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Hydrodynamic Characteristics of Two-Phase Systems in Tapered Bubble Columns

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Abstract: A tapered bubble column (TBC) features a cross-section that gradually expands along its height, forming a distinct type of bubble column reactor. Such geometry promotes intensive mixing and broader particle size dispersion compared with conventional cylindrical columns. This work experimentally investigates the hydrodynamic characteristics of gas bubbles in a tapered column. The reactor, 1.8 m in height, has a diameter expanding from 0.07 m at the base to 0.17 m at the top. Underneath the mixing chamber, there is a perforated sinter element with an average pore size of 1 mm. The test program maintained consistent temperatures for both the air and the liquid. Two tips on a modified electroconductivity probe (to improve reading accuracy) and a high-speed digital camera formed the basis of the bubble monitoring and analysis method (BMAS). Three axial sites, Z/D = 4, 15, and 25 m, with radial velocity ranges of 0.002-0.016 m/s, 0.001-0.01 m/s, and 0.001-0.008 m/s, respectively, were studied under the following conditions: air-water and air-0.5M NaCl solutions with a liquid flow rate of 200 l/hr and superficial gas velocity. All other factors remained the same. Bubble coalescence rate, bubble rise velocity, gas hold-up, and bubble diameter were enhanced when the surface gas velocity was increased. Increases in salt content caused a reduction in bubble diameter from 3 to 2 mm in the air-water and air-brine systems studied.

Keywords: Tapered bubble columns, Two phase flow, Modified electroconductivity probe

Introduction

Conventional bubble columns uniform in cross-section are widely applied in chemical, biological, and environmental engineering for diverse mass- and heat-transfer operations. They are essential in petroleum refining, wastewater treatment, fermentation, crystallization, hydrogenation, coal liquefaction, and air-pollution control processes (Abdulla et al., 2024). Bandyopadhyay and Biswas (2006) found that traditional bubble columns outperform other gas-liquid contacting devices in terms of reaction capacity in the liquid phase, mass transfer efficiency relative to energy input, simplicity of construction and operation, and lack of moving parts. Nevertheless, their performance is often limited by challenges such as bubble coalescence and axial back-mixing between successive zones. A column whose diameter expands gradually upward is termed a tapered bubble column (TBC) a configuration defined by its increasing cross-section from bottom to top. It is guaranteed that larger particles will be suspended at the bottom of the process because the superficial gas velocity is higher there than it is at the top. Unlike cylindrical designs, the tapered geometry minimizes the entrainment of fine particles toward the top section, thus allowing stable suspension of a broader particle-size range within the reactor. The gradual expansion of the flow area also facilitates dynamic pressure recovery, a hydrodynamic feature rarely attainable in standard vertical columns. The dynamic pressure recovery is made possible by this expansion in the flow area. Consequently, tapered columns provide two distinct advantages: the ability to accommodate a wider particle-size distribution and to promote more homogeneous phase mixing (Zhang et al., 2003; Uurasjärvi et al., 2020).

Within tapered systems, a continuous annular shear layer forms around the central plume region, extending along the column height. This structure enhances interfacial mixing and sustains high local turbulence. Compared to a tapered system, the flow pattern in a traditional bubble column is quite different (McLaughlin, 1978; Chen et al., 1989). There has been a major shift. As reported by Ting (2016), turbulence originates within the annular shear layer and gradually propagates outward, transferring energy across the bulk liquid during the entire flow-development period.

The primary objective of this work is to evaluate bubble behavior in two-phase gas–liquid tapered systems as a function of air velocity and column taper angle. The results demonstrate that the average bubble size grows as the air velocity rises, with a maximum difference of 26.79% between the two beds at a dimensionless air velocity of 0.15. Beyond that, the bubble size of the tapering bed is somewhat larger than the columnar bed at higher altitudes. Both the bed expansion ratio and the time-averaged bubble percentage are enhanced when the air velocity rises. Furthermore, when the taper angle increases, the mean proportion of the unfluidised region also grows. The ability of a non-Newtonian pseudoplastic liquid to suspend gas in two tapering bubble columns is the subject of the investigation in Jana et al. (2014a, 2014b) and Jana & Das (2016). The research considers variables such as gas flow velocity, liquid viscosity, bed height, and filter plate orifice diameter. We can build an empirical correlation using system parameters to determine gas holdup, and the results are statistically good.

Ghosh et al. (2015) studied crystal violet adsorption from aqueous solutions using a novel air-agitated tapered bubble column adsorber. Adsorbent preparation using carbonised bamboo leaf powder activated with $ZnCl_2$ allowed them to achieve a maximum percentage removal rate of 99.99% at equilibrium time. They also measured the energy dissipation per unit volume of colored liquid, pressure decrease (2719 to 2837 N/m^2), and adsorption capacity (393.16% mg/g). Ghosh et al. (2015) studied how well a new air-agitated tapered bubble column adsorber could remove crystal violet from water. They achieved a maximum removal rate of 99.99% after reaching a stable state, using an adsorbent made from powdered carbonised bamboo leaves treated with ZnCl2. A maximum removal rate of 99.99% was reached at the end of the process using an adsorbent made from powdered carbonised bamboo leaves treated with $ZnCl_2$. Energy dissipation per unit volume of colored liquid was 3931.6 mg/g, and the pressure decrease ranged from 2719 to 2837 N/m^2.

