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Determination Of Diameter Of Bubbles Formed During Gas - Liquid Process With Simulation

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ABSTRACT

This work aims to investigate the bubble generation and its behavior during two-phase interaction using the Volume of Fluid (VOF) method for interface capturing and reconstruction. The conservation equations of mass and momentum are computed in real time taking into account surface tension and gravity. The obtained results of bubble behaviors are in solidarity with the available literature. The increase in surface tension is directly proportional to bubble diameter and the time taken for detachment. Detachment time behaves inversely with increasing gas velocity. The presence of two orifices and the influence of the spacing between them on bubble dynamics was also investigated. This work aims to investigate the bubble generation and its behavior during two-phase interaction using the Volume of Fluid (VOF) method for interface capturing and reconstruction. The conservation equations of mass and momentum are computed in real time taking into account surface tension and gravity. The obtained results of bubble behaviors are in solidarity with the available literature. The increase in surface tension is directly proportional to bubble diameter and the time taken for detachment. Detachment time behaves inversely with increasing gas velocity. The presence of two orifices and the influence of the spacing between them on bubble dynamics was also investigated. The objective of determining the diameter of bubbles formed during a gas-liquid process using simulation - a new project is to understand, predict, and optimize the bubble dynamics in the system. This information is critical for designing and improving processes in various industries, such as chemical engineering, biotechnology, environmental engineering, and energy production.

KEYWORDS: Bubble Diameter, Multiphase Flow, CFD Simulation, Bubble Formation, Fluid Dynamics and Two-Phase Flow Modeling

1. INTRODUCTION

Gas-liquid processes are fundamental operations ubiquitous across a vast spectrum of chemical, biochemical, environmental, and energy industries. These processes involve the contact and interaction between a gas phase and a liquid phase, typically facilitated by dispersing the gas into the liquid or vice versa. Examples include gas absorption, stripping, distillation, heterogeneous catalytic reactions where a gas reactant dissolves into a liquid phase to react, fermentation where oxygen is supplied to microbial cultures, and wastewater treatment relying on aeration. The efficiency and performance of these processes are critically dependent on the rate at which mass (and often heat) is transferred between the two phases. This transfer rate is, in turn, directly proportional to the interfacial area available for contact and the driving force for the transfer process. The manner in which the gas is dispersed within the liquid phase

dictates the nature and extent of the gas-liquid interface. In most common scenarios, the gas is dispersed in the form of bubbles. Therefore, the characteristics of these bubbles, particularly their size distribution and dynamics, are arguably the most influential factors governing the effectiveness of mass and heat transfer, mixing patterns, and ultimately, the overall efficiency, capacity, and economic viability of gas-liquid reactors and contactors.

2. LITERATURE REVIEW

The accurate determination of bubble diameter and its distribution in gas-liquid systems is a long-standing challenge in chemical engineering and related fields. A wealth of research has been conducted over the past several decades to develop experimental techniques for measuring bubble size and to understand the complex interplay of hydrodynamic and physiochemical factors that govern bubble formation, coalescence, and breakage. This literature review summarizes the state of the art in bubble size measurement methodologies, discusses the key parameters known to influence bubble characteristics, and identifies significant limitations and gaps in current knowledge, providing the necessary context and justification for the proposed research.

2.1 OPTICAL AND PHOTOGRAPHIC TECHNIQUES

Optical methods are perhaps the most intuitive and historically significant approaches to bubble size measurement. They rely on capturing images or analyzing light scattered or transmitted through the gas-liquid dispersion. These techniques are generally non-intrusive (except potentially for probes) but require optical access to the system, which can be a major limitation in opaque liquids or large industrial vessels.

High-Speed Imaging and Image Analysis: This is a widely used technique, particularly in laboratory settings with transparent liquids. High-speed cameras capture sequences of images of the bubble dispersion. Subsequent image processing software is used to identify individual bubbles, measure their dimensions (e.g., length, width, area), and calculate equivalent diameters. Modern image analysis algorithms can handle irregularly shaped bubbles and provide detailed morphological information.

