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Analysis of Currents and Mixing in a modified Bubble Column Reactor

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Abstract. *A modified bubble column reactor to be used as Photobioreactor (PBR) is studied. PBRs are used to grow photosynthetic microalgae, which depend on light, nutrients and carbon dioxide for their growth. Carbon dioxide availability is dependents up on the amount of volumetric mass transfer taking place in the reactor. Bubble columns are known for high mass transfer rates, modifications to the existing bubble columns shows to increase the volumetric mass transfer in the system. The major modifications that are incorporated in the present PBR are rectangular flat walled columns and porous membrane for gas dispersion. Based on the previous work done in the area, hydrodynamics of bubble columns are influence by superficial gas velocity, gas holdup, bubble diameter, column geometry, use of antifoaming material and pressure. By using porous membrane, volumetric gas transfer was shown to improve over spared systems. Due to the interdependence of the factors influencing hydrodynamics, computational fluid dynamics (CFD) simulations based on eulerian equations are needed. Further CFD simulations are needed to understand liquid current flows and mixing.*

Keywords. Photobioreactor, bubble column, porous membrane, microalgae, algae, carbon dioxide, mass transfer, gas holdup, pressure, mixing, liquid currents, biomass.

Introduction

A modified bubble column reactor is designed to be used as a Photobioreactor (PBR). A PBR is a system that provides an artificial environment for photosynthetic organisms (Algae) to perform a chemical conversion. Scientists and engineers have been developing several types of photobioreactors (PBR's) over the past fifty years to grow microorganisms that are used in a wide variety of applications. Many factors influence the design of an efficient photobioreactor. The main factors are light, carbon dioxide and nutrients. During the design of a PBR, care should be taken so that optimizing the design for one factor does not adversely affect other factors.

Bubble columns are used extensively in chemical, petrochemical and biochemical industries. Bubble columns cannot be directly incorporated in PBR design without modifications. The bubble columns, which are designed for the chemical industry, generally work under high pressures and temperatures, which are not generally suitable for a PBR. Apart from pressure and temperature these bubble columns are designed to be cylindrical resulting in uniform wall effects. This geometry is not suitable for a PBR because a flat surface is needed to achieve maximum light penetration into the system.

Bubble column reactors offer some unique features not found in other types of photobioreactors. Bubble columns are well suited for slow reactions taking place in the liquid phase, which is the case with a PBR (Urseanu and Krishna, 2000). Growth of algae is a fairly slow process. A normal growth run is estimated to be anywhere from a few days to months depending on other factors like light source and nutrient concentration. Bubble columns can be easily isolated from environmental bacteria, hence low contamination. This is difficult to achieve in open systems like raceways and ponds. Bubble columns have better mass transfer rates than other types of PBR's (Miron et. al., 2000; Kommareddy and Anderson, 2003). Carbon dioxide is very essential for photosynthetic microalgae to grow, its availability is defined by the amount of volumetric mass transfer coefficient from gas to liquid that is a function of interfacial area. The higher the interfacial area, the more gas transfers from gaseous phase to liquid phase, hence more gas holdup (increase in interfacial area) in the liquid phase that results in higher concentration of carbon dioxide in the growth medium for algae. Apart from higher concentrations of carbon dioxide, bubbling also helps in mixing the culture medium which helps moves algae from lower light intensity areas to high light intensity areas and back.

To efficiently design a PBR, it is essential to understand the factors, which influence hydrodynamics of bubble column reactor such as reactor walls, superficial gas velocity, bubble size etc. Up until present, most of the information available specifically addresses cylindrical bubble columns not rectangular flat wall systems. The mixing characteristics of rectangular bubble column needs to be studied. Most of the bubble columns use a sparger to inject air in to the cultural medium. A porous membrane offers smaller bubbles and greater bubble distribution with a low-pressure drop. Using porous membrane with average pore size of 35 micrometer has an advantage of acting like a filter, blocking bacteria passage. The two major modifications, which are incorporated in the design of the PBR, are rectangular geometry instead of cylindrical and a porous membrane as gas dispenser rather than spargers. Computational Fluid Dynamic (CFD) models can be used to study and understand current patterns and mixing in this type of PBR. Using CFD modeling will help to reduce the number of experiments needed to understand all these factors and optimize the system. Unfortunately CFD software capable of analyzing multiphase reactions is not available to the authors at this time. FLUENT has been ordered and will be available this fall for the study.

