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Research Article

Design and Fabrication of Quadrilateral Bubble Column Test Rig for Multiphase Flow Investigations

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Abstract: Bubble column reactor belongs to the general class of multiphase reactors in which gas come in contact with liquid. This reactor purposely used to mix the two phases or substances where the gas is dispersed into the column from the bottom and rises within the liquid and escapses from the upper liquid surface. Throughout the design and development phase, the reactor design specifications were identified to meet the experimental requirements for hydrodynamics study in a bubble column using the high-speed camera, industrial radiotracer, and radioactive particle tracking techniques. This bubble column reactor design comes with six different type of sparger design for various mixing pattern optimization. The design methodology structured as design development process, conceptual design selection process, detailed design specifications, product fabrication, and final product testing. This versatile reactor is developed to overcome the problems faced in understanding hydrodynamics behavior of using different types of sparger design, leading to design optimization for better mixing and blending efficiency in multiphase flow investigations. This study has demonstrated that the newly quadrilateral bubble column reactor is ready to be used for the various types of laboratory assessment including industrial radioactive experiments.

Keywords: high-speed camera, industrial radiotracer, radioactive.

INTRODUCTION

Bubble column reactors frequently employed in biological, chemical and petrochemical industry because of their simple construction and ease of operation [1, 2]. The bubble column is also applied in biochemical processes such as fermentation and biological wastewater treatment [3]. Other application such as Fischer-Tropsch process also used the bubble column concept, for example, indirect coal liquefaction process to produce transportation fuels, methanol synthesis, and manufacture of other synthetic fuels which are more environmentally friendly than petroleum-derived fuels [3, 4]. This type of multiphase system have no moving parts where the contact between two or more phases are more efficient in bubble column reactor compared to another type of multiphase reactor such as stirred tank reactors [2].

In general, multiphase reactors can be divided into three main categories, which are trickle bed reactor, packed bed reactor, fluidized bed reactor, and the bubble column reactor [3, 4]. According to Kantarci [3], the design of bubble column reactor is an only cylindrical vessel with a gas distributor at the bottom. However, in this experiment, we are using a quadrilateral column equipped with sparger plate as the gas distributor. The gas dispersed in the form of bubbles in either the liquid phase or a liquid-solid suspension. The reactors are referred as slurry bubble column reactors when solid phase exists. For this experiment, we are only dealing with gas-liquid phase only.

There are two objectives will be discussed in this study. The main goal is to develop and design a bubble column reactor for liquid-gas multiphase reaction. The second aim is to evaluate the stability, functionality, and performance of the bubble column reactor at normal condition. The current practices of bubble column development are using cylindrical column and stainless steel material. Therefore, the newly designed is expected to apply transparent material for the column to allow flow visualization investigations using the high-speed camera. The target dimension for the reactor is similar to the existing high-pressure bubble column setup. This setup will increase the flexibility of the reactor to perform various research methodologies. Additionally, six different type of sparger design was introduced for various mixing pattern investigation and optimization process.

METHODOLOGY
Design Development Process
The design of bubble column reactor is focusing on parameters variation from an existing product. The improvement of an existing bubble column reactor involves minor redesign efforts. The tendency of using off-the-shelf components instead of designing complicated bubble column is the main goal of this design process. A good bubble column design should consist of acceptable performance, physical, environmental, and aesthetic requirements for the successful establishment of experimental investigation works. Ulrich and Eppinger [5] highlighted that the development process of product creation or invention follows a well-organized structure and systematic process flow of research activities as can be seen from the Figure 1 below. The following section will further discuss and explain the details of the development of bubble column reactor.

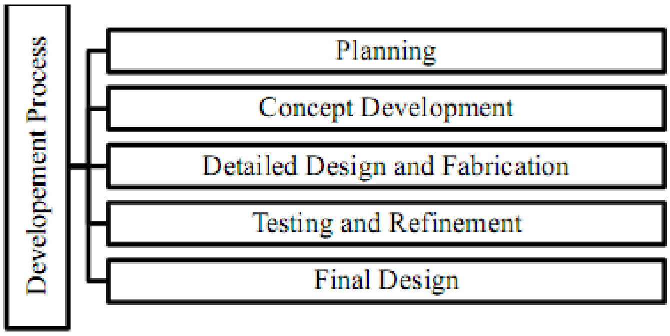


Fig-1: Flow chart for the development process of bubble column reactor

Planning Design
This project was undertaken to design quadrilateral bubble column reactor and evaluate the performance of bubble column reactor for conducting radioactive tracer experiment. The current bubble column reactor designed for high-temperature and high-pressure applications. Plus, the cost of operation and maintenance is higher. In addition, the available test rig is not suitable for external photographic imaging techniques. Therefore, the newly designed bubble column reactor is expected to provide better sight of multiphase interaction for hydrodynamics study using the high-speed camera, industrial radiotracer, and radioactive particle tracking techniques.