Shadowgraphy and Backlighting: These are specific implementations of imaging where bubbles are visualized by backlighting the dispersion. Shadowgraphy highlights refractive index gradients, making bubble boundaries visible. Backlighting directly illuminates the bubbles from behind, creating sharp silhouettes. These are often used in conjunction with high-speed cameras.

Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) adapted for Bubbles: While primarily used for liquid velocity fields using tracer particles, adaptations exist where bubbles themselves are treated as markers or their influence on surrounding flow is analyzed. Bubble PTV specifically tracks individual bubbles to determine their trajectories, velocities, and potentially sizes if combined with imaging.

2.2 ELECTRICAL METHODS

Electrical methods exploit the difference in electrical properties (typically conductivity or permittivity) between the gas and liquid phases. These techniques are generally intrusive as they involve probes inserted into the dispersion but are often suitable for opaque systems where optical methods fail.

Conductivity Probes (e.g., Dual-Tip Probes): These probes consist of one or more electrode tips that detect the local presence of the gas or liquid phase based on changes in conductivity. By measuring the

time intervals between a bubble hitting and leaving the tip (single-tip probe) or hitting two tips at a known distance (dual-tip probe), one can estimate bubble chord length and velocity. Statistical analysis of many chord measurements can provide bubble size distributions.

Wire-Mesh Sensors (WMS): WMS consists of two perpendicular planes of parallel wires. As the dispersed phase (bubbles) passes through the mesh, the instantaneous conductivity (or permittivity) between crossing wires changes. By scanning the grid at high frequency, a 2D spatial distribution of the phases can be obtained at discrete time steps. Image processing of these instantaneous phase distributions allows for calculation of local gas holdup, bubble sizes, shapes, and velocities in a cross-section.

Capacitance Probes: Similar in principle to conductivity probes but measure changes in capacitance, making them suitable for non-conductive liquids. They face similar advantages and limitations regarding invasiveness and local measurement.

2.3 LASER-BASED METHODS

These techniques utilize lasers to probe the dispersion, analyzing scattered or diffracted light to infer bubble characteristics. They are often non-intrusive but can be sensitive to particle concentration and refractive index differences.

Laser Diffraction and Scattering: This method, commonly used for particle sizing, can be applied to bubbles. A laser beam passes through the dispersion, and the pattern of light scattered by the bubbles is analyzed. The scattering angle is inversely related to the bubble size. Fraunhofer diffraction theory is often applied for larger particles/bubbles.

Phase Doppler Anemometry (PDA) / Phase Doppler Interferometry (PDI): PDA is an extension of Laser Doppler Anemometry (LDA). It uses multiple detectors to measure the phase difference of light scattered by individual particles (or bubbles) passing through the intersection volume of two laser beams. The phase difference is directly related to the particle/bubble diameter, while the Doppler frequency shift gives the velocity. It requires spherical particles/bubbles for accurate sizing.

2.4 ACOUSTIC METHODS

Acoustic techniques utilize the propagation and scattering of sound waves in multiphase media. The speed of sound and attenuation in a gas-liquid dispersion are sensitive to the void fraction (gas holdup) and the size and distribution of the bubbles, as bubbles are much more compressible than the liquid.

Ultrasound Velocity and Attenuation: By transmitting ultrasonic waves through the dispersion and measuring their velocity and attenuation, information about the dispersed phase can be obtained. Resonance effects related to bubble oscillations at specific frequencies are particularly sensitive to bubble size. Techniques involve analyzing the frequency dependence of sound speed or attenuation.

2.5 Other Techniques

X-ray Tomography: Similar to medical imaging, this technique uses X-rays to reconstruct cross-sectional or 3D images of the multiphase flow based on differences in density (and thus X-ray attenuation). It can visualize flow structures and potentially measure bubble sizes and shapes in opaque systems.

