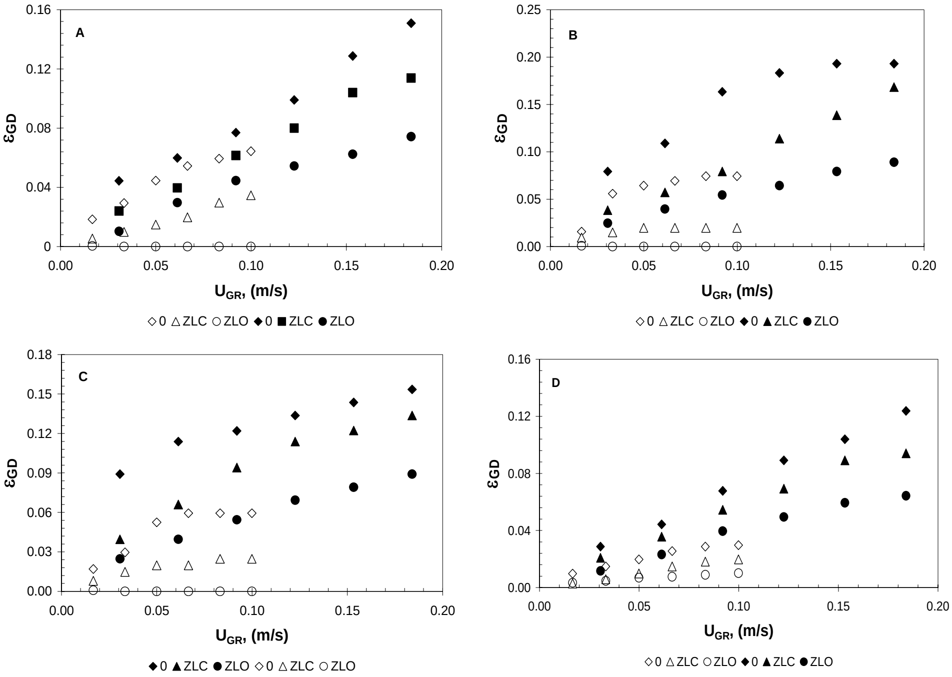


Fig. 8. Effect of TVR on downcomer gas holdup. A antifoam, B hexanol, C pentanol, D paper fibers. A_D/A_R=0.25 filled symbols, A_D/A_R=0.55 unfilled symbols.

Effect of T_{VR} on liquid circulation velocity are shown in Fig. 10. The trends are similar to the general trends demonstrated earlier in air-water system. At T_{VR}=0, the transitional superficial gas velocity U_{GRT} for the 100 ppm antifoam (Fig. 10A) in the small and large CBCs was ≈ 0.06 m/s. For hexanol (Fig. 10B) and pentanol (Fig. 10C), U_{GRT} at T_{VR}=0 had lower values of 0.03 m/s and 0.05 m/s for the small CBC and large CBC, respectively. These results are expected since with the antifoam the bubble velocity is higher than the bubble velocity in the surfactant solutions, leading to higher superficial gas velocity in the riser needed to force the circulation with the antifoam, than with the surfactants. The effect of surface active substances concentrations on liquid circulation are shown in Fig. 11. The tap water has slightly lower U_{LR} with the antifoam for both CBCs used. With the surfactants used, at lower concentration and A_D/A_R=0.25, U_{LR} is lower than the tap water. Increasing the surfactant concentration leads to an increase in U_{LR} approaching the tap water. This can be explained by the decrease in the circulation driving force given by:

$$\frac{\Delta P}{\rho\, g\, H_D} = \varepsilon_{GR} - \varepsilon_{GD} \tag{3}$$

