A novel approach of micro-pollutant separation in a stagnant water column

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Abstract:
Filtration and precipitation are generally used in waste water treatment to separate pollutants. However, they are not cost effective and have problems of filter waste and time consumption. This research proposes a new approach using compressed air to lift-up micro suspended particles in wastewater treatment. The novelty of the approach is its sustainability, robustness, and cost effectiveness in micro pollutant separation. Air is forced through submerged nano diffuser to produce micro bubbles, which flow upward and lift-up suspended particles to separate them from water.

A lab scale stagnant water column (100mm W x 100mm L x 240 mm H) is used in this micro pollutant separation process. Submerged sintered glass modules with porosities ranging from 1 to 40 microns are used to study the effect of air pressure and flow on the size of bubbles. The Phase Doppler Anemometry (PDA) is used to measure the bubble velocity (horizontal and vertical) and its diameter.

Various forces that act on the bubble during its detachment from the micro diffuser are established and correlations for the forces acting on the particle-bubble system have been developed for different particle to bubble diameter ratios. Effects of air flow through diffuser, inlet air pressure and various porosities on bubble size are presented in this paper. The bubble velocity is characterized by Froude number and Reynolds number. The amount of suspended particles in relation to turbidity has also been investigated and found that the turbidity level of 6.9 NTU decreases to 3.66 NTU, using 1-10 micron porous sintered glass at 0.2 l/min air flow.

Keywords: micro bubble, suspended particle lift-up, Froude number, porous sintered glass diffuser, Turbidity.

I. Introduction

Bubbles flowing in a water column have been used for many applications, i.e. air absorption into water (aeration), stirring process, and suspended particle lift-up. The purpose of air dissolution is to supply oxygen or other gases into water that supports micro-organisms living in the water as wrote in Metcalf (2004). Stirring process is to transfer mass or heat into water, hence forming a uniform solution, see Fan L (1999); while suspended particle lift-up is for removing impurities from water studied by Nguyen (2004).

The main principal of suspended particle lift-up depends on bubble forces and particle-water interaction. Bubble forces were investigated by Hong (1998) using micro force balance. The diameter of the bubble and particle was approximately 1 cm. A simulation of collision between the bubble and a stationary particle revealed that the force on the particle oscillated: first increased, then decreased, and increased again. The oscillation of the measured force showed a discontinued particle lift-up process. The Atomic Force Microscope (AFM) was used to measure the hydrodynamic drag force of the collision between 20 μm hydrophilic silica particle and 230 μm air bubble, see Shoeleh Assemi (2008). The hydrodynamic interaction forces between a solid sphere attached to an AFM cantilever and air bubble were studied by Nguyen (2004). Nguyen and Anh found that hydrophobic particle has adhesion force to air bubble that makes it easier to separate from water, while hydrophilic particle has adhesion force to water, which makes it harder to attach to air bubbles and remains suspended in water, Anh (2003). Due to the preference of hydrophilic particles to remain in water, a certain size of bubble is therefore required to produce a sufficient lifting force to separate the
suspended particles from water. The surface force between hydrophobic surfaces causes an “adhesion” as discovered by Rada A. Pushkarova (2005). The changes of air bubble shape continuously refuse the process of lifting up the suspended particles. The existence of surfactant would reduce the adhesion force between suspended particles and water molecule. The interaction particles to air, is studied by John Ralston (1999), and Vamsi K. Paruchuri (2006) produced repulsion between air and water surfaces Nguyen (2003). The attraction between AFM probe and a flat hydrophobic surface in water is also studied by Anh (2003). The study of the adhesion between suspended particle and bubble is done by Florin Omata (2006) and it is reported that adhesion force influences gas-liquid mass transfer, bubble coalescence and particle agglomeration. According to Anh (2004), once the suspended particle is attached on the air bubble, it slides down along the bubble surface and remains attached to the underside of the air bubble. The bubble-particle interaction during bubble upward movement consists of collision, attachment and detachment, Chi M. Phan (2003). The other force that influences air bubble movement is wake-induced force, studied by Katz (1996). The stirring effect of air bubble upward movement is induced by force oscillation due to bubble shape deformation and wake-induced force. These forces need to be decreased by controlling the bubble size and velocity. Millimetre air bubbles (3-6 mm) always produce turbulent flow Shawkat (2008) due to shape deformation and oscillation Wenzeh Zhang (2003). Finally, the bubbles coalesce and produce sufficient kinetic energy to create the turbulence effect in the water column Ning Yang (2010). The relationship of bubble shape (spherical or non spherical) and upward velocity was investigated by Kracht W (2010). The primary cause of widely scattered velocity is more influenced by bubble deformation; low deformation results in low velocity and large deformation results in high velocity Tomiyama A.(2002), and fine bubbles can stabilize the flow to become laminar Alexander Zaruba (2007).