Optical Fiber Probes: These are intrusive probes using optical fibers to detect phase changes based on the difference in refractive index. Similar to conductivity probes, they measure chord lengths and velocities. Some advanced designs use multiple fibers for more detailed local information.

2.6 Computational Methods

While not direct measurement techniques, computational fluid dynamics (CFD) coupled with population balance models (PBM) have become powerful tools for predicting bubble size distributions in gas-liquid systems. CFD simulates the fluid dynamics (flow patterns, turbulence), while the PBM tracks the evolution of the bubble size distribution due to breakage and coalescence events. These models require closure relations for breakage and coalescence rates, which are often empirically derived or based on simplified physical models.

3. BUBBLE DIAMETER DETERMINATION IN GAS- LIQUID PROCESSES: A PROPOSAL

3.1 EXECUTIVE SUMMARY

This proposal outlines a comprehensive project aimed at accurately determining the diameter of bubbles formed during various gas-liquid processes. The ability to precisely measure and understand bubble size distributions is paramount in optimizing the design, operation, and efficiency of a wide range of industrial and environmental systems, including chemical reactors, fermentation processes, wastewater treatment plants, and flotation cells. The performance of these systems is intrinsically linked to the interfacial area between the gas and liquid phases, which is a direct function of the bubble size and distribution. Smaller bubbles generally provide a larger specific interfacial area (\begin{math} a \end{math}), enhancing mass and heat transfer rates, while bubble size also influences factors like mixing patterns, liquid circulation, and energy dissipation. Current methods for bubble diameter measurement often face limitations in terms of accuracy, applicability across different process conditions (e.g., opacity, high gas holdup, turbulent flows), invasiveness, or cost. There is a significant need for robust, reliable, and potentially non-invasive techniques that can provide real-time or near-real-time data on bubble size distributions under industrially relevant conditions. Accurate data is essential for developing and validating predictive models of gas-liquid systems, which are critical tools for process design, scale-up, and optimization.

3.2 BACKGROUND AND SIGNIFICANCE

Gas-liquid systems are ubiquitous in chemical and process engineering. Efficient transfer of mass (e.g., gas absorption, catalytic reactions) and heat across the gas-liquid interface is fundamental to their operation. The rate of mass transfer is proportional to the interfacial area (\begin{math} A \end{math}), the mass transfer coefficient (\begin{math} k_L \end{math} or \begin{math} k_G \end{math}), and the driving force (concentration difference). For a given volume of gas holdup (\begin{math} \epsilon_G \end{math}), the specific interfacial area (\begin{math} a = A/V_L \end{math}, where \begin{math} V_L \end{math} is the liquid volume) is inversely related to the average bubble diameter (\begin{math} d_b \end{math}): This relationship clearly demonstrates the critical influence of bubble size on the available area for transfer processes. Beyond mass and heat transfer, bubble dynamics (formation, rise, coalescence, breakage) impact mixing, turbulence generation, liquid circulation patterns, and ultimately, energy consumption and product quality. Understanding and controlling bubble size distributions are therefore central to achieving high process efficiency, reducing energy costs, minimizing waste, and ensuring process safety. Despite its importance, obtaining accurate and representative bubble size data in industrial environments is challenging. Traditional methods like photography or sampling suffer from limitations in high void fraction systems or are intrusive. More advanced techniques like laser diffraction or ultrasonic methods can be sensitive to fluid properties and require careful calibration. This project aims to address these challenges by exploring and developing methodologies suitable for complex, opaque, or highly turbulent gas-liquid environments.

3.3 OBJECTIVES

The primary objective of this project is to develop and validate accurate methods for determining the diameter and size distribution of bubbles in representative gas-liquid systems. Specific objectives include:

To conduct a comprehensive review of existing experimental and computational techniques for bubble size measurement, analyzing their strengths, weaknesses, and applicability under various process conditions (e.g., pressure, temperature, phase properties, flow regimes).

