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Hydrodynamic and RTD of Sectionalized Bubble Column

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HYDRODYNAMICS AND RTD OF SECTIONALIZED BUBBLE COLUMN

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ABSTRACT

The sectionalization of conventional bubble columns to tray partitioned bubble column using perforated trays has been used to investigate the effect of tray hole diameter, tray open area, superficial gas velocity, gas sparger design, and liquid phase properties on gas holdup, residence time distribution (RTD), and overall liquid-phase backmixing. The erected column is sectionalized into three stages using two perforated plates of different holes diameter and open free area. Overall gas holdup is measured experimentally by bed expansion technique. Liquid backmixing, mixing time and axial dispersion model (ADM) is determined using tracer response experiments. In general, it seems that the partitioned trays are significantly increases the overall gas holdup. Tray holes diameter and superficial gas velocity are found to be the most important factors on gas holdup. Axial mixing of the liquid phase is numerously reduced by the presence of partitioned trays. Comparison of the results with the published data of other authors indicates good agreement which enforced the reliability and confidentiality of computational procedure to be used for design and scale-up purposes.

INTRODUCTION

The first suggestion of the addition of perforated trays into conventional single stage bubble column is made by Schugerl et al., (1977) (1) to reduce the liquid phase backmixing and hence to increase process efficiency, especially in biological fermentation process. At the time, Kato et al., (1984) (2) investigate the effect of stage height, superficial gas and liquid velocities, and column diameter on the overall gas holdup in a gas-liquid co-current tray bubble column, Nishikawa et al., (1985) (3) report that a decrease of 40 % in the tray hole diameter yield an increase of up to 5 % in gas holdup. Chen et al., (1986) (4) study two types of plates in two different co-current tray partitioned bubble columns; the Karr tray design with 53% of open area, and a perforated plate made of mesh screen with 64% open area. Once more but now Chen et al., (1989) (5), investigate the overall gas holdup for various gas-liquid systems in both batch and co-current upward multistage units, whereas, Yang et al., (1989) (6), correlate the experimental overall gas holdup in a co-current upward tray partitioned bubble column with both the superficial gas and liquid velocities using slip velocity concept at low values of superficial gas velocities. Yamashita (1993) (7) investigates the effects of partitioned plates and gas layers on gas holdup in bubble column with and without a draught tube. Whereas, Yamada et al., (1998) (8) studies the effect of superficial gas and liquid velocities, stage height, and catalyst weight in a gas-liquid-liquid-solid (G-L-L-S) co-current bubble partitioned column. Kemoun et al., (2001) (9) works on the effect of sieve trays on the time-average gas holdup profiles and the overall gas holdup in a cold-flow bubble column. Dreher et al., (2001) (10) after his study on the influence of partitioned plate on liquid-phase backmixing in different diameters columns 10, 15, and 38 cm and different superficial gas velocities 0.05 – 0.4 m/s, they estimate the liquid circulation velocity in bubble columns without trays of about one order of magnitude higher than in tray partitioned bubble columns sectionalized by perforated trays of 18.6% open area, besides, they report that the axial dispersion coefficient increases with tray open area, whereas, column diameter has shown insignificant effect on liquid backmixing. Recent literature of VanBaten et al., (2003) (11) report the independence of superficial liquid exchange velocity, U_{ex}, at the partition plate on column diameter, and its dependence on the open area of the partition plates, they also report the significant dependence of the height of the gas cap beneath the partition plates on column diameter. In so condensed study, Pandit et al. (2005) (12) examine the mixing time in the sectionalized bubble column over a wide range of superficial gas velocity, liquid height to column diameter ratio, percent free area of sectionalizing plates and electrolyte concentration for air-water system. At the same time, Doshi et al., (2005) (13) report the effect of the internals and sparger design on mixing time and fractional gas holdup in the sectionalized bubble column over a wide range of superficial gas velocity, liquid height to column diameter ratio, percent open area of sectionalizing plates and electrolyte concentration for air-water system. Recently, Alvare et al., (2006 a) (14) reports the effect of tray geometry and operating conditions on the overall gas holdup in co-current tray partitioned bubble column. In their study it seems that the tray holes diameter plays a more important role than total open area on the gas holdup. Once more, Alvare et al., (2006 b) (15) study the effect of tray design and operating conditions on the overall liquid mixing in a bench-scale tray partitioned bubble column. Among the other authors only Alvare et al., (2006 a, b) (14, 15) takes into his consideration the effect of tray design on gas holdup and liquid backmixing, therefore, this work will also fill the current gap that exists in available information of the design and scale-up of batch tray partitioned bubble column.