Cylindrical bubble columns' interfacial area (a) and hold-up (g) were investigated in research by Bandyopadhyay et al. (2006,2009,2011). The researchers found a dearth of comparable investigations in tapered bubble columns. Within the range of 0.466 to 0.534, the εg values produced by the CO_2-NaOH system were 20% higher than those produced by the air-water system. Not only that, but these numbers were far greater than those of previous buildings. We discovered that the g values from the air-water system were greater compared to the data presented for a column with a shorter tapered angle.

According to Saien et al. (2007), a UV light was placed in the center of a circulating up flow reactor that had an annular and conic body shape to avoid dead zones. With these parameters set – 40 mg/l catalyst, 6.2 pH, 45 degrees Celsius, and 2 hours of irradiation – we were able to remove around half of the COD and degrade nearly all of the dye.

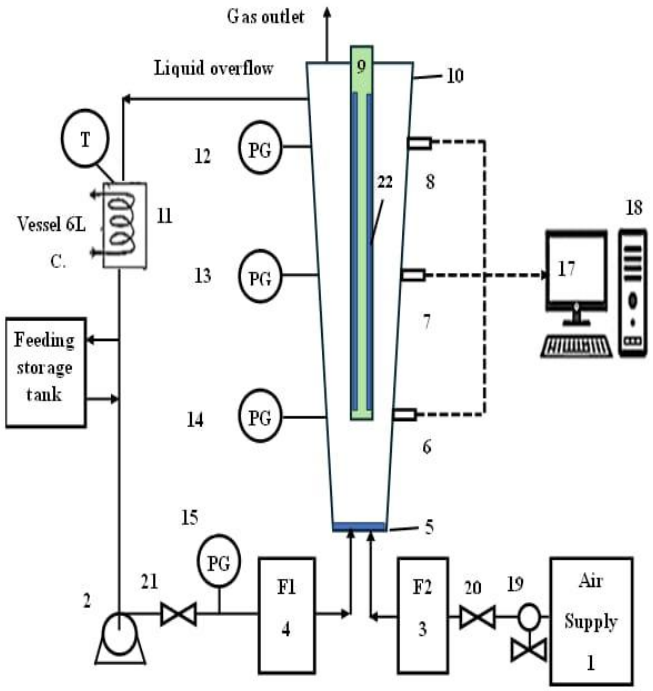
Despite several prior investigations, comprehensive experimental data on tapered bubble columns employing modified electro-conductivity sensors remain limited, warranting further research. Gas holdup (both locally and globally), bubble diameter, and bubble rise velocity are some of these factors. Moreover, the influence of dissolved salts (NaCl) on the hydrodynamic parameters of TBCs has not yet been systematically explored, representing a critical gap addressed in the present stuy.

Hydrodynamic parameters such as bubble size, rise velocity, and gas hold-up were measured at three different locations: in the column's center, halfway between the center and the wall, and near the wall using a set of three screw probes. After studying two different systems (air-water and air-brine) to predict gas holding up, a practical relationship was created based on the pressure drops in the two-phase flow in tapered bubble columns.

Method

Description of the Apparatus

The hydrodynamic experiments were conducted in a transparent tapered bubble column made of Plexiglas®, as illustrated in Figures 1 and 2. The system consisted of a lower plenum where air and the working liquids (tap water and 0.5 M NaCl solution) were mixed, and an upper plenum serving as the gas–liquid separator. The column had a total height of 1.8 m and a taper angle of 1.6°, with the internal diameter gradually increasing from 0.07 m at the base to 0.17 m at the top. The liquid was circulated using a centrifugal pump, while air was supplied from a 120 LT compressor. The air was introduced through a sintered distributor positioned at the base of the column. This distributor contained 91 perforations, each with an average pore diameter of 1 mm, ensuring uniform gas dispersion throughout the test section. Flow meters were used to regulate and monitor both air and liquid flow rates, with air ranging from 0 to 12 L/min and liquid from 0 to 1600 L/h. Measurements were obtained at three axial locations corresponding to dimensionless heights Z/D = 4, 15, and 25. Each axial position was equipped with conductivity measurement ports labeled INF (bottom), MED (middle), and SUP (top). Gas holdup and bubble characteristics were evaluated at three radial positions – center, midway, and near the wall. The electro-conductivity probe used for this purpose was modified with two fine tips to enhance sensitivity and signal resolution. Pressure measurements were collected via four tap points placed 0.1, 0.4, 0.4, and 0.25 m above the gas distributor, connected to Bourdon-type pressure gauges (0–250 mbar). The differential pressures at these locations were employed to calculate overall gas holdup. Figure 3 presents the interface system connecting the sensors to the computer, while Figure 4 shows the signal calibration and processing arrangement.