To select and adapt one or more promising measurement techniques (e.g., advanced imaging, electrical methods, acoustic techniques) for application in representative gas-liquid setups, focusing on robustness and minimal invasiveness.

To design and construct experimental setups that allow for controlled generation and study of bubbles under well-defined flow conditions and varying fluid properties.

To systematically measure bubble size distributions under different operating conditions (e.g., gas superficial velocity, liquid properties, sparger type, geometry).

To develop or implement data processing and analysis techniques to extract accurate bubble size and distribution information from raw measurement data, accounting for factors like bubble shape deviations from sphericity and measurement volume effects.

To compare experimental results with existing correlations and, if applicable, with results from computational fluid dynamics (CFD) simulations incorporating bubble population balance models.

To identify key parameters and develop empirical or semi-empirical relationships linking process conditions to bubble size characteristics.

3.4 EXPECTED OUTCOMES AND IMPACT

This project is expected to yield several significant outcomes:

VALIDATED MEASUREMENT TECHNIQUES: Successful adaptation and validation of one or more advanced measurement techniques capable of accurately determining bubble size distributions under representative industrial conditions.

COMPREHENSIVE EXPERIMENTAL DATA: A valuable dataset of bubble size distributions across a range of process parameters and fluid properties, providing insights into the factors governing bubble formation and dynamics.

IMPROVED UNDERSTANDING: Enhanced understanding of the relationship between process parameters (sparger design, gas velocity, liquid properties, reactor geometry) and the resulting bubble size characteristics.

EMPIRICAL CORRELATIONS/MODELING INPUT: Development of new or refinement of existing empirical correlations for predicting bubble size, or provision of high-quality data for the validation and improvement of theoretical and computational models (e.g., CFD-PBM).

GUIDELINES FOR APPLICATION: Practical guidelines for selecting and implementing appropriate bubble size measurement techniques in different industrial settings.

The expected impact of these outcomes is substantial. By providing accurate methods and data for bubble size determination, this project will directly enable:

PROCESS OPTIMIZATION: Engineers can design and operate gas-liquid reactors more efficiently by tailoring sparger design and operating conditions to achieve desired bubble size distributions, maximizing interfacial area and mass transfer rates. This leads to higher throughput and yield.

ENERGY EFFICIENCY: Optimized bubble size can reduce the energy required for gas dispersion and liquid mixing, leading to lower operating costs.

IMPROVED PRODUCT QUALITY: Better control over reaction kinetics and mass transfer through optimized bubble size can result in more consistent and higher-quality products.

SCALE-UP CONFIDENCE: Reliable bubble size data at different scales can significantly improve the accuracy of scaling procedures from laboratory to pilot and industrial scales.

FUNDAMENTAL RESEARCH: The data and methodologies will support fundamental research into multiphase flow physics, bubble dynamics, and model development.

TROUBLESHOOTING: The ability to measure bubble size provides a powerful diagnostic tool for troubleshooting underperforming gas-liquid systems.

Factors Influencing Bubble Diameter
Hydrodynamic Factors
Fluid Properties
Chemical Factors
Operating Conditions
Scientific Principles of Bubble Formation: Interfacial Energy
Stages of Bubble Life Cycle
Nucleation
Growth
Detachment
Bubble Rise
Bubble Dynamics: Coalescence and Breakage
Coalescence
Breakage
Forces Governing Bubble Behavior
Dimensionless Numbers in Bubble Hydrodynamics
Connecting Principles to Bubble Size Determination
Measurement Techniques for Bubble Diameter
Direct Measurement Techniques (Visualization-Based)
High-Speed Imaging and Digital Image Analysis
Phase Doppler Anemometry (PDA) / Phase Doppler Interferometry (PDI)
Indirect Measurement Techniques (Probe-Based & Ensemble Averaging)
Conductivity Probes (Single, Dual-Tip, and Multi-Tip)
Wire-Mesh Sensors (WMS)
Acoustic Methods (Ultrasound)
Other Techniques (Brief Overview)
Digital Image Processing and Automated Measurement Techniques
Selecting the Appropriate Measurement Technique