Even though the addition of surfactants increases the adhesion force between air bubbles and suspended particles, nevertheless in some circumstances, the existence of surfactant is unwanted, for example in drinking water. Surfactants exist in wastewater due to detergent, oil, and other surfactant materials. The separation of suspended particles in oily wastewater using induced air floatation (IAF) has been done by Paimanakul P.(2009). In this research, study both type of particles, hidrophobic and hidrophilic.

The main objectives of this research are; the micro bubbles production using the reversed of sintered glass mounted in submerged diffuser, the monodispersed and polydispersed bubbles production and the lifting-up process of suspended particles. The success of suspended particles removal from water is indicated by the water turbidity level decreasing has been done. A correlation between turbidity level and rate of removal of suspended particles is discussed in this research.

II. Methodology

A. Suspended particles Lifting-up mechanism

Fig. 1 shows the milli bubbles and suspended particles circulating within the vertical water column. The circulation carried the water and suspended particles upward. When the water carried from the bottom of the column reaches top of the column, the bubbles are released into air. Just before the trapped air is released, the bubble breaks and produces a longitudinal wave towards the walls of the container. This small wave would push the suspended particles to move closer to the edge of the vertical water column. The particles continuously circulate.
Fig. 1. Experimental visual of The milli air bubbles trajectory and suspended particles circulation in vertical water column.

Fig. 2. shows the micro bubbles and suspended particles circulating within the vertical water column. The circulation carried the suspended particles upward, while the water would remain its place due to the insufficient energy to push the water upward, enough space among bubbles and adequate time to slide to the side. Some of the immersed particles, in close proximity to the container wall, would move down due to the higher density than water and settle down around the diffuser. The non-immersed (settled) particles would form scum on the water surface close to the container wall. The water would be clearer (3.8 NTU) than before aeration process (6.9 NTU).

The process of removing the suspended particles is continued for a certain period of time, but not all the suspended particles can be removed from the water; however, a significant reduction of water turbidity indicates the effectiveness of this system.

The bubble characteristics, such as diameter, rise-up velocity and horizontal velocity are investigated for their relationship with air pressure and flow through the diffuser.
Figure 2. The visual of micro air bubbles trajectory and suspended particles in vertical water column.

B. Forces acting on the bubble

There are two conditions when the bubble is influenced by various forces namely at the time of bubble generation, and bubble detachment. Both conditions have their own force balance and different force compositions. The forces are influenced by gas momentum force, surface tension, viscosity of liquid, and air-water density differences, when the bubble is generated. In addition, after detachment from the diffuser, two forces act on the bubble, which are viscous drag and buoyancy. These two forces are dependent on liquid viscosity and air-water density difference respectively, whereas, in viscid inertia force and bubble interaction forces are neglected. Details of the forces that act on bubbles have been reported by Fan(1999), Vazquez A.(2010), and Yeoh G.H.(2005).

The bubble forces at Reynolds number 50 to 200 was studied by Ruzicka (2000). The bubble lifting force by balancing the upward and downward forces acting on the bubble was studied by Kulkarni A. A.(2008). The buoyancy force depends on the density difference between water and air, while the drag force depends on $C_d$ (drag coefficient), length of chord (effective bubble diameter) and velocity. The $C_d$ equal to $24/\text{Re}$ when the value of $\text{Re}=1$ was described by Fan (1999), and for value of $\text{Re}$ in the range of 1 to 500 Rivikind and Ryskind suggested the following equation which was cited by Xu H.(2004):

As $K$ depends on air and water viscosity, therefore, the $C_d$ equation becomes:

\[ C_d = \frac{0.484}{\text{Re}} + \frac{0.081}{\text{Re}^{1/3}} + \frac{14.6}{\text{Re}^{0.78}} \quad ...(2). \]

Where Reynold number is : $\text{Re} = \frac{\rho v L_c}{\mu_l}$

$L_c$ is length of chord, and in this case bubble diameter is $(d_b)$.