Item No.	Description
1	Air supply(compressor)
2	Water pump
3	Gas flowmeter
4	Liquid flow meter
5	Micro bubble distributer (91 Holes, 1mm Di. of each hole)
6 to 8	Conductivity probe1,2,3
9	Quartz glass pipe
10	Tapered column (1.8m height, 0.07m at the bottom to 0.17m at the top)
11	Heat exchanger
12 to 15	Pressure gage
16	Feeding storge tank
17	Laptop for data record
18	data acquisition
19	Air filter regulator
20	Liquid flow control valve
21	Gas flow control valve
22	LED lamps

Figure 1. The preliminary schematic of the experimental setup.

Figure 2. Photographic picture of the experimental setup

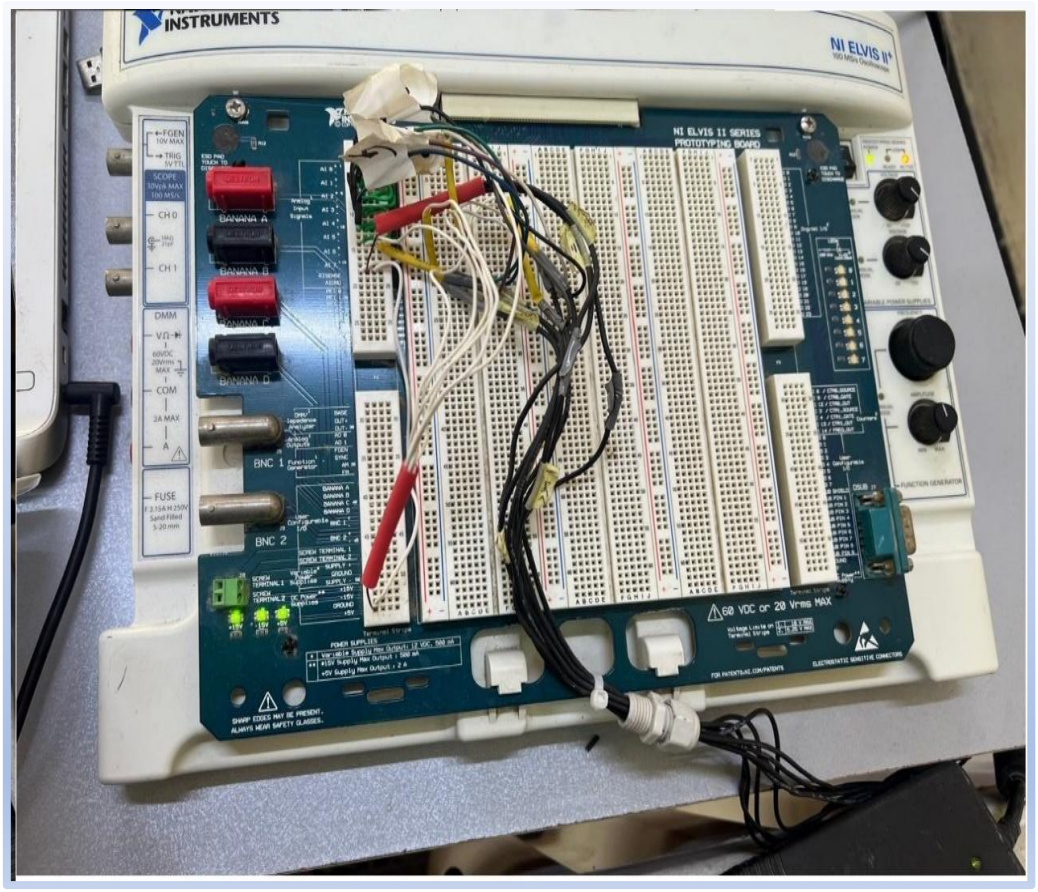


Figure 3. The interface of electroconductivity signals to the computer

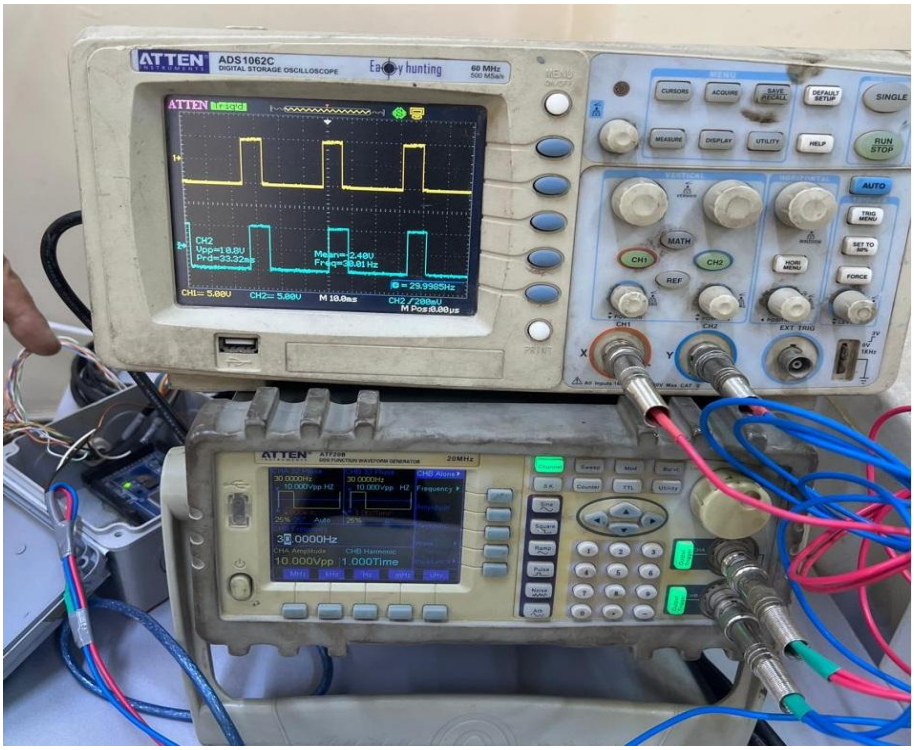


Figure 4. Modified electroconductivity signals output from computer and calibration using standard puls generation device

Experimental Procedure

The experiments were performed using two liquid systems: air–water and air–0.5 M NaCl. The superficial gas velocity varied from 2 mm/s to 16 mm/s, while the liquid flow rate was fixed at 200 L/h. Sodium chloride was dissolved in distilled water to prepare the salt solution, and all tests were carried out under ambient temperature and atmospheric pressure. Air was introduced at the base of the column through the perforated distributor to generate bubbles uniformly.

Hydrodynamic parameters, including gas holdup, bubble size, and rise velocity, were measured at three radial positions using the modified conductivity probe. Each set of measurements was repeated three times to ensure reproducibility and statistical reliability. The liquid temperature was controlled and maintained at 303 K using an external chiller.

For each run, the steady-state condition was confirmed before recording data. Gas holdup was determined by both the local conductivity signals and the overall pressure-drop method. The recorded signals were processed to extract bubble frequency, size distribution, and rise velocity. The high-speed digital camera, positioned at the column midpoint, captured bubble motion to support visual analysis. All experimental results were subsequently correlated with operating parameters such as gas and liquid velocities, density, and viscosity of the working fluids. Table 1 lists the physical properties of the two liquid systems, which were used to interpret the hydrodynamic variations between air–water and air–brine configurations.

Physical Properties Comparison

The physical properties of the two different systems (air-water) and (air-0.5MNaCl) were displayed in Table 1.

Table 1. Physical properties of the two different systems

Physical properties	Air-water system	The salt solution system
Density	988 kg/m3	1021 kg/m3
Viscosity	0.98 mPa.s	1.05mPa.s
surface tension	0.072 mN/m	0.074 mN/m
Contact angle	98°	102°