Concept Development
There are a number of the major cross-sectional studies showed that different methodology are used in conceptual design such as modeling representation [6], functional reasoning [7], flow-charts method [5, 8], backwards design method [9], and brainstorming method [10].

The design of a bubble column reactor for hydrodynamics behavior investigations in this study applied the front-end engineering design (FEED) process technology of the concept development. The FEED process of concept development started with the establishment of the target specifications, concept generation, concept selection, concept testing, and identifying user needs in the first place. After final specifications have established, benchmarking study and development of prototype will take place.

Primarily, the user (such as researchers, scientists, engineers, technicians, and industrial workers) needs must identify before desired specifications established. After then, conceptual designs could be developed to decide the suitable concept that fulfills all the desired criteria and specification. All the conceptual designs generated were selected using both concept screening and concept scoring which is known as six step concept selection process. Both concept selection methodologies are known as Pugh's concept selection developed by Stuart Pugh [11]. The use of this method can quickly reduce the number of concepts and improve the concepts [5]. This concept selection method includes the preparation of selection matrix, rate the concept, rank the concept, combine and improve the concept, select one or more concept, and reflect on the result and the process.

Afterward, the concept testing carried out to verify the user needs have been fulfilled, to evaluate the potential of the design, and to identify any defect or imperfection that must address for final product development. Benchmarking study and prototyping were conducted after a final specification was finalized. Detailed concept design and drawings of the prototype reactor were produced using the CAD software of SOLIDWORKS 2013. Product blueprints were created for prototype fabrication process after the details of concept design finalized earlier. Before fabrication process performed, all the drawings was last checked, verified, and finalized that the most favorable concept design submitted to the certified product fabricator. Table 1 shows testing and validation criteria summarized for the prototype reactor design.

Table 1: Testing and validation criteria of the bubble column reactor

Testing Criteria	Validation Criteria
Convenience	User-friendly, easy to handle, transport, assemble and set up
Flexibility	Measurement, adaptable parameters, innovative design,
Functionality	Capable of running continuously, experimental friendly
Maintainability	Easy to store, clean, service, and maintenance
Manufacturability	Use of cost effective standard part and material
Reliability	Test-retest variability and variation of measurement
Robustness	Well-built and stable when operation
Performance	Speed efficiency, repetitive

RESULTS AND DISCUSSION

FEED Concept Development Process

Identifying User Needs

To date, various designs of the bubble column reactor have been developed and created to measure hydrodynamic behavior and other related parameters. Operations of large-scale bubble column reactor for industrial application readily utilized in the chemical and petrochemical industries. Almost all bubble column test rig developed and designed with integration of device or equipment for process monitoring, evaluation, and control. In the present state, the user must obtain more than one bubble column test rig to perform different techniques of measurement such as radiotracer experiment, radioactive particle tracking method, and high-speed camera recording. Therefore, it is necessary to develop a new versatile bubble column consists of transparent column material for fluid visualization, highly safety features for radiation works, a stable column with well-built frame holder, easy to handle and transport, cost-effective material, and innovatively easy to clean, service, and maintenance.

Establishing Target Specifications

In general, the reactor design is targeted to overcome the problems faced in understanding hydrodynamics behavior of using different types of sparger design, leading to design optimization for better mixing and blending efficiency in multiphase flow investigations. Thus, the reactor design specifications were identified to meet the experimental requirements for hydrodynamics study in a bubble column using the high-speed camera, industrial radiotracer, and radioactive particle tracking techniques.