Porous Membrane

A company known as Porex™ Porous Plastics makes a porous membrane by sintering of high-density polyethylene particles. The resulting product is a porous sheet material that offers tortuous paths rather than perforated holes for air distribution, see Figure 1 (Kleinjan and Anderson, 1999). The porous membrane, which is used, is 1/32 inch thick, with 35 micron average opening. This product is bought from Interstate Specialty Products (Item id POR-4896). Performance of the porous membrane is presented in Kommareddy and Anderson, 2003.

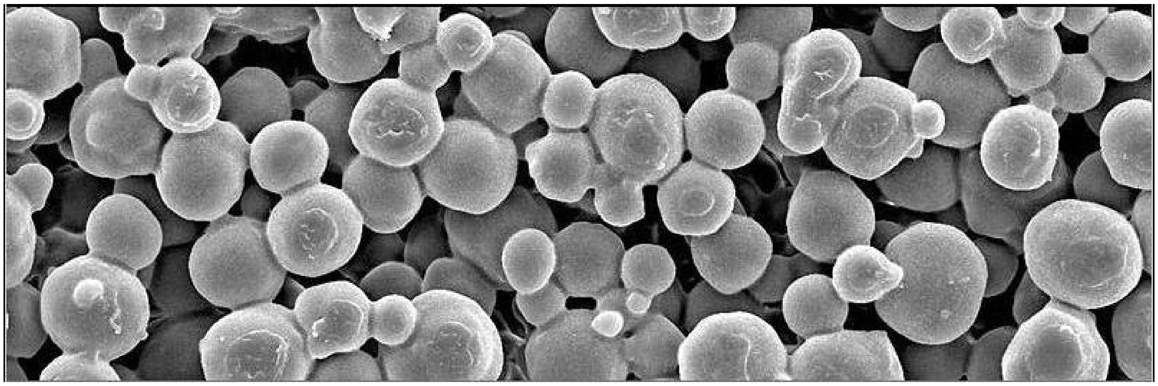

Figure 1: Porous membrane under scanning electron microscope (adapted from www.porex.com)

Factors influencing hydrodynamics of Bubble Column Reactors

Factors that influence hydrodynamics of Bubble Column Reactors are superficial velocity, bubble diameter, column geometry (reactor walls), use of antifoaming agents and pressure (Urseanu and Krishna, 2000). These factors are interdependent requiring them to be discussed in relation to each other rather than independently. Previous design work is examined for both bubble column reactors and PBR's. Inferences are drawn from them to improve the design of a PBR. Though bubble columns are simple to construct, their hydrodynamics are complex.

Superficial gas velocity can be defined as volumetric gas flow rate per cross sectional area of bubble column. Generally superficial velocities are 0.07 m/s (Miron et. al., 1999; Miron et. al., 2000; Wu and Merchuk, 2002). Air-lift columns are used in conjunction with tubular photobioreactors that had superficial velocities as high as 0.21 m/s (Miron et. al., 1999; Contreras et. al., 1999). Superficial velocity is dependent on column dimensions (Miron et. al., 1999). The relationship between gas-liquid mass transfer coefficient (k_La_L), gas holdup and superficial velocity were derived theoretically and compared to experimental results in Miron et. al., 2000. Relationship between volumetric mass transfer coefficient and superficial velocity was found to be linear when a sparger is used. The relation for tap water is given by equation 1 (Miron et. al., 2000).