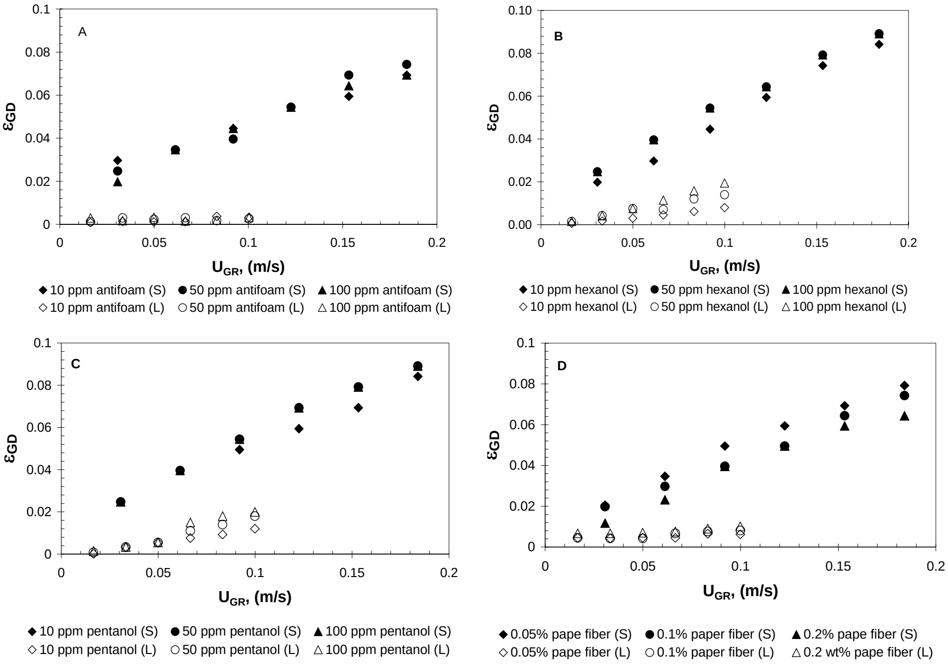


Fig. 9. Effect of additives concentration on downcomer gas holdup at T_{VRO}. A antifoam, B hexanol, C pentanol, D paper fibers. A_D/A_R=0.25 filled symbols, A_D/A_R=0.55 unfilled symbols.

3.3. Suspended solids

Wettable solid particles of paper fibers were used as a solid phase and added to the air-tap water at three different concentrations. Effect of T_{VR} on gas holdup are shown in Fig. 6D. Again the general trend of the effect of T_{VR} on riser gas holdup is repeated here, with notice of lower holdup values at T_{VRC} compared to the surface active agents results. The gas holdup decreases with increase of A_D/A_R. Figure 8D shows the effects of T_{VR} on downcomer gas holdup, with very clear reduction of gas holdup with increase of A_D/A_R, and optimum gas separation at A_D/A_R=0.55. Liquid circulation velocity is shown in Fig. 10D. At T_{VRO}, liquid circulation reduces with increasing A_D/A_R. The effect of paper fibers concentration on riser gas holdup are shown in Fig. 7D. At A_D/A_R=0.25, there is a clear reduction of gas holdup with concentration, while the lower concentrations approaches the tap water values. Figure 9D show the downcomer gas holdup at T_{VRO}. For the small CBC, the gas holdup in the downcomer decreases with increasing concentration. Increasing the scale-up factor to 0.55 resulted in a significant reduction of gas bubbles recirculation in the downcomer. It is generally reported that the addition of solids to a two-phase systems decreases the holdup. Also, several researchers concluded that an increase in solids concentration generally reduced gas holdup (Li and Prakash [20], Pino *et al.* [21], Krishna *et al.* [22], van Benthum *et al.* [23]). Figure 11D shows the liquid circulation as a function of T_{VRO}. The general trend is reduction of liquid velocity with addition of solid fibers.