Results and Discussion

Gas Hold-Up Measured by Modified Electroconductivity Probe

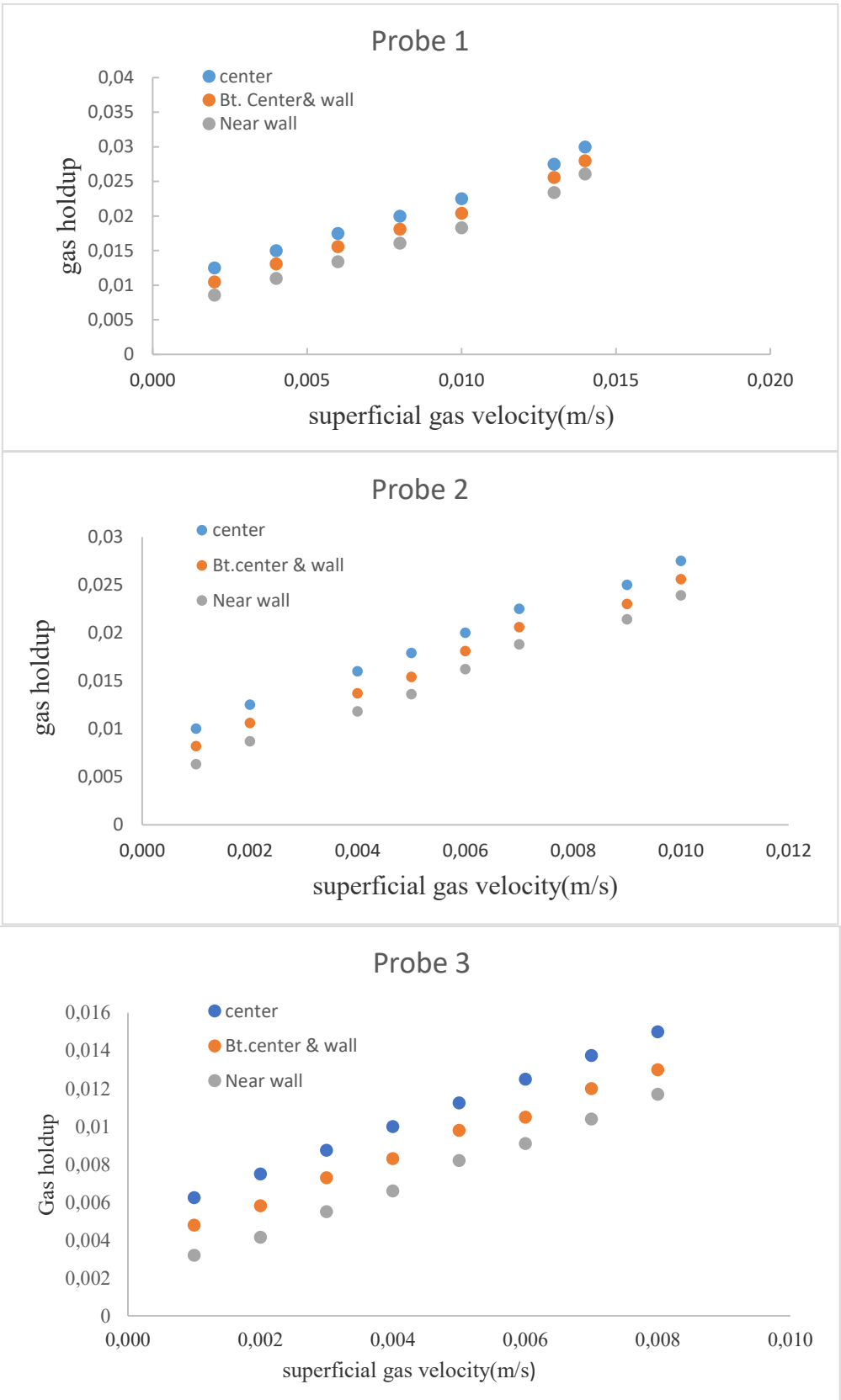


Figure 5. Effect of superficial gas velocity on gas hold-up at probes 1, 2, and 3 respectively at 200L/hr. liquid velocity

Understanding the variation of gas holdup in bubble columns is fundamental for analyzing velocity distributions and residence times of each phase. The gas-phase parameters—including bubble frequency, local gas holdup, and total gas content—strongly influence mass and heat transfer efficiency. Figure 5 illustrates the influence of superficial gas velocity on gas holdup at different axial and radial points within the column. At the middle axial location (probe 2), gas holdup was observed to be approximately 25% higher than at probe 3, while probe 3 showed nearly 95% higher holdup than the lower probe. This pattern confirms that gas velocity decreases progressively along the column height due to the expanding cross-sectional area, which prolongs gas residence time and increases overall gas retention. In radial comparison, the gas holdup was highest at the column center and lowest near the wall, showing a consistent decline along the axial direction. These findings confirm that gas expansion in the tapered column leads to more uniform holdup and extended gas-phase interaction time.

Gas Hold-Up Measured by Pressure Drop

Pressure differences were measured under steady-state conditions with air injected at 1 kg/cm². The pressure data were used to evaluate the overall gas holdup profile along the column. Figures 6 and 7 display how superficial gas velocity affects both bulk and local holdup. The results follow the same trend reported by Rodrigues et al. (2019) and Mokhtari et al. (2019), where an increase in superficial velocity led to enhanced gas holdup due to the formation of a higher number of smaller bubbles, improving gas–liquid contact.

$$\varepsilon g = 1 - \frac{\Delta P}{\Delta P^{\circ}} \quad (1)$$

The overall gas holdup (εg) was determined from the total pressure drop along the column using the relationship described by Su & Heindel (2005).

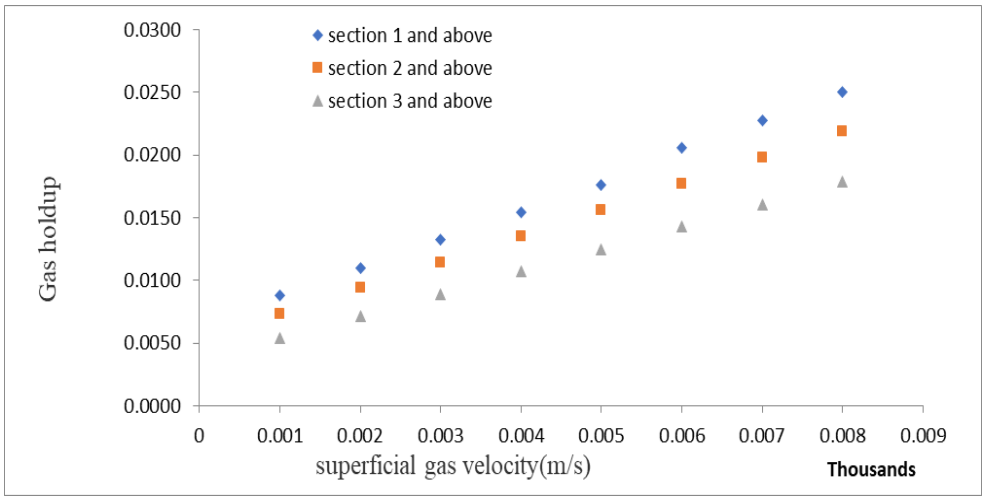


Figure 6. Effect of superficial gas velocity on local gas holds up for three probs in various sections.