The forces acting on the bubble and particle, when they are in contact, are shown in Fig. 3. In this research, the upward movement of the suspended
particle has been studied under the following 3 conditions:

1. When the particle diameter is smaller than the bubble diameter.
2. When the particle diameter is similar to the bubble diameter.
3. When the particle diameter is bigger than the bubble diameter.

The vortex inside the bubble due to air-water friction is shown in Fig. 3a. The vortex would help the smaller particles to remain attached to the bubble as long as they are in the line of motion. A similar behavior is expected for the larger particles. However, in case the line of motion is changed, then the bubble would be separated and would not force the particle upward. A next inline bubble would take place and pushes the particle upward, unless, the particle has reached the top.

The drag force acting on a free floating bubble is described as follow:

By assuming upward forces as positive and downward as negative, the balance on the free bubble is:

$$\sum F_1 = F_a - F_D \quad \text{...............(3)}$$

When bubble is bigger than particle, the drag force consist of particle drag and bubble drag. Force balance on the bubble-particle pair is:

$$\sum F_2 = F_{BB} - F_{DB} - F_{DP} \quad \text{.........(4)}$$

Assuming the bubble-particle pair combined velocity ($v_c$) is the same as that of bubble upward velocity ($v_b$) and particle upward velocity ($v_p$), the velocity ratio becomes:

$$\frac{v_b}{v_p + v_b} = \frac{(0.06\mu_i d_p + 0.01\mu_i^{1/3} d_p^{2/3} \mu_i^{0.78} d_p^{1.22})}{(0.06\mu_i + 0.01\mu_i^{1/3} d_b^{2/3} + 1.9\mu_i^{0.78} d_b^{0.22})(2d_p - \mu_i \mu_i^{1/3} d_p^{2/3} \mu_i^{0.78} d_p^{1.22})} \quad \text{...............(5)}.$$

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**Figure 3.** The illustration of bubble and bubble particle pair interaction a. The free bubble forces. b. The bubble is bigger than the particle. c. The bubble is smaller than the particle. Assuming the bubble and suspended particle are vertically in line.

When bubble is smaller than particle, or the other word particle is bigger than bubble, the force balance is:

$$\sum F_3 = F_{BB} - F_{DP} \quad \text{...............(6)}$$
C. Experimental set-up

The experimental set-up to produce air bubbles through a submerged diffuser at the base of a water column is shown in Fig. 4. It shows various transducers to monitor different parameters at the inlet. A vertical water column of 100 mm W x 100 mm L x 240 mm H was used. The sintered glass with three different porosities of 1 to 10 µm, 10 to 16 µm, and 16 to 40 µm were used to produce micro-bubbles.

Compressed air at a pressure range of 5 to 33 kPa was forced through the diffuser at the bottom of the water column. A fluid flow valve was used to control air flow in the system within the range of 0.25 to 1.8 liter/minute.

The experiment was carried to find out the behaviours of air bubbles in distilled water, ordinary tap water, and polluted water. The vertical movement of air bubbles lifts-up suspended particles, which will form scum on the water surface and precipitation of particles will occur at the bottom of the vertical water column. The initial air pressure, at which the bubble emerges, depends on the depth of the water column. The bubbles are measured in the homogeneous regime in a location at 10 mm above the submerged diffuser or 390 mm below the water surface. The bubbles distribution was taken from the most populated bubbles in the measurements.

A diffuser was mounted at the base of the water column. Sintered glass of various porosities (1-10µm; 10-16µm and 16-40µm) was used as diffusers to produce micron size air bubbles. The bubble diameter and rise-up velocity were measured using PDA, where the laser beam refraction was captured as an input signal. The transparency of water was one of the necessary to forward the laser refraction beam to the signal receiver. Without transparency the beam will scattered to all direction and reduced the signal energy.