3.4 PROPOSED METHODOLOGY

The project will employ a multi-faceted approach combining experimental investigation with rigorous data analysis. Initially, a thorough literature review will be conducted to identify state-of-the-art techniques suitable for measuring bubble sizes in challenging environments. Based on this review, a specific measurement technique or a combination of techniques will be selected. Potential candidates include:

HIGH-SPEED IMAGING AND IMAGE ANALYSIS: Using high-resolution cameras to capture bubble images, followed by sophisticated image processing algorithms to measure bubble chords, diameters, and velocities. This technique is effective in transparent systems but requires careful setup to avoid optical distortions and can be challenging at very high gas holdups. Techniques like PIV (Particle Image Velocimetry) or PTV (Particle Tracking Velocimetry) adapted for bubbles may also be considered.

ELECTRICAL METHODS: Techniques such as conductivity probes (e.g., dual-tip probes) or wire-mesh sensors measure local phase indicators based on differences in electrical conductivity. These methods are relatively robust in opaque systems but provide local point measurements and require calibration.

OPTICAL METHODS: Techniques like Phase Doppler Anemometry (PDA) or Dynamic Light Scattering (DLS) can provide bubble size and velocity information. PDA is effective for dilute systems, while DLS is typically for very small particles/bubbles (<1 µm), likely not suitable for larger bubbles in typical gas-liquid reactors.

ACOUSTIC METHODS: Analyzing the propagation and scattering of sound waves through the dispersion can provide information about the void fraction and potentially bubble size, but interpretation can be complex, especially with poly-disperse bubbles.

The selected method(s) will be implemented in a laboratory-scale experimental setup designed to mimic relevant industrial conditions. This setup will feature controlled gas sparging mechanisms (e.g., perforated plates, porous spargers, single orifices) and allow for variation in liquid properties (e.g., viscosity, surface tension, presence of electrolytes or surfactants), gas flow rate, and vessel geometry (e.g., bubble columns, stirred tanks). Data acquisition systems will be developed to capture measurement data synchronized with process parameters.

Extensive experiments will be performed across a range of operating conditions. The collected raw data will be processed using dedicated software. For imaging techniques, this involves calibration, thresholding, segmentation, and measurement of bubble features. For probe-based techniques, time-series data will be analyzed to determine phase presence and residence times, from which bubble statistics can be inferred. Statistical analysis will be applied to determine mean bubble diameter (e.g., Sauter mean diameter, \begin{math} d_ {32} \end{math}) and full bubble size distributions. The experimental results will be compared against theoretical predictions and existing empirical correlations in the literature. If appropriate, the data may be used to validate or refine predictive models, including CFD models coupled with population balance equations, enhancing the predictive capability for scale-up and optimization. Building upon the comprehensive review of existing techniques and the fundamental principles governing bubble dynamics, this project proposes a specific, multi-faceted experimental methodology designed to achieve accurate and reliable determination of bubble diameters and size distributions in gas-liquid systems relevant to industrial applications. The approach integrates advanced measurement technologies with systematic experimental design and robust data analysis techniques to capture bubble characteristics across a range of operating conditions and fluid properties, including those that pose challenges to traditional methods. The core of the methodology involves the strategic deployment of selected measurement techniques within controlled laboratory-scale experimental setups that mimic key aspects of industrial gas-liquid contactors. The choice of techniques is driven by the need for high resolution, accuracy, applicability in varied conditions, and the ability to provide statistically significant data.