$$k_L a_L = \frac{0.874}{U_G^{-0.979} - 1} \qquad 1$$

Where

k_L = liquid mass transfer coefficient ($m \cdot s^{-1}$)

a_L = specific gas-liquid interfacial area per unit liquid volume (m^{-1})

U_G = superficial gas velocity ($m \cdot s^{-1}$)

Apart from Equation 1, there are many different formulas put forth by other authors (Poulsen and Iversen, 1998) but a common factor in all the equations is that the volumetric gas transfer coefficient is a linear function of superficial gas velocity. Equation 1 and other equations given by Poulsen and Iverson (1998) are based on the assumption that gas holdup is directly proportional to superficial gas velocity and inversely proportional to mean bubble velocity, see equation 2 (Miron et. al., 2000; Poulsen and Iversen, 1998). Gas holdup is defined as the amount of gas entrapped in the liquid as bubbles at a given time in the system.

$$\varepsilon = \frac{U_G}{U_b} \qquad 2$$

Where

ε = gas holdup (dimensionless)

U_G = superficial gas velocity ($m \cdot s^{-1}$)

U_b = mean bubble velocity ($m \cdot s^{-1}$)

Equation 2 shows that for a constant superficial gas velocity, the slower the bubble travels the higher gas holdup in the system is. As bubbles have more time to travel in the liquid more gas mass transfers to the liquid. Equation 2 also shows that for a given mean bubble velocity, increase in superficial gas velocity would increase gas holdup. In a sparged system there are a fixed number of openings, dictating that an increase in superficial gas velocity leads to an increase in mean bubble velocity, so improvement in the gas holdup is marginal.

Bubbling through a porous membrane system does not mean that the mean bubble velocity will increase proportionally with an increase in the superficial gas velocity because more pores will open and the mean bubble velocity will be the same per pore as before resulting in more gas holdup. Figures 2 and 3 show the experimental results discussed in Kommareddy and Anderson (2003). Pressure change across the membrane with change in superficial gas velocity is basically constant for a given depth of tap water. When pressure due to water depth is subtracted from the results of the experiments, a small pressure change in the range of 380 - 840 Pa with change in superficial gas velocity from 0.9 to 6.5 m/s is observed, see Figure 3. Comparing Figures 2 and 3, it can be seen that resistance offered by the membrane is very small and reaches a constant at 0.127 m depth. As seen from figure 3, increases in superficial gas velocity result in a pressure difference that is marginal when compared to rigid spargers with pressure differences as large as 10 kPa (Poulsen and Iversen, 1998). Equation 2 shows that porous membrane systems would have larger gas holdups than sparged systems when the airflow rate is increased because the mean bubble velocity increased proportionally to superficial gas velocity in a sparger but not with the porous membrane.

Bubble column flow regimes are broadly classified as homogeneous and heterogeneous flows (Krishna and Baten, 2003). Homogeneous bubble flows have a narrow bubble size distribution between 1-7mm. Heterogeneous bubble flow regimes generally consist of large and small bubbles. A large bubble generally moves faster than a small bubble causing coalescence and breakup. Heterogeneous bubble flows are further classified into churn turbulent flow, slug flow and annular flow see Figure 4 (Urseanu and Krishna, 2000). Figure 4 shows that an increase in superficial gas velocity will cause bubble flow to change from a homogeneous flow regime to a heterogeneous flow regime. A porous membrane was observed to produce uniform bubble sizes (Kleinjan and Anderson, 1999), suggesting that it works in the homogenous bubble flow regime.