The reactor designed for fluid visualization, easy to handle, and safely operated when dealing with dangerous materials. Therefore, the bubble column test rig is completely designed based on eight (8) selected criteria as shown in Table 1 which is convenience, flexibility, functionality, maintainability, manufacturability, reliability, robustness, and performance. The convenience of the machine means that it must be user-friendly, easy to handle, easy to transport, assemble, and setup. Flexibility is the reactor capacity to have good measurement environment, easy to adapt designed parameters and innovative design for better user experience. Functionality is the capability of the reactor to running continuously and experimental working friendly. For maintainability of the reactor, it must be easy to store, clean, service and maintenance. The manufacturability of the reactor is to use cost effective standard parts and materials. The most important, the reliability is the capability of the reactor to measure the variation and perform test-retest variability. Furthermore, the robustness of reactor, that it must be well-built and stable when operated. Finally, for the performance of the reactor, it must be experimentally repetitive and show the support of speed efficiency.

The target design specifications of a bubble column reactor concentrate on the different hydrodynamic behavior produced in various flow regime and bubble dispersion pattern by a mechanical method with different sparger/air distributor designs. The mechanical parts involved in the processes are the air supply units, flowmeter, size and a number of holes in sparger design, and demister structure.

Concept Generation

Concept generation begins with proposed three bubble column reactor concept designs in order to select the most promising one and most favorable for the future experimental. Figure 2 illustrates the three types of concept designs of the bubble column reactor. Concept B (Figure 2b) was the concept design for the high-pressure application. It is an existing pilot scale concept for bubble column reactor available in the laboratory that is mainly for industrial process investigations under high-pressure environment up to 200 Psi. Reactor concept was used as a reference known as DATUM by Pugh matrix for evaluating another concept generated for this reactor design (Concept A and Concept C). Reactor design concept A and C are the concept designs for similar application at normal atmosphere no additional pressure involve.

In a comprehensive study of concept generation process, Ulrich and Eppinger [5] found that the reference concept design normally either an industrial standard or straightforward concept that can be a commercially available product, a best-in-class benchmark product, an earlier generation of the product, any product of the concepts under consideration, or a combination of subsystems assembled to represent the best features of different products. All concept designs (A, B, and C) were further evaluated and developed by using the six-step concept selection methodology of concept screening and concept scoring during the structured concept selection later.

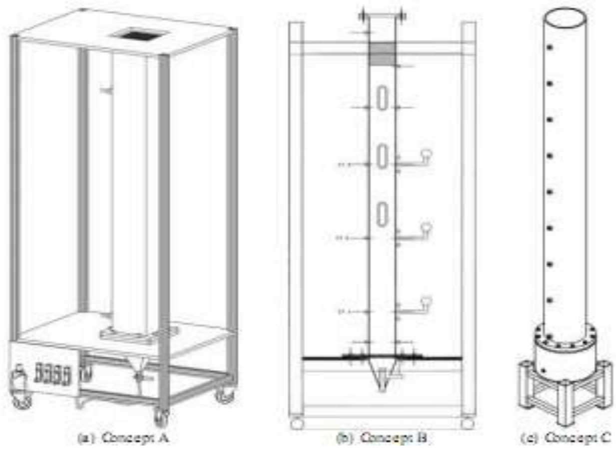


Fig-2: Types of concept design

Concept Selection

Three generated concept designs underwent the six-step concept selection method of concept screening and concept scoring in order to select the most promising concept. The three concept designs were evaluated by the method of concept screening to select most favorable and preferred concept designs for further evaluation and development. Table 2 shows Pugh concept screening and scoring matrix for bubble column reactor for concept A, B (a promising concept used to compare with concept A and C) and C.

Table 2: Pugh concept screening and scoring matrix for bubble column reactor

Testing Criteria	**Validation Criteria**	**Weight**	**Concept**		
			A	**B**	**C**
Convenience	User-friendly, easy to handle, transport, assemble and set up	5	+	D	+
Flexibility	Measurement, adaptable parameters, innovative design,	5	+	A	–
Functionality	Capable of running continuously, experimental friendly	5	+	T	–
Maintainability	Easy to store, clean, service, and maintenance	3	+	U	+
Manufacturability	Use of cost effective standard part and material	3	+		+
Reliability	Test-retest variability and variation of measurement	5	+	M	+
Robustness	Well-built and stable when operation	5	+		–
Performance	Speed efficiency, repetitive	4	+		+
Sum of +'s			8	0	5
Sum of –'s			0	0	3
Net Score			8	0	2
Sum of weight +'s			35	0	20
Sum of weight –'s			0	0	15
Weight Overal Score			35	0	5
Select and Continue?			Yes	No	No

Based on the results of concept screening and concept scoring matrix obtained (Table 2), it is observed that concept C is not favorable for further design evaluation and development due to its too simple design, less stable design without holding assistance, and inappropriate materials used. Therefore, the concept A and B is selected due to its better design and high-quality materials use. The weight value for each criterion was rated equally as five (5) (Lowest weight value = 1 and highest weight value = 5) and rating based on one user requirement only. Finally, concept A is selected as the most promising conceptual design due to its ability to meet all the user requirement including good stability design, whole-in-one mechanical parts, using the high-quality material, and well-built design. Hence, the conceptual design was further evaluated and reviewed during concept testing.