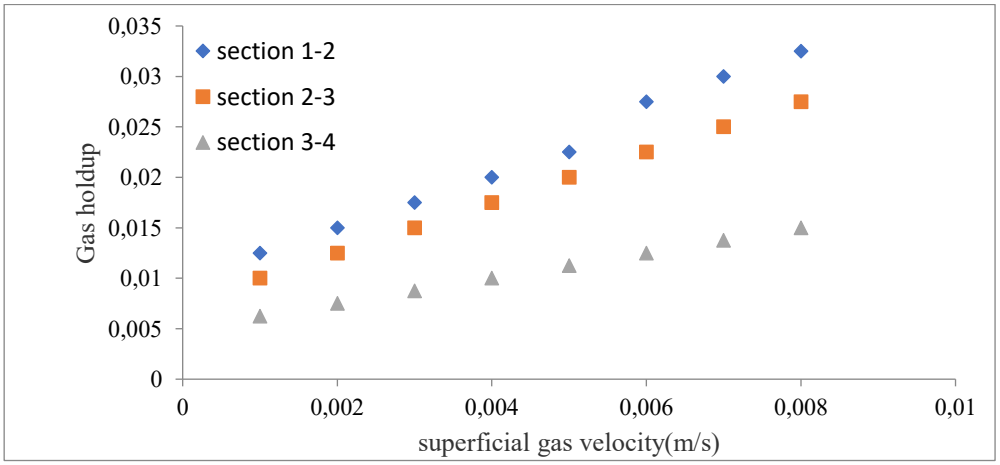


Figure 7. Effect of superficial gas velocity on bulk gas holdup for three probs at different sections.

Bubble Characteristics

Bubble Size Distribution

The dimensions of bubbles are governed by various factors, including gas distributor geometry, buoyancy, drag forces, surface tension, and inertial effects. In this work, bubble size and distribution were evaluated using a modified electro-conductivity probe. Figure 8 shows how bubble diameter varies with superficial gas velocity at three probe positions for both air–water and air–NaCl systems. At probe 1, the central bubble diameter (dbcw) was 12% larger than the bubble diameter between the center and wall (dbbw) and about 25% larger than that measured close to the wall (dbNW). The wall region exhibited reduced bubble coalescence, likely due to higher shear and restricted growth.