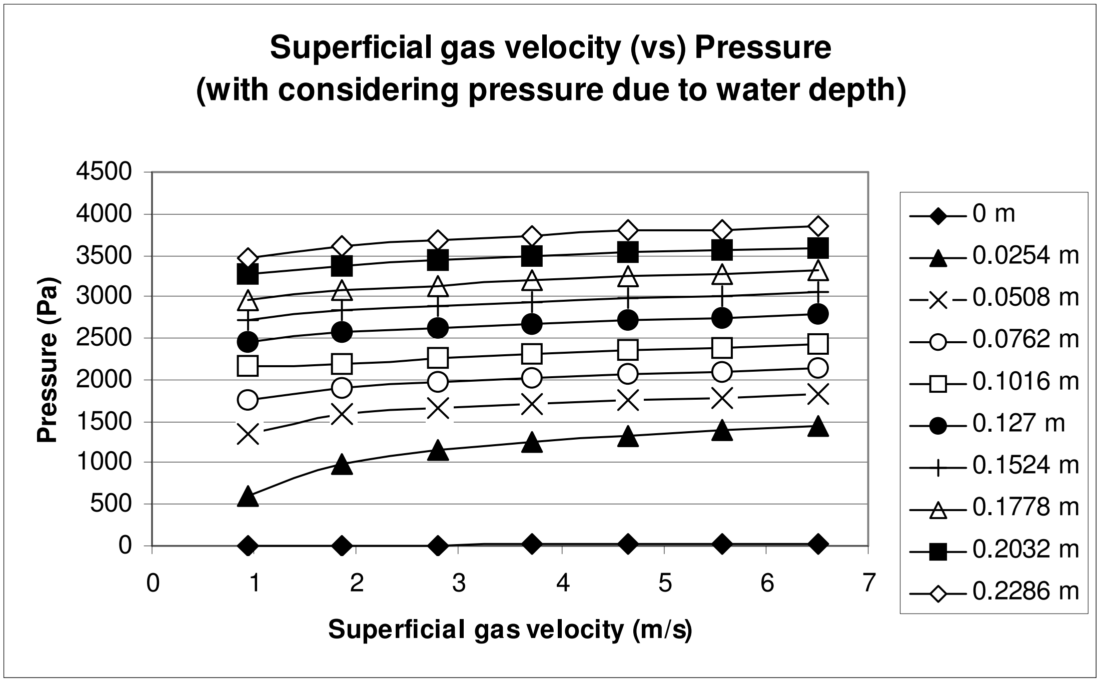

Figure 2: Superficial gas velocity (vs) Pressure when water depth pressure is considered.