EXPERIMENTAL

A batch tray partitioned bubble column setup is erected as schematically shown in Fig. (1). The column consists of three intermediate sections of 10 cm ID and 54 cm height and a bottom (plenum) section of 45 cm height, all made of PVC. To erect a three-stage setup unit, two trays are mounted. To study the effect of tray designation on gas holdup and axial dispersion coefficient, five types of trays are employed as shown in Fig (2). In order to study the effect of the design parameters of the gas distributing system (gas sparger), two different designations have been used; these are a 10 mm diameter single point nozzle, and a perforated plate with 1 mm hole diameter, 55 holes, and 0.6 % of total open area. Measurements of (RTD) are carried out by an electrical conductivity meter linked to a personal computer. The experimental work is divided into two routes; first route studied the effect of hydrodynamic in a conventional bubble column and sectionalized bubble column on overall gas holdup and transition flow regime; whereas the second route studied the axial dispersion and mixing time in both conventional bubble column and sectionalized bubble column. All experiments are performed at atmospheric pressure and room temperature. For attaining high level of reliability, each experiment has been repeated three times and average results are considered. Residence time distribution (RTD) of the liquid phase is measured using tracing amounts of saturated solution of NaCl. Different volumes of tracer are used to obtain the optimal amount of tracer that corresponds to optimal signal within the range of conductivity cell. This optimal amount of a saturated solution of NaCl is found equal to 3.38 wt %. The conductivity probes used in this work was manufactured by Philips Company, of dimensions 1 cm diameter and 15 cm long. They simply consist of two electrodes, erected approximately 3 mm apart, and encapsulated in plastic tube. The probes are properly calibrated by measuring their responses to solutions of known tracer concentrations. Time for each experiment has been chosen large enough in order to reach the final concentration in the column. According to Pandit et al., (2005) (12) the mixing time was calculated from measuring the conductivity of the slowest response of the probe that located at the bottom section of the column, where timing of 95% homogeneity is recorded. Figure (3) shows the typical conductivity responses from three installed probes, herein, the straight line represents the simulated results from solving the equations of the reactor model which based on gas mixing model that initially proposed by Gupta et al., (2001) (16). Thereof, a differential element along the reactor length in the developed part of the flow is regarded to consist of four zones into which the reactor cross-section is compartmentalized which results in a coupled set of four PDEs and four ODEs.