A food grade solution thickening agent, Carboxy Methyl cellulose, HP-8A Multi-kem corporation (2010) was used to represent suspended particles in water. The 0.25 percent of CMC (Carboxy Methyl cellulose) diluted in distilled water was used to represent suspended particles in water. The contaminants (CMC) created the cloudiness in the water solution, mentioned as a turbidity number. The turbidity was measured by Hach turbidimeter at the middle of the water column (200mm under water surface) and is denoted by NTU (Nephelometric Turbidity Unit) number.

\[
\frac{v_b}{v_b + v_p} = \frac{(0.06\mu_p d_p + 0.01\mu_i^{1/3} d_i^{2/3} + 1.9 \mu_i^{0.78} d_i^{1.22})}{(0.06\mu_p d_p + 0.01\mu_i^{1/3} d_i^{2/3} + 1.9 \mu_i^{0.78} d_i^{1.22})} \tag{7}
\]
Figure 4  a. A schematic diagram of the experimental set-up to produce bubbles in a vertical water column. b. 50 mm porous sintered glass.
Pure glycerine was used to simulate polluted water in terms of viscosity, surface tension and density. A volumetric concentration of pure glycerine ranging from 0.1% to 0.5% was used to study the effects of physical properties of the bubbles such as their diameter at the time of its generation and upward movement.

III. RESULTS AND DISCUSSIONS

A. Relationship between micro bubble and inlet air parameters

The bubble diameter produced by the sintered glass depends mainly on the porosity and supplied air parameters i.e. pressure or flow. Lower porosity produces nearly uniform size bubbles in a certain air pressure range due to smaller differences among porous holes, while higher porosity produces polydispersed bubbles with a variety of bubble diameter and horizontal and vertical velocities. The polydispersed bubbles move up and have a non-linear trajectory motion due to the variance of their velocity, eventually, creating a stirring effect in the water. A similar movement of bubbles have been reported by Kracht W. (2010), and Tomiyama A.(2002). Micro bubbles have a smaller stirring effect because only a small component of their velocities is in the horizontal direction. A slower upward movement can be obtained and turbulent effect can be avoided, if the bubbles size is controlled to be in microns. The uniform upward bubble movement carries the suspended particles to surface of the water column. This mechanism is able to remove water pollutants when the production of micro bubbles is continuous. A plot of the bubble diameter against inlet pressure yielded a second order polynomial curve, which is used to establish the relationship between bubble diameter and inlet air pressure for 1-16 and 16-40 µm porosities sintered glass, as shown in Fig. 5. To control the bubble diameter, first a lower porosity sintered glass must be used, and second a very good control of the low inlet air pressure. The uniformity of pores on the surface of the sintered glass is a necessary requirement to produce uniform size bubbles called monodispersed bubbles.

![Figure 5: The effect of various inlet air pressures on the bubble diameter through different porosity diffusers in distilled water. Error bar in y direction is ± 5.](image)
Fig. 6 shows the relationship between inlet pressure and bubble diameter for two different porosities sintered glass diffuser, when the volumetric range of pollutant in water is 0.5%. Comparing with Fig. 5, it is observed that the 1-16 micron porous line in Fig. 6 is shifted closer to the 16-40 micron porous glass. This shows that increasing water surface tension by adding glycerin would reduce the bubble diameter. Therefore, in order to produce bubbles of the same diameter, an increase of the inlet air pressure is required.

By comparing Fig. 5 and Fig. 6, it is evident that air inlet pressure required to produce micron bubbles in 0.5% glycerin polluted water using 1-16 μm porous sintered glass has increased to 20 ~ 30 kPa. One of the obvious reasons for this increased inlet air pressure is the increase in viscosity of water solution due to the addition of glycerin. Due to the increased viscosity, a slightly higher pressure is required to produce similar size bubbles.

In the market, the preferable dimensions of sintered porous glass just the 1-10μm, 10-16 μm and 16-40 μm porosity are provided. They have their own characteristic that differ from each other, therefore the maximum of bubble diameter can be produced are not depend on its porosity only but the air intake pressure also. The other factor influence the bubble dimension is the uniformity of glass cristals that contain on the sintered porous glass surface. The goal of micro bubble production have been acieved and can be applied in suspended particle entrain can be investigated.

![Figure 6](image_url)

**Figure 6**: The effect of various inlet air pressures on the bubble size through different porosity diffusers in 0.5% glycerin pollutant. Error bar in y direction is ± 5.

**B. Bubble generation vs pollution**

Usually, vertical component of velocity is dependent on the bubble size, whereas, bubble size is dependent on porosities, and inlet air flow and pressure; Figure 7 shows the relationship of vertical velocity to bubble size in distilled water. Generally, bubbles of larger size would have more vertical velocity.
The 1-10 and 10-16 μm porosities give comparable results between vertical velocity and bubble size. On the other hand, the 16-40 μm porosity produces different results, which do not show significant changes in bubble diameter with increasing vertical velocity as shown in Fig. 7.