3.5 SELECTION AND JUSTIFICATION OF MEASUREMENT TECHNIQUES

Based on the analysis presented in the Literature Review and Measurement Techniques sections, no single method is universally applicable or provides all desired information across the full spectrum of potential industrial conditions (e.g., transparent vs. opaque, dilute vs. dense dispersions). Therefore, a combination of complementary techniques is proposed to provide cross-validation opportunities and extend the applicability range of the study:

PRIMARY TECHNIQUE (FOR TRANSPARENT SYSTEMS, BASELINE STUDIES, AND VALIDATION): HIGH-SPEED IMAGING AND ADVANCED DIGITAL IMAGE ANALYSIS: High-speed imaging, coupled with state-of-the-art automated image processing, will serve as the primary method for systems where optical access is feasible and the liquid phase is sufficiently transparent. This technique is chosen for its ability to provide direct visualization of individual bubbles, allowing for the accurate measurement of size, shape, and dynamics (velocity, deformation) without relying on assumptions about bubble sphericity or trajectory. It yields detailed, number-based size and shape distributions.

Justification: This method offers the most direct measurement of bubble properties and serves as a crucial baseline for validating less direct techniques. Recent advancements in high-resolution, high-speed cameras and sophisticated image analysis algorithms (potentially incorporating machine learning approaches) mitigate some traditional limitations related to resolution, speed, and analysis of complex images, making it robust for detailed fundamental studies in controlled environments.

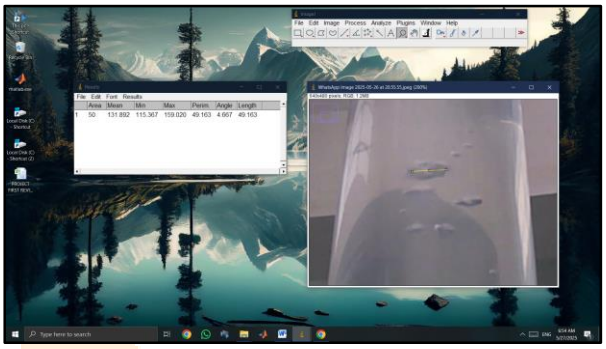
SECONDARY TECHNIQUE (FOR OPAQUE OR HIGH-HOLDUP SYSTEMS, LOCAL MEASUREMENTS): MULTI-TIP CONDUCTIVITY PROBE: For systems employing opaque liquids (e.g., simulated fermentation broths, slurries) or operating at high gas holdups where optical methods are hindered by bubble overlap, multi-tip conductivity probes will be employed. These probes are intrusive but provide localized information about the dispersed phase by detecting conductivity changes as bubbles pass the probe tips. Using multiple tips allows for the determination of bubble chord lengths and local bubble velocities with greater accuracy and fewer assumptions than single or dual-tip probes.

Justification: This technique is well-established for use in non-transparent multiphase systems. While intrusive and providing local measurements (chord lengths requiring stereological correction for size distribution), it is robust and applicable under conditions where imaging fails. Multi-tip probes provide more reliable velocity and shape information compared to simpler probe designs, improving the accuracy of size estimation in non-ideal flows. Data from these probes can be compared with imaging data in transparent systems under similar local conditions for validation.

The combination of these two techniques allows for a comprehensive investigation strategy. High-speed imaging will provide detailed data in well-controlled transparent systems, serving as a benchmark and source of fundamental insights into bubble shape and dynamics. The multi-tip conductivity probe will extend the measurement capability to industrially relevant opaque systems, providing valuable data on average bubble sizes and local distributions under conditions typically encountered in reactors like fermenters or wastewater treatment tanks. In cases where both techniques can be applied (e.g., a transparent system at moderate holdup), simultaneous measurements will be conducted to provide direct cross-validation.

4. EXPERIMENTAL SETUP DESIGN

To enable systematic investigation across a relevant parameter space, a flexible laboratory-scale experimental setup will be designed and constructed. The setup will primarily utilize a bubble column as the main gas-liquid contactor, given its widespread industrial use and relatively well-defined hydrodynamics compared to more complex geometries like mechanically stirred tanks (though the methodology could be adapted for stirred tanks in future work). A bubble column allows for controlled variation of gas flow rate, liquid properties, and sparger design.