Setting Final Specifications

Specifications which originally were only targets expressed as a broad range of values were now refined. The target specifications set earlier were revisited after a concept was selected and tested. In a nutshell, the reactor was specially designed to generate and disperse tiny bubbles through sparger plate and air distributor component to initializing mixing pattern inside the column reactor.

Eventually, the sparger design or gas distributor will be utilized for originating the flow regime and bubble dispersion pattern by a mechanical method. The mechanical driven parts involved in the processes are the air supply units, flowmeter, size and a number of holes in sparger design, and demister structure. Centralized air supply unit is utilized for supplying continuous air to the regulator. Then, the flow regime was controlled by four (4) different range of flowmeter unit to the air distributor area resulting axially dispersed gas throughout the sparger onto the reactor.

The reactor design does not include the power-driven mechanism unless for the experimental device for data acquisition and storage. For cleaning and sparger changing purposes, the eight (8) pieces of hex bolts were removed, and column can be dismantled easily. Moreover, the aluminum framework is practical to hold the column steadily and easy to handle, moving and reassemble. In general, the bubble column operation is easily distinguished and executed for liquid-gas interaction.

Fabricated Structure of the Reactor

The construction material of the bubble column reactor was chosen transparent Perspex® glass because it was important to have a transparent wall for image visualization and flow regime identification can be conducted using the high-speed camera. The reactor also consists of 6 different types of sparger design as shown in Figure 3. This bubble column prototype is easy to clean, maintenance, and changeable sparger plate makes it most favorable design to date. It contains aluminum body framework of the top plate, and a lower plate which lead to hold column position at the place and provide better column stability, especially when involving high-speed inlet velocity that resulting high vibration frequency to the column material. In addition, stainless steel air distributor area in the pyramidal form also designed onto the column body for holding the sparger plate, locking purposes, and to change desired sparger plate easily. The top demister is used to prevent the volume of liquid loss because the formation of bubble breakups resulting a cloud of tiny water droplets. In this case, demister used to aggregate vapor mist into water droplets that heavy enough not to leave the column domain. In addition, the major mechanical components such as flowmeter and air regulator for inlet air velocity control and experimental variation safely fixed outside the aluminum space.

Figure 4 shows that the prototype bubble column reactor consists of 13 major mechanical parts. The 13 major mechanical parts specified names are Aluminium profile, air distributor, air regulator, ball valves, bolt, bottom plate, caster, column, demister, double O-ring, flowmeter, sparger, and top plate. The total quantity of the 13 major mechanical parts used in the reactor fabrication is 36 units. The details of the bill of materials, mechanical parts and functions for the bubble column reactor shown in Table 3. However, aluminum profile corner joint was neglected in the material bill due to the possibility of part specifications altered during the fabrication process. Any possible variation to the bubble column reactor invention satisfied the overall product practicability in continuous flow purposes without affecting the original principle of the design concept and practical application.

Table 3: Mechanical parts of the prototype, quantity, and their functions

Part No.	Part Name	Quantity	Part Function
1	Aluminium profile	8	Framework to ensure column stability and easy to assemble
2	Air distributor	1	Area for air distribution before sparger plate
3	Air regulator	1	Control valves for specified input pressure
4	Ball valves	3	Control liquid/gas flow through in/out the column
5	Bolt	8	Special for fastening between column and bottom plate
6	Bottom plate	1	To hold and support column weight and profile
7	Caster	4	Steered wheel that serve as an absorbing shock and vibration
8	Column	1	Contain and control gas-liquid reactions
9	Demister	1	Component for aggregation of vapor mist into water droplets
10	O-Ring	2	Elastomer sealing gasket to prevent liquid leakage
11	Flowmeter	4	Meter for measuring flow rate or quantity of gas
12	Sparger	1	Porous plate for break the incoming air into tiny pores
13	Top plate	1	To hold and support aluminum profile and column