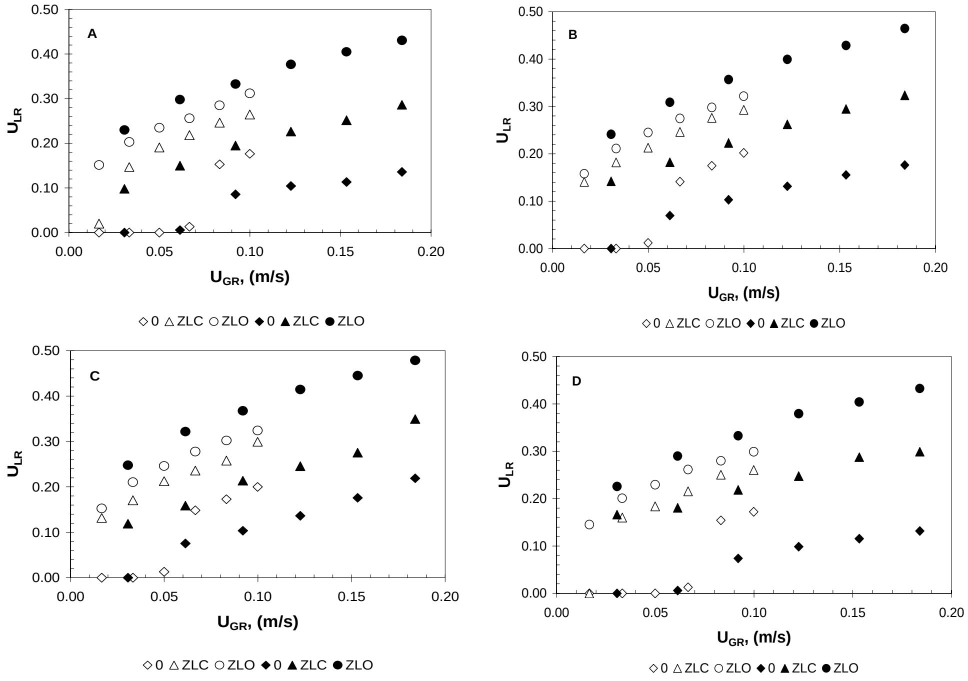


Fig. 10. Effect of T_{VR} on circulation velocity. A antifoam, B hexanol, C pentanol, D paper fibers. A_D/A_R=0.25 filled symbols, A_D/A_R=0.55 unfilled symbols.

4. Conclusions

Extensive and systematic experimental program has been conducted in our multiphase laboratory to elucidate the hydrodynamics of external loop circulating bubble columns with open channel gas separators in the presence of additives like surface active substances and wettable suspended solids. Open channel gas liquid separators play a significant role on improving the hydrodynamics of external loop CBCs. They have excellent characteristics in comparison with other types of gas separators such as closed channel or internal loop CBC without separators. In the presence of various types of additives, there is always an optimum volume of liquid in the gas separator, so that the entrapment of gas bubbles into the downcomer is minimized. The effect of increasing scale-up factor on the hydrodynamics was found to improve the CBCs performance in the presence of surface active substances and in the presence of light suspended wettable solids. The presence of antifoam and surfactants affected significantly the driving force for liquid circulation. The results presented here augment our earlier work for viscous Newtonian air-glycerol systems. The present work together with the previous work (Al-Masry [3, 10]) provide for the first time complete and comprehensive data on the effects of T_{VR} and A_D/A_R on the hydrodynamics of external loop CBCs with open channel gas separator with various media and additives. All these data are now being further analyzed in our multiphase laboratory using computational fluid dynamics CFD techniques to provide better design parameters for CBCs.