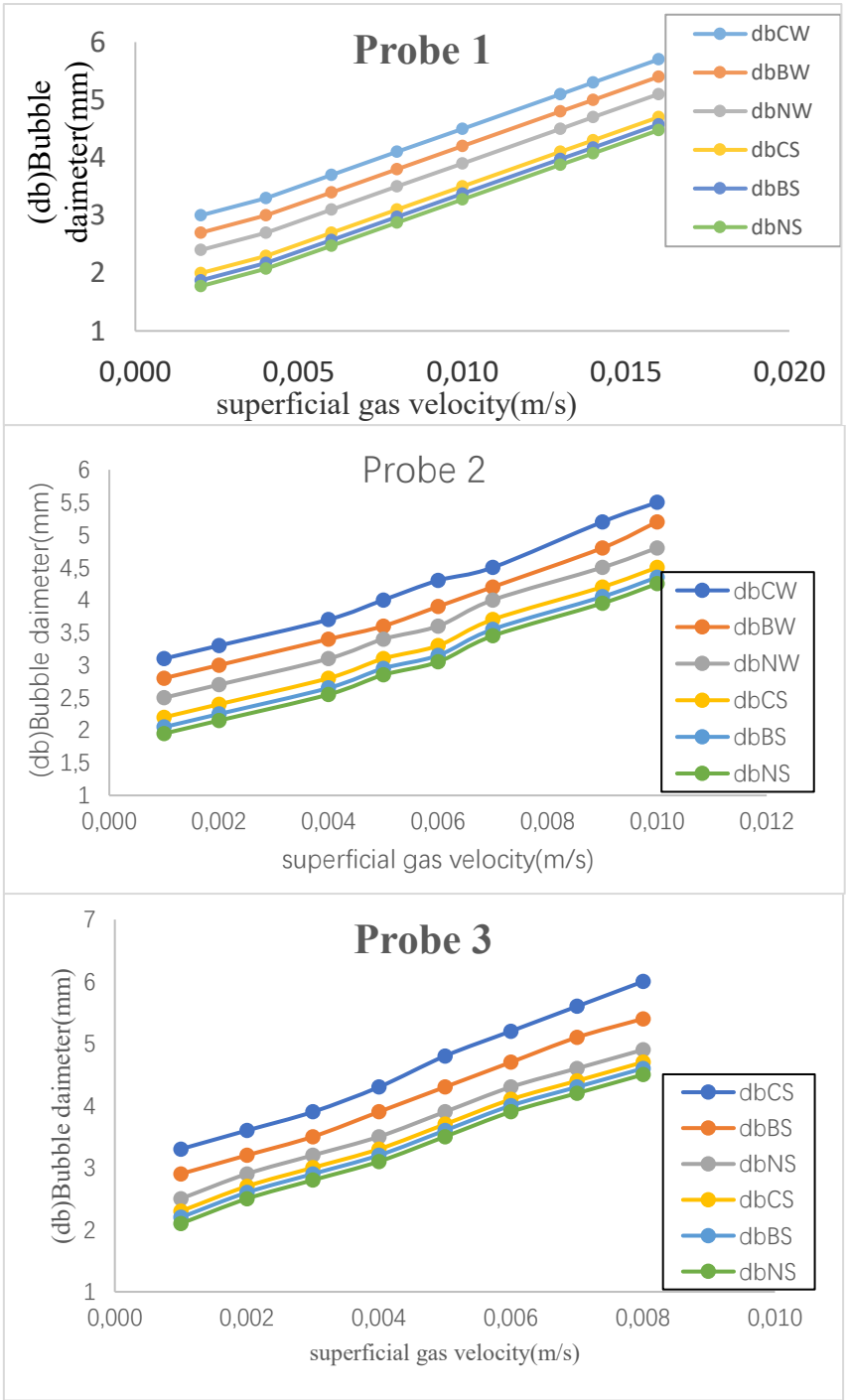


Figure 8. Bubble diameter vs superficial gas velocity at various positions in probes 1, 2, and 3 in the water gas system and (NaCl solution-gas system)

When NaCl was introduced to the system, a notable reduction in bubble size was observed. The average bubble diameter at the column center in the saline system (DBCS) was about 45% smaller than in the pure air–water system (DBCW), confirming that elevated ionic strength suppresses bubble coalescence. This outcome is consistent with results from Biswas et al. (2024) and Hessen Kemper et al. (2020). Figures 9 and 10 further visualize bubble dispersion patterns at gas flow rates ranging from 1 to 5 L/min for both media, showing that bubbles become more uniformly distributed as the gas rate increases.

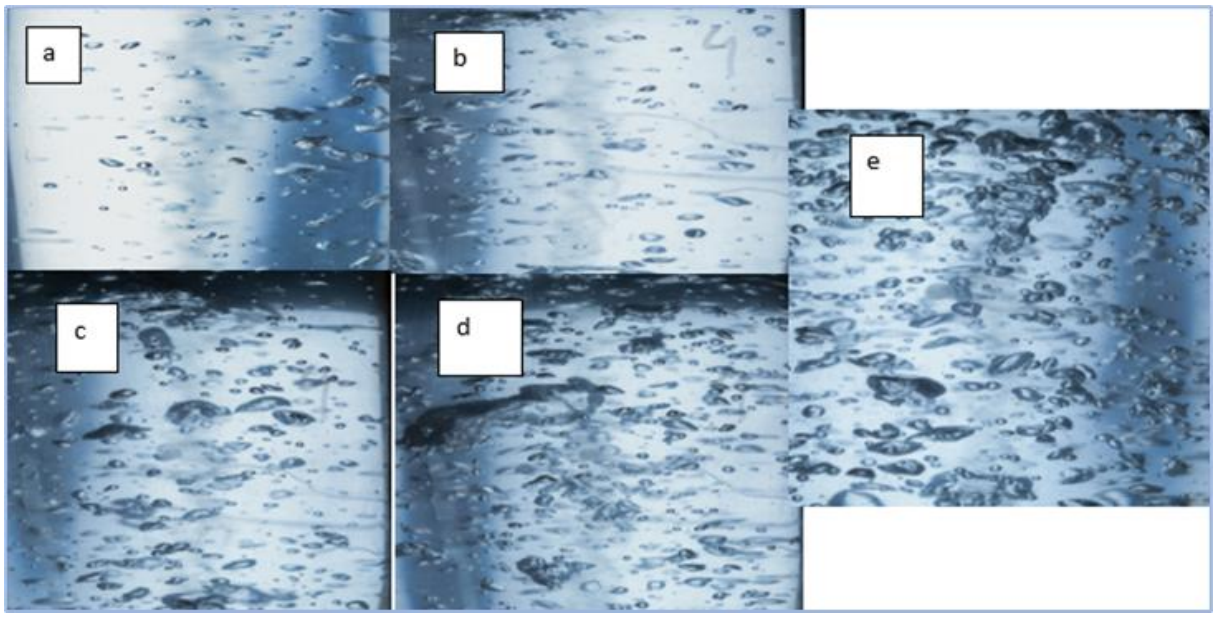


Figure 9. Bubble distribution at various gas flow rates (a) 1 L/min, (b) 2 L/min, (c) 3 L/min, (d) 4 L/min, and (e) 5 L/min in the (water-gas) system.