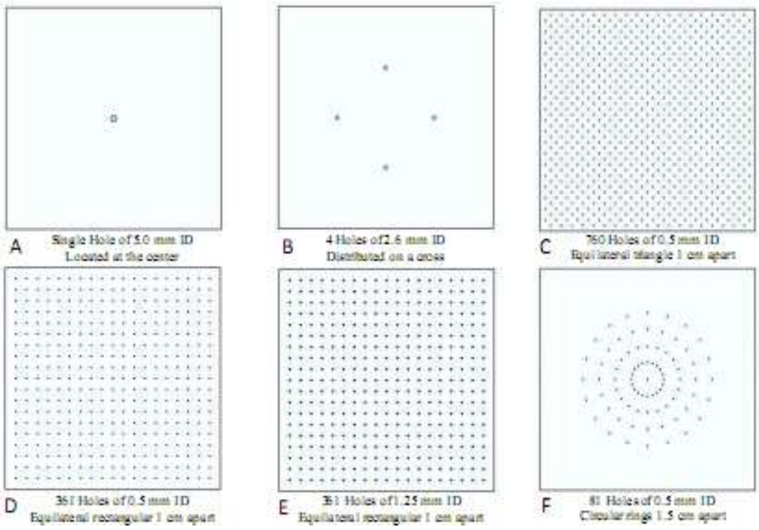


Fig-3: Different types of 200 x 200 mm sparger plate design with 1 mm thickness

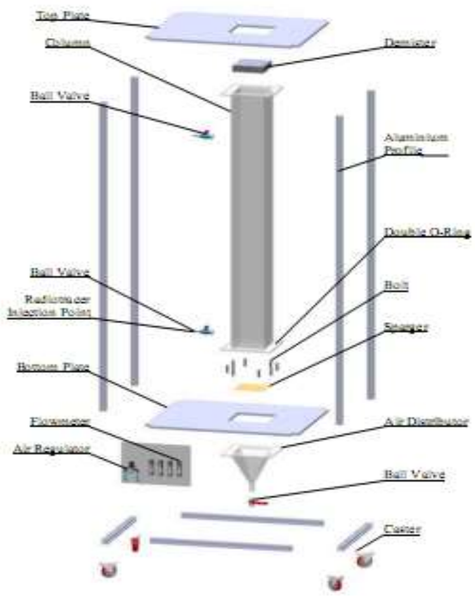
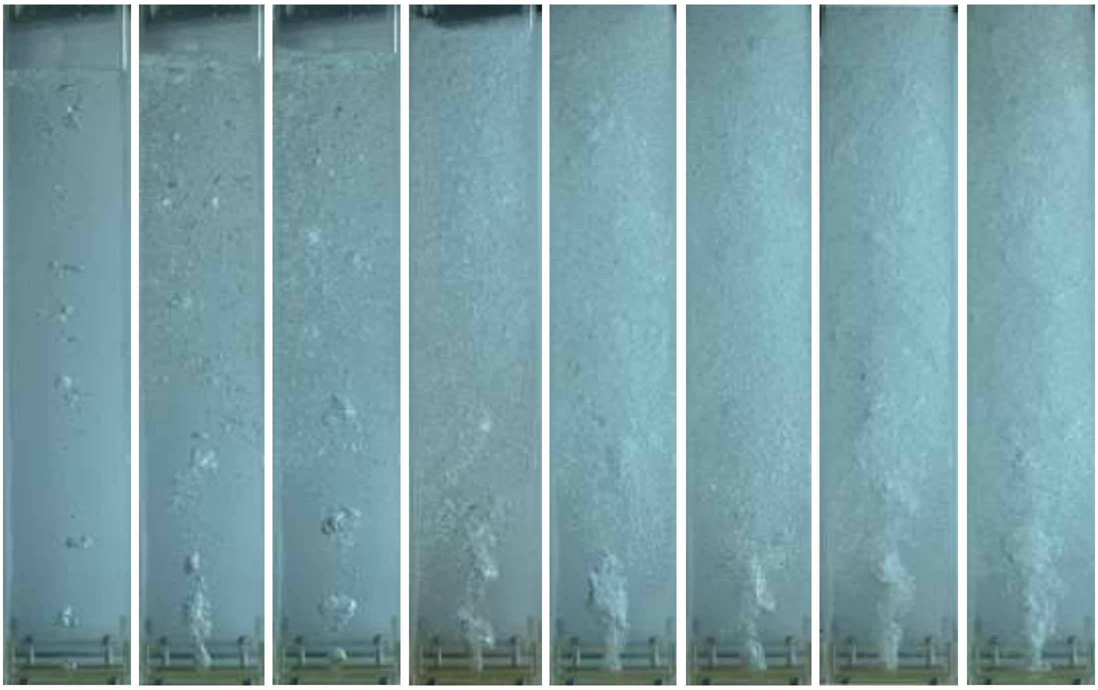