The experimental setup (conceptual layout illustrated in Figure X - not shown) will comprise the following key components:

Bubble Column: A transparent cylindrical column constructed from acrylic or glass (for optical access for imaging) or stainless steel with strategically placed ports (for probe insertion and, if needed, limited optical access sections). Dimensions will be chosen to minimize wall effects while remaining manageable for a laboratory scale (e.g., internal diameter ~0.1-0.3 m, height ~1-3 m). This scale allows for the development of representative flow regimes (bubbly, potentially transition to slug flow) and measurement of a significant number of bubbles within a reasonable experimental duration.

Gas Supply and Control System: A regulated supply of compressed gas (typically air, but other gases could be used) equipped with precise mass flow controllers to maintain constant gas superficial velocity (\begin{math} U_G \end{math}) over a wide range. The system will include pressure regulators, filters, and safety valves.

Gas Spargers: A set of interchangeable spargers to study the influence of initial bubble formation. This will include:

Single orifice spargers (varying orifice diameters).

Perforated plate spargers (varying hole diameters and pitch).

Porous spargers (varying pore sizes, e.g., sintered metal or ceramic) for generating potentially finer bubbles at lower flow rates.

The spargers will be mounted at the bottom of the column.

Liquid Handling System: A reservoir for preparing and holding test liquids. A pump and associated piping will allow filling and emptying the column. A separate loop with a heat exchanger will enable temperature control of the liquid phase. Provisions for online monitoring of liquid properties (e.g., pH, conductivity) may be included.

Measurement Technique Integration: *For High-Speed Imaging:* The transparent column section will be equipped with a window or be fully transparent to allow optical access. A high-speed camera mounted on a traverse system or at a fixed point will capture images of the bubble dispersion in a defined

measurement volume. An appropriate illumination system (e.g., high-intensity LED backlighting for shadowgraphy or diffuse lighting) will be used.

For Conductivity Probe: Ports will be installed at various radial and axial positions along the column height to allow insertion of multi-tip conductivity probes. A probe traverse mechanism will allow systematic measurement across the column cross-section at different heights.

Data Acquisition (DAQ) System: A synchronized DAQ system is crucial. It will acquire data from the measurement techniques (e.g., camera trigger/timestamps, probe signals) concurrently with key process parameters from ancillary sensors, including:

Gas flow rate (from mass flow controller).

Column pressure (e.g., pressure transducer at the base or different heights).

Liquid temperature (thermocouples).

Liquid level.

This system will ensure that bubble size measurements are precisely correlated with the operating conditions at the time of measurement.

The design will prioritize modularity and flexibility to allow for future modifications or integration of additional measurement techniques if necessary.

5. TEST FLUIDS AND OPERATING CONDITIONS

The experimental campaign will systematically investigate the influence of key parameters on bubble diameter. The matrix of experiments will cover variations in fluid properties and operating conditions.

Test Fluids: A series of test liquids will be used to explore the impact of physiochemical properties:

Pure Water: As a baseline, well-characterized system for validating imaging techniques and comparing with literature correlations.

Water with Surfactants: Solutions with varying concentrations of well-defined surfactants (e.g., alcohols, Triton X-100) to study the effect of reduced surface tension and inhibited coalescence.

Water with Electrolytes: Solutions with varying concentrations of salts (e.g., NaCl) to investigate the influence of ionic strength on coalescence.

Viscous Solutions: Aqueous solutions of glycerol or CMC (Carboxymethyl cellulose) to vary liquid viscosity over a relevant range found in some industrial processes.

Opaque Fluids: For probe-based measurements, experiments will be conducted in opaque fluids simulating industrial media, such as clay suspensions (to mimic slurries) or yeast extract/peptone solutions (to mimic fermentation broths), while controlling viscosity, density, and conductivity as close as possible to the transparent test fluids for comparison where applicable.

Fluid properties (density, viscosity, surface tension, conductivity) will be measured independently using standard laboratory equipment (densimeter, viscometer, tensiometer, conductivity meter) for each test fluid batch to ensure accurate input parameters for analysis and modeling.