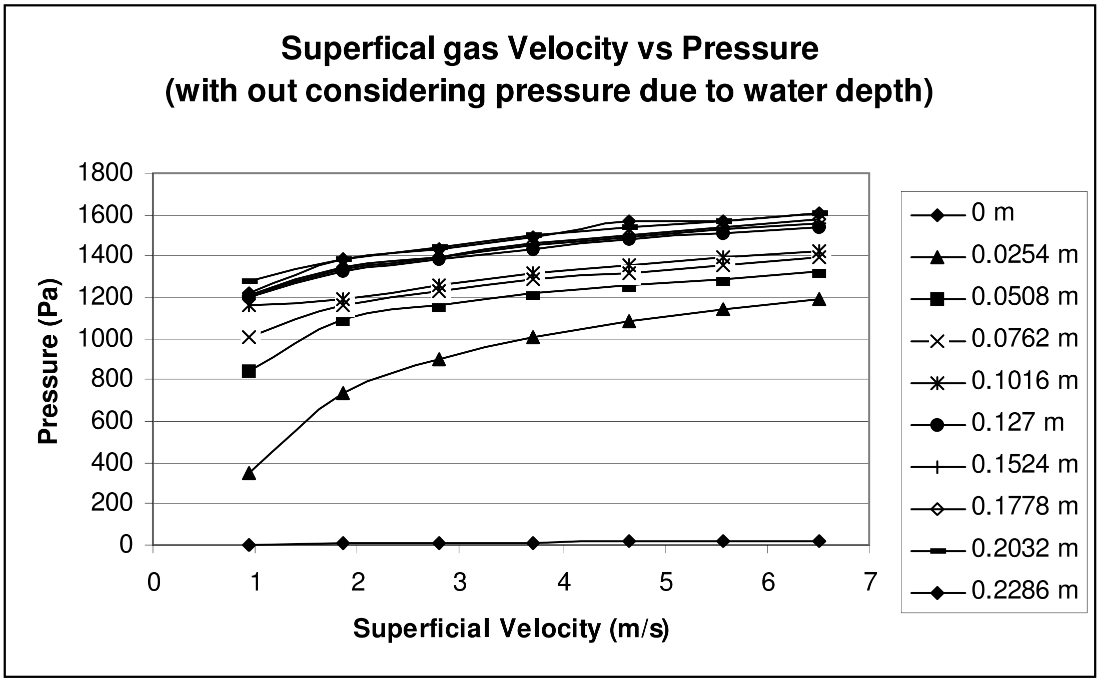

Figure 3: Superficial gas velocity (vs) Pressure when water depth pressure is not considered.

Figure 5 shows that the approximate transition from homogeneous bubble flow to heterogeneous churn-turbulent flow and slug flow is based on the superficial gas velocity and column diameter (Urseanu and Krishna, 2000). From Figure 5, it can be inferred that the mean bubble velocity in slug flow would be high (>0.05 m/s) and not likely suitable for a PBR since high bubble velocity could potentially kill the algae though there is no documented evidence of this (Miron et. al., 1999). Slug flow is not considered suitable, it can be inferred from Figure 4 that annular flow is also not suitable. For a given bubble column, the superficial gas velocity at which transition occurs would be different for sparged systems and porous membrane systems, because sparged systems have a fixed number of openings and fixed opening size while a the number of pore openings in a porous membrane system increases assuming the mean bubble velocity is constant while the superficial gas velocity is increased.

The amount of time the bubble spends in the column is also dependent up on the height of the bubble column. In a taller bubble column the bubble has to travel a greater distance allowing more time for mass transfer. Generally taller bubble columns are preferred over shorter columns to improve mass transfer efficiency. Taller columns would also increase the static pressure against which the system works against proportionally with depth in a porous membrane bubble column. A compromise has to be achieved between height of the column and energy required to bubble air through the column.