Fig-4: Exploded view diagram of a bubble column reactor

Testing and Validation of the Reactor Fabrication

Testing of the prototype machine proved and verified the bubble column reactor capability to provide air-liquid interaction continuously. In addition, expected result of water displacement for each sparger design was also verified because it was important to know the maximum fluid level to prevent overflow and loss of the liquid. The flow visualization studies carried out using digital photography camera Nikon D7000 model to capture the photographed image of hydrodynamic behavior in bubble column reactor. Effect of the inlet gas velocity on the flow dynamic inside sparger A shown in Figure 5. The result indicates that liquid level increase with increasing inlet gas velocity because the volume of air slightly increases and expand. Figure 6 illustrates the detail results from the effect of inlet gas velocity to the height of water displacement at different types of sparger design. Sparger design intentionally designed to provide different flow pattern in mixing and blending purposes. Figure 7 shows that the photograph image visualization of each sparger design captured at 20 L/min flowrate. Based on Figure 7, the height of liquid displacement in bubble column also depends on a number of holes, the size of pitch area, and holes arrangement at the sparger plate.



2 L/min 16 L/min 20 L/min 50 L/min 75 L/min 80 L/min 90 L/min 100 L/min

Fig-5: Photograph image visualization of Sparger A at various inlet gas velocity

The final prototype bubble column was able to operate continuously for about 8 hours. In this period of time, demister pad act as a major component to prevent loss of liquid due to water vaporization. The dimension of the reactor aluminium frame was customized, as well as four casters installed for the transportability (720 mm length x 920 mm width x 2400 mm height). Therefore, the fabricated bubble column was not only meet all the user's need but also provide innovative test rig that could be used for various types of experimental in future. Figure 8 shows the final prototype reactor developed in this research work. Lastly, the verification checklist of the final reactor prototype was verified as tabulated in Table 4. Table 5 shows the finalized design specifications of a bubble column and Table 6 shows the specification comparison.

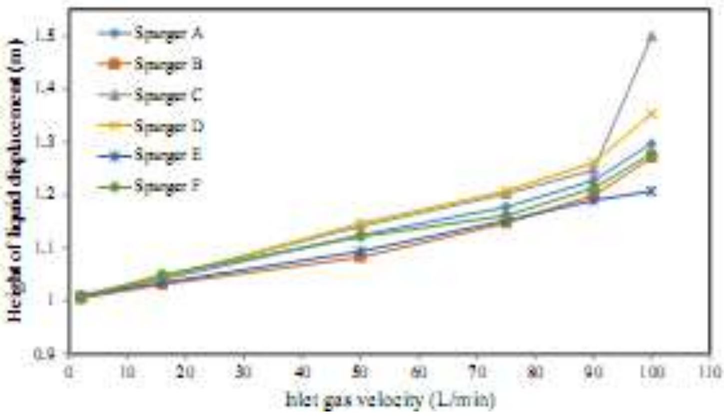
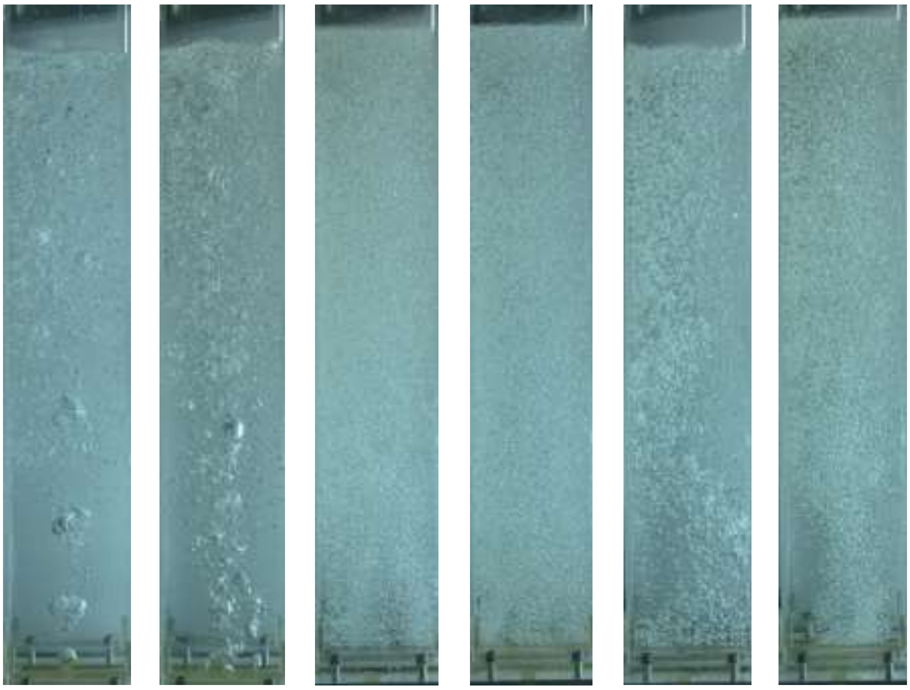