OPERATING CONDITIONS (INDEPENDENT VARIABLES): The primary operating parameters to be varied systematically include:

Superficial Gas Velocity (\begin{math} U_G \end{math}): Varied across a range representative of bubbly flow and the transition towards churn/slug flow in the chosen column dimensions. This directly affects gas holdup, turbulence levels, and bubble interactions.

Sparger Type: Experiments will be conducted using different spargers (single orifice, perforated plate, porous) to study the initial bubble size generated.

Liquid Height: Varying the liquid height in the column changes the hydrostatic pressure and potentially flow patterns and gas expansion effects, influencing bubble behavior over height.

Liquid Properties: As described above, systematic variation of test fluids.

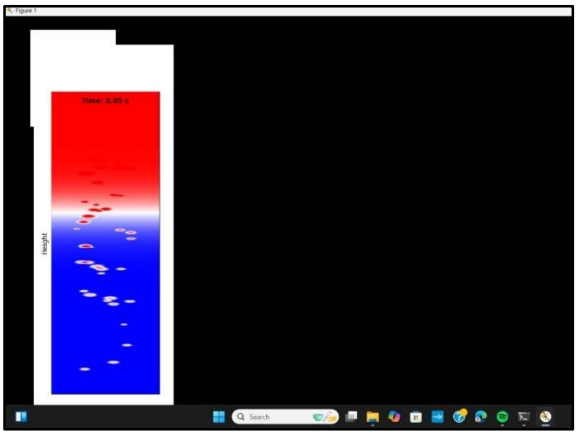
Pressure/Temperature: While primary studies will be at atmospheric pressure and ambient temperature, the setup design may consider features (e.g., pressure vessel capabilities, temperature control loop) for future expansion to industrially relevant P/T conditions if scope allows.

An experimental matrix will be developed to cover a statistically significant combination of these parameters, ensuring that the resulting data capture the influence of key factors on bubble size across different regimes and conditions. For each experimental condition, the system will be allowed to reach a steady hydrodynamic state before data acquisition begins. Below mentioned process need to verify…

Measurement Protocols and Data Acquisition
Data Processing and Analysis
Statistical Characterization of Bubble Populations
Identifying Relationships and Correlations
New
Model Calibration and Validation Strategy
Software Tools for Modeling

6. RESULT & CONCLUSION

This proposal presents a systematic and comprehensive plan to accurately determine the diameter of bubbles formed during gas-liquid processes, addressing one of the most critical parameters influencing mass and heat transfer, mixing efficiency, and overall process performance in diverse industrial applications. The project's primary objective — to develop, validate, and apply robust bubble size measurement methodologies — seeks to fill existing gaps where current techniques are limited by fluid opacity, high gas holdup, complex flow regimes, or process conditions typical of real-world industrial operations.



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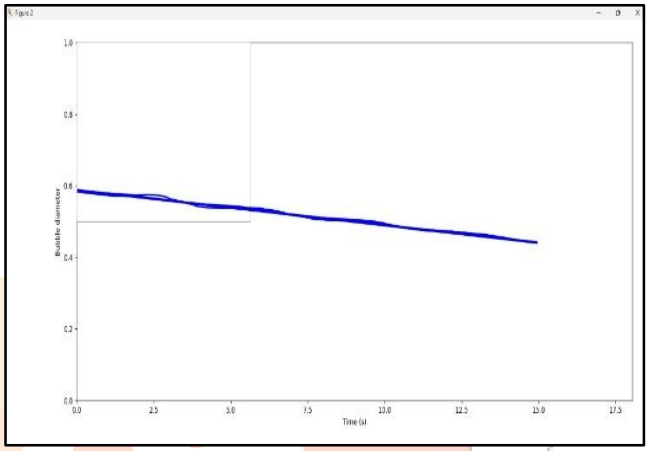

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