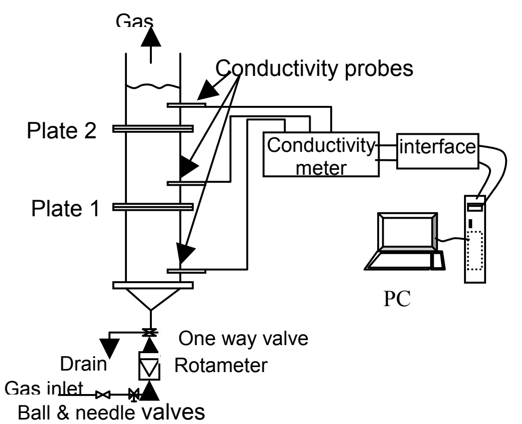

Fig (1) Schematic diagram of the experimental setup

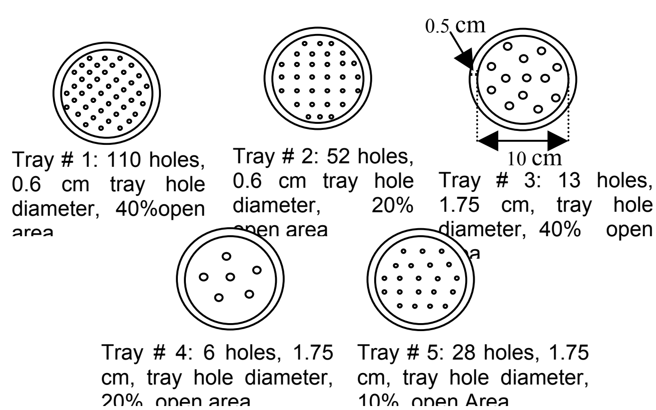

Fig (2) Designations of partitioned plates

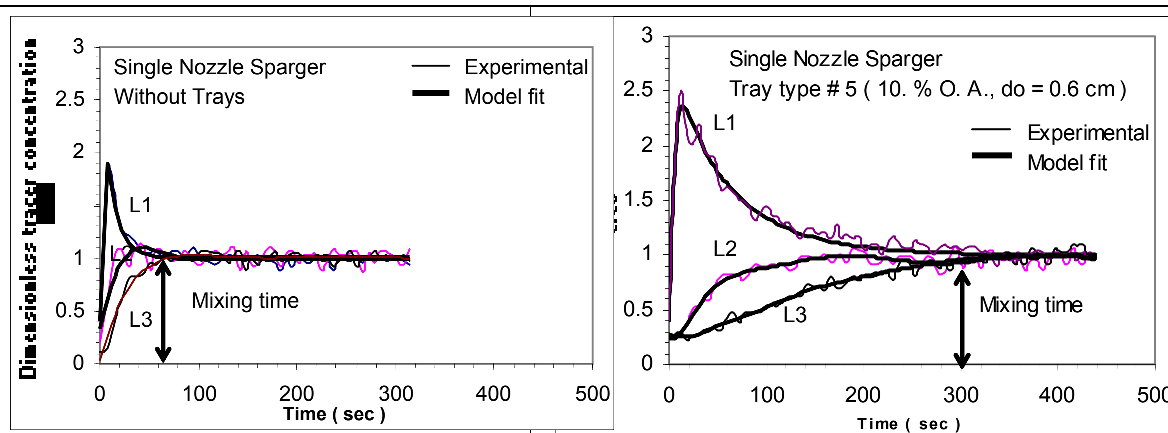

Fig (3) Simulated and measured conductivity responses

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RESULTS AND DISCUSSIONS

For the estimation of the overall gas holdup, according to bed expansion technique, the overall gas holdup is determined by measuring the heights of the dispersed phase at 131-173 cm that corresponds to initial and dynamic liquid heights respectively. According to these two heights, the overall gas holdup is calculated by using ($\varepsilon_g = \frac{H_d - H_o}{H_d}$). Figures (4) and (5) shows the overall gas holdup versus the superficial gas velocity, U_g, of air-water and air-NaCl solution systems, respectively, in a single stage bubble column and tray partitioned bubble column of different tray types where single nozzle sparger is used. Meanwhile, the effect of perforated plate sparger is shown in Fig. (6). It depicts the overall gas hold up against the superficial gas velocity U_g in single stage and different tray type's partitioned column using air-water system. In all mentioned figures, two different regions are recognized. At low superficial gas velocity region (Ug < 4-6 cm/s), which is known as bubbly flow regime, almost a linear relationship between superficial gas velocity and gas holdup is established. Seemingly, tray types shows little influence on gas holdup, as the holes diameter is larger than the average bubble size diameter, that lead to easy swift of gas bubbles through the holes tray. Therefore, the overall gas holdup is highly recommended to obey the following type of dependence ($\varepsilon_g \; \alpha \; U_g^n$). At higher gas velocity, the gas-liquid flow induces more turbulence where hydrodynamic properties of the system are radically changed, in this flow regime, which is known as churn-turbulent flow regime, bubbles induces a wide distribution of sizes, shapes, and rise velocities, where almost no longer linear relationship between gas holdup and superficial gas velocity exists. It is in this turbulent region where the introduction of perforated trays inside the column increasingly affects the overall gas holdup in comparison with single stage bubble column. The redistribution of the gas phase by trays helps to re-adjust the bubble size and reduce the bubble coalescence and break-up. Also, the competition between the gas and the liquid phases to move across the trays enhance the overall staging effect of the gas in the column, which subsequently increases their residence time. The exact determination of regime transition in bubble columns is still an open issue, although many approaches such as frequency and chaos analysis of Letzel et al., (1997) (17) were suggested, none of them can still unequivocally predict the transition, however, a good approximation can be obtained by plotting ε_g versus U_g in logarithmic scale. In this type of representation, the data of different regimes would fall into straight lines of different slopes, where the point of their intersection could consider the regime transition superficial gas velocity. Figure (7) clearly shows without no doubt