The effect of pollutant concentration on bubble diameter and bubble vertical velocity was investigated by varying the glycerine concentration from 0.1% to 0.5%. Our investigation has shown the presence of pollutants in water also affects bubble diameter and its velocity. Increasing the glycerine content increased the bubble size and vertical velocity for the range of porosity included in this study, as shown in Figs. 8. Due to the increased water density, the bubble size and density disparity between air and water also increased. These conditions give higher buoyancy and frequent bubble merge was observed, despite the higher drag force created by a higher friction force between the air bubble and water. Experimentally, it was observed that the 1-10 μm diffuser in 0.3% glycerine solution gives the maximum vertical velocity when the bubble diameter was approximately 120 μm.
Figure 8. Relationship between bubble diameter and vertical velocity in polluted water with 3 different percentages.

Using 16-40 µm porosity sintered glass, a larger population of small bubbles and higher vertical velocity were achieved. The maximum vertical velocity was reached by adding 0.5% glycerine. The physiochemical characteristics bring the changes to the bubble dynamic behaviour.

Increasing the air pressure and flow tend to generate bigger bubble, and merging between bubbles occur more frequently. Bigger bubbles have smaller distance between them, their shape changes continuously, and they move irregularly in a zigzag pattern. Their trajectories give stirring effect in the water column. The change in bubble diameter is controlled by the inlet air pressure. Comparing the earlier results presented in Fig.6, a 9 kPa increment (from 21 to 30 kPa) of inlet air pressure would increase the bubble size up to 2.62 times. The vertical velocity changes 6.04 times and finally the Reynolds number calculation changes 15.83 times. Eventually, to control the Reynolds number, one need to control the bubble size, because of the relationship between bubble diameter and vertical velocities, as shown in Fig.8. For smaller bubbles, more vertical velocity component is recorded, whereas the change becomes less effective for bigger bubble sizes.


Since the bubble movement is dependent on the dynamics as well as gravitational forces acting on it, and the relationships between these forces lead to Froude, Weber, Bond and Archimedes number; therefore the comparison between that numbers are presented and plotted as in Fig. 9, 10 and 11
Figure 9. Relationship between vertical velocity to Froude and Weber number.

The upward velocity and bubble size are the dependent elements to establish to that numbers. According to the graph, the Weber and Archimedes number have significant inclination line, therefore both numbers give better representation to the bubble dynamics. The Bubble velocity less than 0.5 m/s, and bubble diameter smaller than 80 micron have smaller inclination, whereas the velocity more than 0.5 m/s and diameter bigger than 80 micron have significant alteration.

Figure 10. Relationship between Bubble diameter to Froude and Weber number.
The bubble velocity and diameter are the main factors to determine the Reynolds number; therefore the relationships between bubble size, velocity and Reynolds number (experimentally and theoretically) are presented and plotted in Fig. 1. Since the values of theoretical and experimental Reynolds numbers are close in the range of 1 to 70, the turbulent effect does not exist in this region, and the stirring effect can be neglected.

D. Combined velocity ratio of bubble-particle pair

The bubble-particle pair moves through their trajectory when the lifting process occurs. Applying equation 5 (for bubble bigger than particle diameter) and 7 (for bubble smaller than particle diameter) for experimental bubble and interpretation particle size of 1~220 micron, that relationships can be plotted and extrapolated. Assuming the diameter ratio (Rd) as the ratio between bubble diameter ($d_b$) and particle diameter ($d_p$), the relationship between particle size and
velocity ratio are shown in Fig. 13. The graph shows the different sets of Rd, one with Rd<1 and the other as Rd≥1 (dot plotted).

To investigate the potential of the micro bubble to lift up suspended particles, the combined velocity (bubble and particle velocities) is plotted against particle diameter as shown in Fig.14. By taking the 42 microns bubble diameter and its vertical velocity in varied percentage of pollutant, calculation of the combined upward velocity (\(v_c=v_b+v_p\)) in equation 5 and equation 7 can be done, where \(v_b\) is measured bubble vertical velocity and \(v_p\) is assumed particle velocity. From the graph indicate that the better condition for lifting up suspended particles when the particle diameter close to the bubble diameter or smaller than.