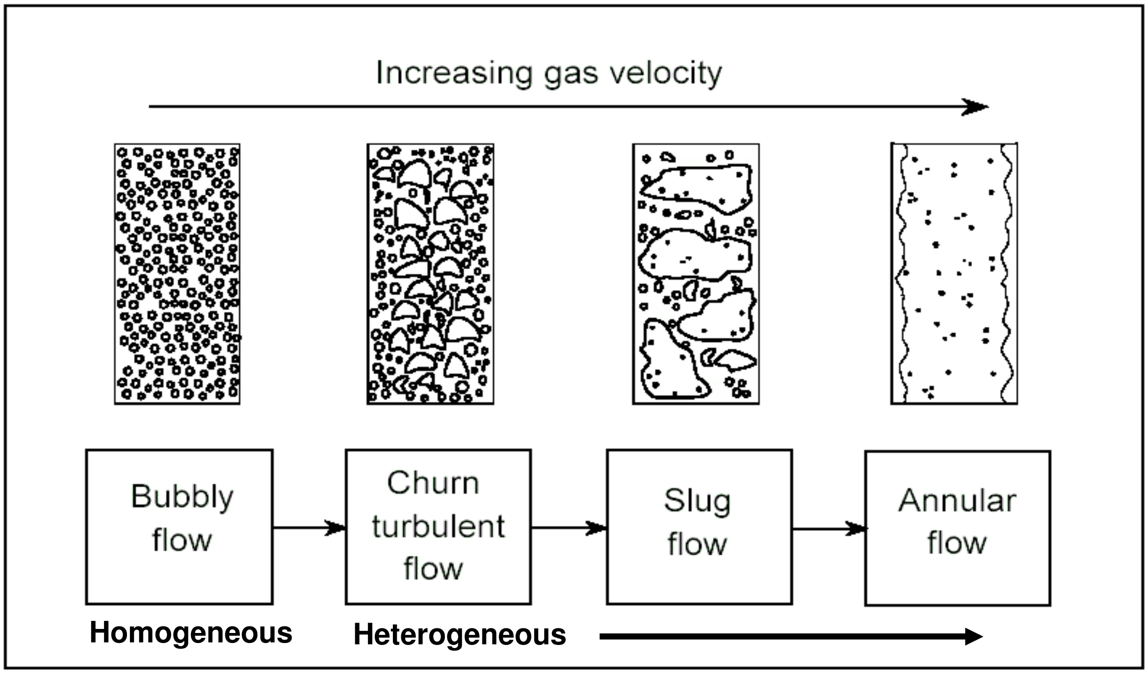

Figure 4. Flow regimes encountered in bubble columns (Urseanu and Krishna, 2000)

Bubble diameter and gas holdup can be related by equation 3 (Poulsen and Iversen, 1998; Miron et. al., 2000). The larger the bubble diameter, the larger the interfacial surface area is which leads to more mass transfer due to large gas holdup. A large number of dense small bubbles is preferred over a small number of large bubbles. The effective interfacial area of a swarm of small bubbles is greater than for a few large bubbles. Porous membrane bubble columns have been observed by the authors to produce small bubble swarms rather than a few large bubbles, see Figure 6.

$$a_L = \frac{6\varepsilon}{d_B(1-\varepsilon)} \qquad 3$$

where,

a_L = specific gas-liquid interfacial area (m^{-1})

ε = gas holdup (dimensionless)

d_B = bubble diameter (m)

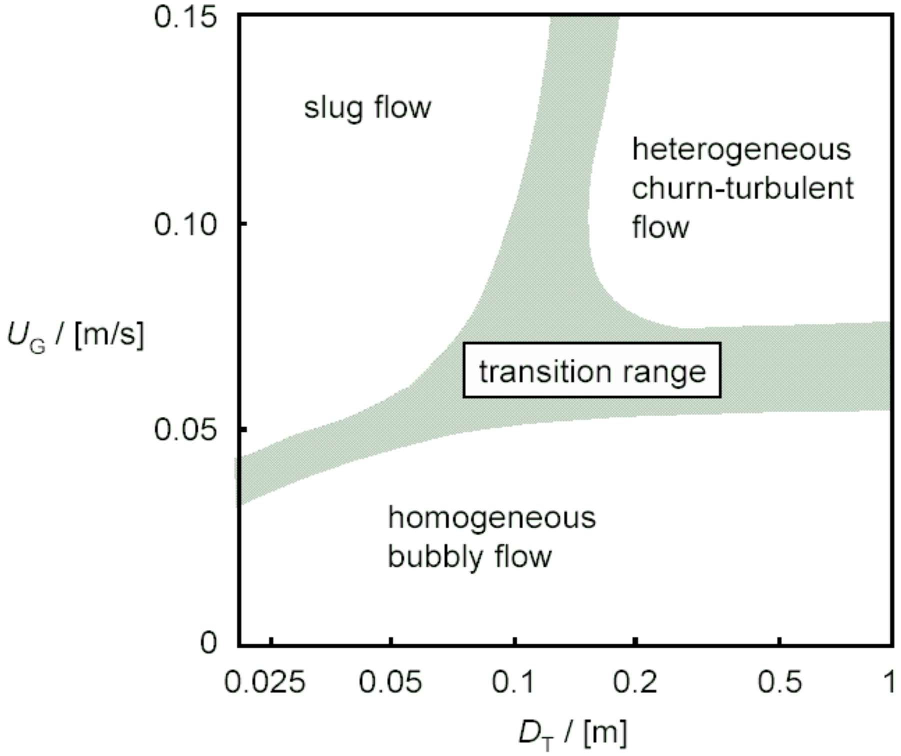

Figure 5: Flow regimes based on superficial velocity and column diameter (Urseanu and Krishna, 2000)