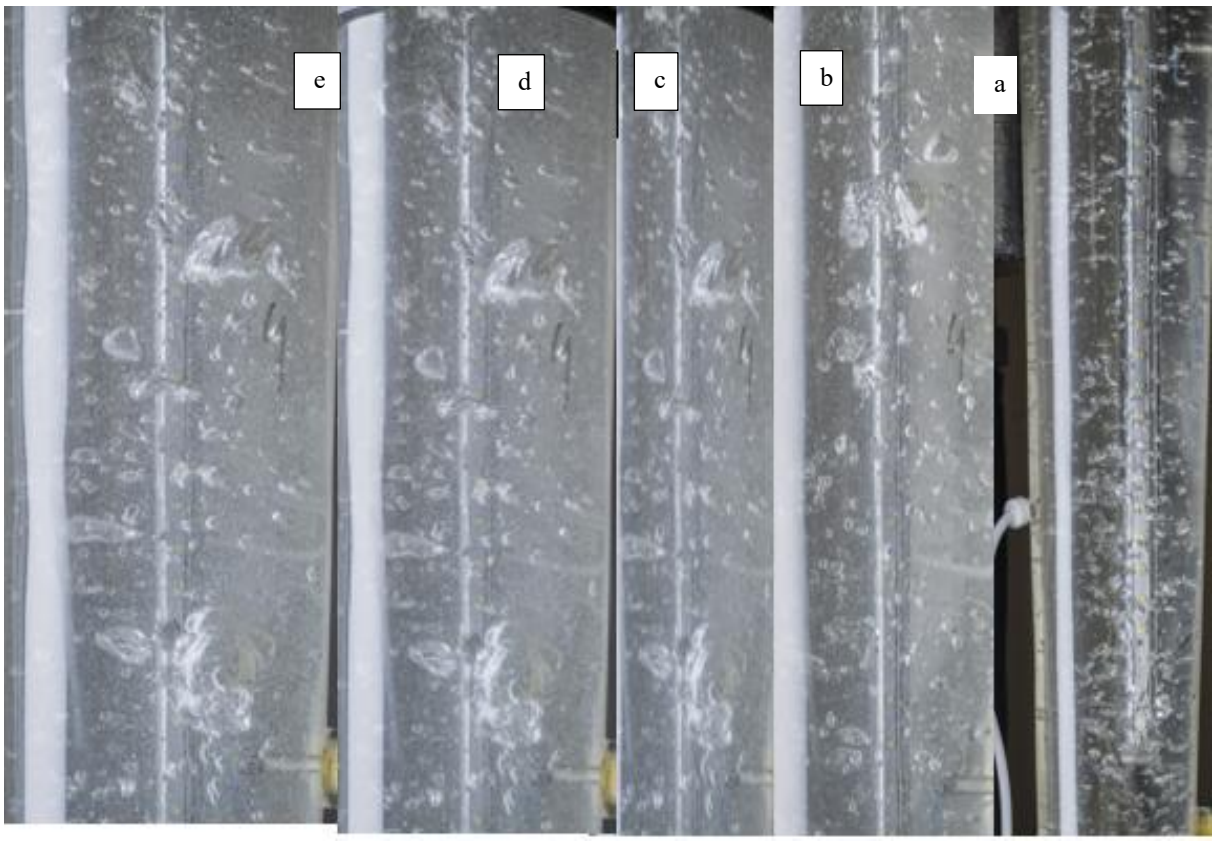


Figure 10. Bubble distribution at different gas flow rates (a) 1 L/min, (b) 2 L/min, (c) 3 L/min, (d) 4 L/min, and (e) 5 L/min (NaCl solution-gas system).

Bubble Rise Velocity

The bubble rise velocity was determined from both probe data and photographic recordings. Figure 11 demonstrates that the bubble rise velocity increases with higher superficial gas velocity but decreases along the column height as the flow area expands. This expansion results in reduced upward momentum and slower terminal velocities at the upper regions. The highest rise velocities occurred near the column center, where both gas velocity and liquid circulation are strongest, while the lowest velocities appeared near the wall. These observations align with the trends described by Raimundo et al. (2019), indicating that larger bubbles ascend faster due to higher buoyancy, while smaller ones experience greater drag.

An experimental study was conducted to investigate hydrodynamic behavior in a tapered gas liquid bubble column. The results indicated that increasing superficial gas velocity led to larger bubble size, faster rise velocity, and higher gas holdup. The expanded column geometry promoted greater mixing and longer gas residence time. Gas holdup values determined from both conductivity and pressure-drop measurements agreed well with the proposed empirical correlation, confirming its predictive capability. The Buckingham π-based dimensionless model effectively represents the interaction between flow variables and column geometry. Future work is recommended to extend this investigation to multi-column configurations and non-Newtonian liquids to broaden the applicability of tapered bubble reactors in industrial processes.

During the time when the superficial gas velocity rose from 0.002 meters per second to 0.016 meters per second, the gas holdup at Port INF decreased from 0.0086 meters per second to 0.0286, which is a large increase. An accurate prediction of gas hold-up is made by the suggested correlation, which takes the form of a dimensionless group. In addition, it is consistent with prior associations that have been documented. One of the most major drawbacks of using TBCs for cleaning purposes is that the installation of sparger discs as column internals may result in substantial cleaning challenges owing to the buildup of pollutants over time. It would be very advantageous to do more studies on the hydrodynamic behavior of a tapered bubble column, making use of fluids that are not often used and a broad variety of physical characteristics. Using digital probes to investigate the hydrodynamic parameter would be very appealing.

Recommendations

Extending the research work on using multicolumn tapered bubble reactor to determine the hydrodynamic parameters of a gas-liquid tapered bubble column.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest to report regarding the present study.

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