the value of gas velocity transition. Herein, trays enhance the transition from bubbly to turbulent regimes as superficial gas velocities are shifted toward higher values in comparison to single bubble column which is mainly attributed to the redistribution of the gas phase in each tray and consequently helps to redistribute both the bubble size and enhance their rise velocity. The increase in the transition velocity is also observed in air-water and air-NaCl solution as well using single nozzle and perforated plate spargers. Also it is shown that tray hole diameter plays an important role in shifting the transition velocity than does the tray open area since smaller holes partitioned trays enhance the production of smaller bubbles which enforce bubbly regime to occur at larger gas velocities. The nature of gas-liquid system also affect the location of the transition velocity, which are attributed to the action of the electrolyte in reducing the bubble coalescence, and lead to lower average bubble size and higher overall gas holdup. In studying the effect of tray geometry on overall gas holdup especially in turbulent regime, Figs (4, 5 and 6) clarify the existence of a significant increase in the fractional gas hold-up as a result of sectionalization due to re-breakage of the bubbles, which reduces the average bubble size, and in return increases the fractional gas hold-up, in addition to the formation of gas pockets below each sectionalizing plate which are proportionally related to U_g, even though, these gas pockets are not in dispersed form, but still they contributes their existence to the observed increase in H_d, (higher ε_g). It seems from Figs (4), (5), and (6), that tray type #3 (40 % O. A., d_o = 1.75 cm) and type #4 (20 % O. A., d_o = 1.75 cm) shows lower overall gas holdup than tray type #2 (20 % O. A., d_o = 0.6 cm), and type #1 (40 % O. A., d_o = 0.6 cm). In non-coalescing gas-liquid system, the bubble size at each tray is maintained along the stage itself, which clarify the importance of the tray holes diameter for controlling the diameter of the bubble at each tray, whereas in a coalescing medium, the tray hole diameter does not have such a strong effect but still its importance is greater than tray open area. In turbulent regime, it seems that smaller tray open area promotes higher energy dissipation rate but still for trays of equal hole diameters and higher open areas, a larger number of bubbles is formed (i.e., more gas-liquid interfacial area), which counter the increase in overall gas holdup due to energy dissipation effect. This gave a good explanation of what actually happened between tray type #1 (40 % O. A., d_o = 0.6 cm and 110 holes) which gave always slightly higher overall gas holdup than tray type # 2 (20 % O. A., d_o = 0.6 cm and 52 holes). These findings are in good agreement with that of Alvare et al., (2006 a) (14).

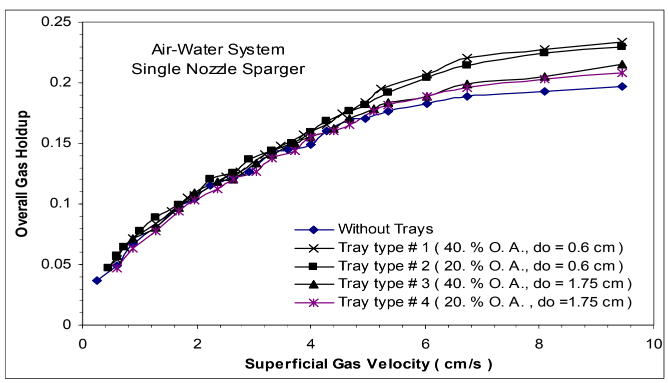

Fig. (4) Overall gas holdup versus superficial gas velocity in single stage and tray partitioned bubble column, air-water system and single nozzle sparger

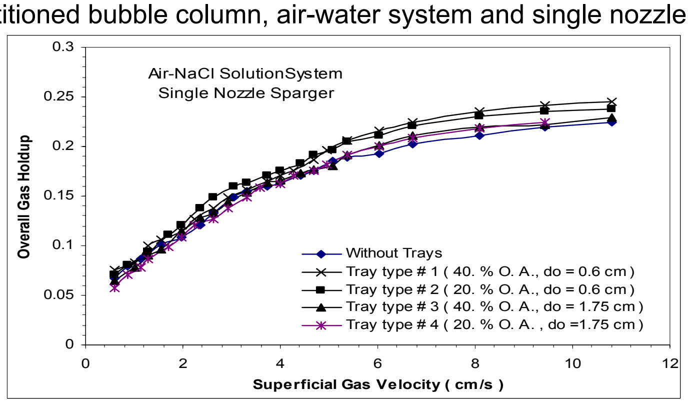

Fig. (5) Overall gas holdup versus superficial gas velocity in single stage and tray partitioned column, air-NaCl salt solution system and single nozzle sparger