Wall effects were found to be negligible in a bubble column with a single opening and a ratio of bubble diameter to column diameter less than 0.125 (Krishna et. al., 1999a). Most PBR's would have more than one train of bubbles in the system. It is expected that wall effects will be of importance in most cases. Also, bubbles in adjacent trains may interact and this effect has yet to be studied. Antifoaming agents when added have been shown to decrease the mass transfer coefficient (Kawase et. al., 1992). Care should also be taken so that the antifoaming agents are not allowed to contaminate algae growth medium.

Pressure affects the flow of bubbles in bubble columns. When there is an external pressure applied on the surface of the growth medium or when the height of the bubble column is large there is an appreciable pressure difference from bottom of bubble column to the top. When external pressure is applied on the bubble column, bubbles are more homogenous and the mean bubble velocity is small, increasing gas holdup, equation 2, and increasing mass transfer, equation 3. Buoyancy force of a bubble is a function of cube of bubble diameter and drag force is a function of square of bubble diameter (Adkins et. al., 1996). As the bubble rises from the bottom of the reactor bubble diameter increases. With the change in diameter of the bubble the buoyancy force and drag force change, and in turn change the velocity of the bubble. The mean bubble velocity changes from inception to death or burst at the top of the column. Equations 2 and 3 show that the mass transfer rate will vary with depth in the columns as velocity changes and bubble diameter change.

Figure 6: Air bubbling through porous membrane.

Need for Computational Fluid Dynamic (CFD) Simulations

All the a fore mentioned factors which influence hydrodynamics of a bubble column greatly influence the liquid currents in the column. Since the hydrodynamics of the bubble column are not easily predicted the liquid currents are hard to predict. Recent publications have shown that hydrodynamics of bubble column can be estimated with computational fluid dynamic simulations based on Eulerian equations. The results of the simulations are close to experimental results (Baten et. al., 2003; Krishna et. al., 1999; Krishna et. al., 2000; Baten et. al., 2004). The simulations are the best way to study the mixing and liquid current flows in a bubble column because experimentation is time consuming, costly, and it is difficult to separate effects of interdependent variables by testing. CFD simulations will allow variable affects to be studied and optimized before a system is designed and tested.

Summary

1. Factors influencing hydrodynamics of bubble columns are superficial velocity, bubble diameter, column geometry (reactor walls), use of antifoaming agents and pressure.
2. Porous membrane based bubble column reactors may have larger volumetric gas transfer coefficient than traditional sparged bubble columns.
    - From Equations 1 and 2 the volumetric mass transfer coefficient is a linear function of superficial gas velocity and superficial gas velocity is directly proportional to gas holdup.
    - From Equation 2 gas holdup increases when superficial gas velocity is increased and mean bubble velocity remains constant. Bubble columns with a porous membrane allow the phenomenon to take place while a sparged system does not.
    - Equation 3 relating interfacial area of the gas-liquid phase, bubble diameter and gas hold up shows that a large number of small bubbles is more suitable than a large fewer bubbles at transferring mass from the bubble to the liquid. Porous membranes have been shown to produce more bubbles with increased superficial gas velocity.
    - Resistance to air flow offered by a porous member with an increase in superficial gas velocity is marginal when compared to sparged systems.
3. Different types of gas-liquid flow regimes are bubbly flow, churn turbulent flow, slug flow and annular flow. Of the different flows bubbly flow and churn turbulent flows are suitable for PBR.
4. Antifoaming agents decrease mass transfer coefficients and could contaminate growth cultures.
5. When external pressure is applied on the growth medium or when tall bubble columns are used, gas transfer rate is increases.
6. CFD simulations are needed to understand and study the liquid current flow patterns and mixing. The factors affecting mixing are difficult to study individually by experimentation as their hydrodynamic factors are interdependent.

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