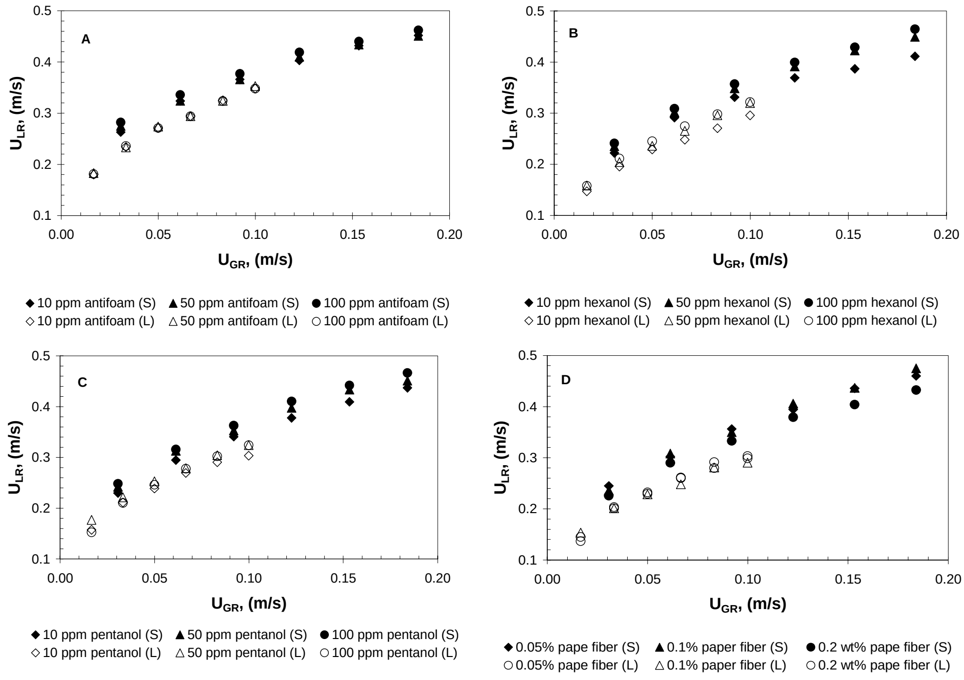


Fig. 11. Effect of additives concentration on liquid circulation velocitty at T_{VRO}. A antifoam, B hexanol, C pentanol, D paper fibers. A_D/A_R=0.25 filled symbols, A_D/A_R=0.55 unfilled symbols.

5. Notations

A_D	down comer cross-sectional area, (m^2)
A_R	riser cross-sectional area, (m^2)
c	concentration, ($kmol/m^3$)
c_t	critical concentration, ($kmol/m^3$)
D_D	downcomer diameter, (m)
D_R	riser diameter, (m)
H_D	height of dispersion, (m)
L	length of gas separator, (m)
L_{RD}	centerline distance between riser and downcomer, (m)
n_c	number of carbon atoms
T_{VR}	volume ratio
T_{VRC}	critical volume ratio
T_{VRO}	optimum volume ratio
U_{GR}	superficial gas velocity in the riser, (m/s)

U_{LR}	liquid circulation velocity in the riser, (m/s)
V_R	reactor volume, (m^3)
W	width of gas separator, (m)
x	additive concentration, (ppm)
Z_{GL}	height of gas-liquid dispersion in gas separator, (m)
Z_L	height of liquid in gas separator at zero throughput, (m)
ψ	coalescence ratio
σ	surface tension, (Nm^{-1})
ε_{GD}	downcomer gas hold-up
ε_{GR}	riser gas hold-up

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تأثير عوامل التصميم والتشغيل على هيدروديناميكية أعمدة الفقاعات الدوارة ذات فواصل الغاز المفتوحة

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ملخص البحث. تم معمليا دراسة هيدروديناميكية أعمدة الفقاعات الدوارة ذات فواصل الغاز المفتوحة. عملت الدراسات الهيدروديناميكية تحت تأثير ثلاثة عوامل للتشغيل وعامل واحد للتصميم. عوامل التشغيل الثلاثة هي سرعة الغاز السطحية في العمود الصاعد U_{GR} وخاصية الانتشار الغازي مع السائل σ وكفاءة فاصل الغاز T_{VR}، أما عامل التصميم فكان عامل التكبير من حيث مساحة مقطع العمود الهابط إلى العمود الصاعد A_D/A_R. تم تغيير قيم وخاصية الانتشار الغازي مع السائل باستخدام محاليل ذات تراكيز مختلفة من مضادات الرغوة والأغوال ومواد صلبة معلقة مبتلة. تم عمل جميع التجارب باستخدام الماء والغاز المضغوط من نظام الإمداد العام في الجامعة. تم تقليل تأثير تغير العوامل الهيدروديناميكية المتعلقة بنوعية الهواء-الماء عن طريق استخدام عينات متناسقة من أجل الحصول على نتائج ممكنة الإعادة. وضحت النتائج لأي نظام مكون من الغاز-السائل-مادة مضافة أن هناك قيمة مثلى لحجم السائل في فاصل الغاز T_{VRO} التي تعطي أقل قيمة لإعادة تدوير الغاز في العمود الهابط ε_{GD}. عند أي قيمة لـ A_D/A_R و T_{VR} وجد أن تأثير مضاد الرغوة والجسيمات الصلبة المعلقة المبتلة يقلل من الكسر الغازي، بينما وجود الأغوال يزيد الكسر الغازي. عند T_{VRO} فإن كفاءة فاصل الغاز تتحسن بشدة عند زيادة معامل التكبير A_D/A_R. سرعة تدوير السائل زادت في وجود مضاد الرغوة ولكنها قلت في وجود الجسيمات الصلبة. لقد وجد أن ظروف التشغيل والتصميم كانت أحسن عند معامل التكبير $A_D/A_R=0.55$ ونسبة الحجم $T_{VR}>20\%$ من التي وجدت عند $A_D/A_R=0.25$ وذلك لجميع المواد المضافة التي استخدمت.