**Figure 13.** \(v_b/v_c\) ratio versus particle diameter. The \(v_b/v_c \leq 1\) when \(d_p\) is smaller than \(d_b\), the \(v_b=v_c\) when \(d_p\) is equal to \(d_b\), and the \(v_b/v_c \geq 1\) where \(d_p\) is bigger than \(d_b\).

**Figure 14.** Relationship between suspended particle diameter and combined velocity \(v_c\).

**E. Turbidity decreasing**

The smaller air flow produces smaller air bubbles and gives better performance of lifting-up suspended particles. Stirrer effect is limited by reducing the air flow and pressure (less energy distributed). The 0.4 and 0.6 l/min air flow produce the stirring effect. The
Turbidity decreases from 6.9 to 3.8 NTU in 5 hours aeration, and is equivalent to 2369 to 1314 ppm, respectively. This lower quantity of CMC adding avoids the liquid viscosity changing, therefore it simulates the real wastewater viscosity that still in water-particle system.

The minimum air flow rate is 0.2 l/min for bubble generation. Higher flow rates polydispersed bubbles are produced with varied of horizontal and vertical components of velocity. Reaching 2 l/min most of the bubbles produced are in millimetres size. The better result for suspended particle lift-up was obtained using 10-16 micron porosity diffuser and 0.2 l/min air flow. Figure 15 shows that the turbidity level decreases proportionally with aeration time. Once the change in turbidity level is no longer observed after a certain period of aeration time, then further reduction of the turbidity level can only be done by changing the bubble size.

Figure 15: The turbidity of CMC solution in distilled water vs micron bubble aeration time using 1-10μm porosity sintered glass.

IV. Conclusions

The inlet air pressure and flow are effective parameters to control the bubble diameter. The porosity of sintered glass determines the applied pressure and flow to generate the micro bubbles. Adding pollutant to distilled water increases the surface tension, which consequently affects bubble generation. The bubble size determines its velocity, both horizontally and vertically, which generate the upward movement. There are two kinds of flow; laminar and turbulent. The smaller bubbles have laminar upward movement and the bigger bubbles have turbulent movement due to the deformation of their shape.

Increasing the inlet air pressure and flow, generate bigger bubbles having higher horizontal and vertical velocity components. The larger bubbles have tendency to deform easily and are dominant to produce higher forces that affect the Reynolds number to increase. Any further increase of bubble diameter and velocity would increase the Reynolds number, changing the flow characteristics and making the bubbles less effective to lift up the suspended particles. The Weber and Archimedes give better representation to the micro bubble dynamics, where the 0.5 m/s bubble velocity and 80 micron bubble diameter has optimal condition for lifting-up the suspended particles.

The minimum turbidity level is 3.8 NTU (equivalent to 1314 ppm) after 5 hours aeration, achieved by 1-10 μm porosity and 0.2 l/min air flow. Initially the turbidity removal rate is faster than later stage.

The physicochemical water characteristic is a determinant factor besides bubble diameter, particle diameter and air water density differences for suspended particle lifting force phenomena.
\textbf{NOMENCLATURE}

\begin{center}
\begin{tabular}{ll}
\textit{C_d} & drag coefficient \\
\textit{d_b} & diameter of bubble \\
\textit{d_p} & particle diameter \\
\textit{F_B} & buoyancy force \\
\textit{F_{BB}} & bubble buoyancy force \\
\textit{F_D} & liquid drag force \\
\textit{F_{DB}} & bubble drag force \\
\textit{F_{DP}} & particle drag force \\
\textit{Fr} & Froude number \\
\textit{g} & gravity acceleration (ms^{-2}) \\
\textit{K} & viscosity comparison of air and water \\
\textit{L_C} & length of chord \\
\textit{NTU} & Nephelometric Turbidity Unit \\
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\begin{center}
\begin{tabular}{ll}
\textit{P} & pressure (kPa) \\
\textit{P_a} & air pressure \\
\textit{q} & air flow \\
\textit{Re} & bubble Reynolds number based on liquid properties \\
\textit{V} & volume (m^3) \\
\textit{v_b} & bubble rise velocity \\
\textit{v_c} & combined velocity bubble-particle \\
\textit{\nu_p} & particle rise velocity \\
\textit{\rho_g} & gas density \\
\textit{\rho_l} & liquid density (kgm^{-3}) \\
\textit{\mu_g} & air viscosity \\
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