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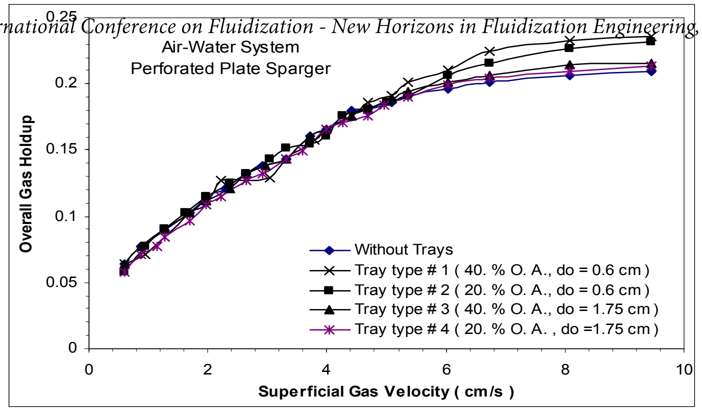

Fig. (6) Overall gas holdup versus superficial gas velocity in single stage and tray partitioned bubble column, air-water system and perforated plate sparger

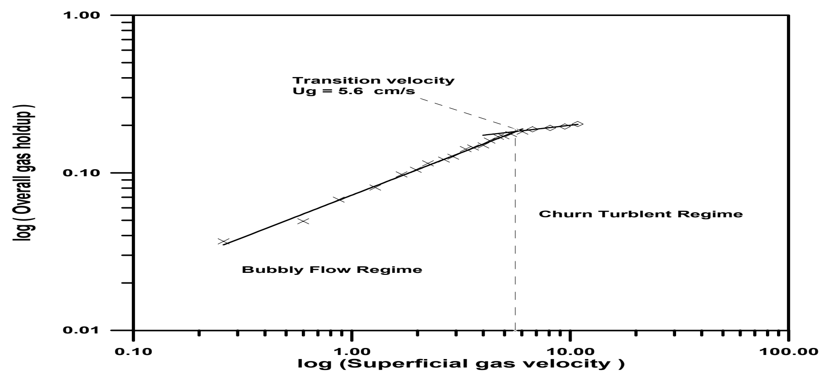

Fig. (7) Logarithmic plot of the overall gas holdup versus superficial gas velocity in single stage bubble column

In order to test the reliability of the developed program using the mechanistic sub-model, a comparisons are made between predicted results of this study, experiment data of Krishna et al., (2001) (18), and CFD simulation results of Krishna et al., (2000) (19), Joshi (1980) (20), Gupta et al., (2001) (16), and Kumar et. al.,(1994) (21). These are shown on Figs (8), (9), and (10). Figures (8) and (9) show the relative performance of three mixing lengths in predicting liquid phase recirculation. In these two figures, the experimental data of Gupta et al., (2001) (16) are extracted using two different columns, 10 cm and 44 cm diameters and two different superficial gas velocity U_g = 12 cm/s, and 10 cm/s respectively. It seems that Nikuradse's mixing length always over-predicts the level of liquid recirculation since the effective turbulent viscosity from his formulation is only a representative of the shear contribution to the total turbulence where no account for the higher turbulence generation and dissipation due to the presence of the bubbles is encountered, thereof, Nikuradse's mixing length for determining the liquid recirculation velocity profile is not recommended. Modifications to Nikuradse's mixing length that could be sought to account for the bubble-induced turbulence, however, the dependence of mixing length on bubble diameter and its velocity fluctuation is not well established as already stated by Geary et al., (1992) (22). Although, Joshi correlation (1980) (20) and Kumar et al., (1994) (21) gave reasonable predictions in comparison to both experimental studied cases by Gupta. However correlation of Kumar et al., (1994) (21) seems to work somehow better. In comparison to the predictions of this study it seems that the good agreements between the predictions of the sub-mechanistic model used in this study with experimental data of Gupta (2001) (16), and Kirshina (2001) (18) and the simulation results of Kirshina (2000) (19) enforce the reliability of the proposed model to be used for design and scale-up purposes.

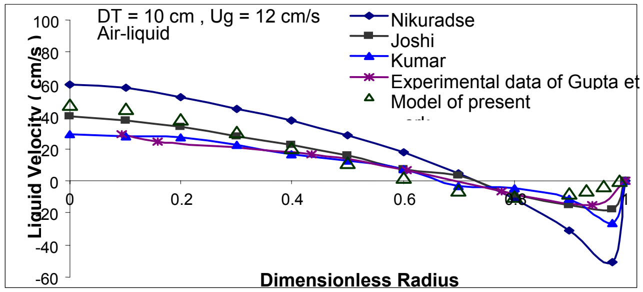

Fig. (8) Effect of mixing length profile on liquid velocity profiles for 10 cm diameter

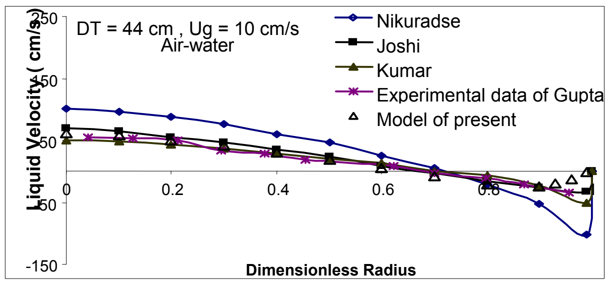

Fig. (9) Effect of mixing length profile on liquid velocity profiles for 44 cm diameter

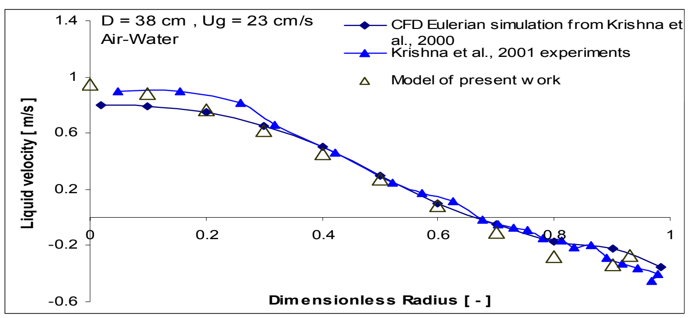

Fig. (10) Comparison between present simulation and experimental results of Krishna et al., (2001) and CFD simulation of Krishna et al., (2000)

CONCLUSIONS

Experimental data had shown significant increase of the overall gas holdup in the presence of partition plates in comparison with conventional bubble column where holes diameter plays an important role in comparison to tray open area which directly related to the bubble size diameter. In addition, it seemed that the transition from bubbly regime to churn-turbulent regime occurs at a larger superficial gas velocity when trays are used. Eventually In tray bubble column, the sparger design shows no effect on the overall gas holdup. Seemingly, the trays had redistributed the gas phase at each stage, and thereby their effect is only noticeable in the first stage.

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NOTATION

C_L	Liquid concentration, kg/m^3	R_x	Reaction rate, kg/m^3.s
C_o	Final concentration, kg/m^3	r'	Radius where the liquid velocity profile inverts
$D_{ax,L}$	Liquid axial dispersion coefficient, m^2/s	r''	Radius where the gas velocity profile inverts
$D_{L,m}$	Molecular diffusivity, m^2/s	U_g	Superficial gas velocity (m/s)
$\overline{D}_{zz}$	Average axial turbulent eddy diffusivity, m^2/s	U_L	Superficial liquid velocity (m/s)
$\overline{D}_{xx1}$	Axial turbulent diffusivity of small bubbles and liquid going up, m^2/s	U_r	Relative velocity between the gas and the liquid phase
$\overline{D}_{xx2}$	Axial turbulent diffusivity of small bubbles and liquid going down, m^2/s	$U_{G,sup}$	Gas superficial velocity, cm/s , according to the Gupta et al., (2001)
H_o	Total liquid height in the column, m	$U_{L,sup}$	Liquid superficial velocity, m/s , according to the Gupta et al., (2001)
H_s	Height of the stage (tray spacing), m	u	Velocity, m/s
H_D	Dispersion height, m	x	Axial position in the column, m
H	Total height of the column, m	ε_g	Fractional gas hold-up
k	Mass transfer coefficient, m/s	ε_L	Fractional liquid hold-up

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