Fig-6: Effect of inlet gas velocity to the height of water displacement at different types of sparger design



Sparger A Sparger B Sparger C Sparger D Sparger F Sparger E

Fig-7: Photograph image visualization of sparger design at 20 L/min inlet gas velocity

Table 4: Verification checklist of the final product

Testing Criteria	Validation Criteria	Verification
Convenience	User-friendly, Easy to handle, transport, assemble and set up	Verified
Flexibility	Measurement, adaptable parameters, innovative design,	Verified
Functionality	Capable of running continuously, experimental friendly	Verified
Maintainability	Easy to store, clean, service, and maintenance	Verified
Manufacturability	Use of cost effective standard part and material	Verified
Reliability	Test-retest variability and variation of measurement	Verified
Robustness	Well-built and stable when operation	Verified
Performance	Speed efficiency, repetitive	Verified

Fig-8: The final prototype reactor

Table 5: Design specifications of a bubble column reactor

Operation	Controlling gas-liquid chemical reactions
Method	Mixing circulation and aeration is performed by gas dispersion
Function	Mixing the two phases or substances using gas sparger and it require less energy than mechanical stirring
Design Specifications	1. Aluminium frame size (720 mm x 920 mm x 2400 mm) 2. Column size (20 mm x 20 mm x 2000 mm) 3. Initial water level up to 1800 mm 4. Four (4) types of flowmeter ranged from 1 L/min to 100 L/min 5. Portable bubble column test rig, installed with four (4) casters 6. One (1) demister pad to change vapor to water droplet 7. Variable sparger design, six (6) different types of sparging 8. Inlet and outlet valve for liquid recirculation

Table 6: The comparison of new concept design with other conceptual design

		Concept	
Specification	**A (New)**	**B**	**C**
Column material	Acrylic glass	SS 304	Acrylic glass
Transparency	Yes	No	Yes
Column shape	Quadrilateral	Cylindrical	Cylindrical
Column height	2000 mm	2000 mm	1200 mm
Column diameter	200 mm	200 mm	200 mm
Demister Pad	Yes	Yes	No
Sparger material	Brass	Stainless steel	Stainless steel
Sparger design	6	5	5
Holding frame	Yes	Yes	No
Caster wheel	Yes	Yes	No
Water circulation	Yes	No	No
Flowmeter	4	3	1
RTD* capability	Yes	No	No
RPT* capability	Yes	Yes	No

*SS – Stainless Steel *RTD – Residence time distribution experiment
*RPT – Radioactive particle tracking experiment

CONCLUSION

This study has demonstrated the entire design development process of a bubble column reactor for industrial radiotracer and radioactive particle tracking applications. Finally, a new bubble column reactor was developed and fabricated for experimental and laboratory investigations; specifically for sparger optimization, results validation, and understanding hydrodynamics behavior of gas-liquid multiphase flow system. This bubble column reactor design comes with six different type of sparger design for various mixing pattern optimization. This research has also found that the engineering design and performance of the bubble column reactor to maintain the stability and functionality of the rig much better than the conceptual design B and C. Compared to the rejected design concepts, the final design of bubble column able to operated up to 100 L/min gas flow rate and up to 10 L/min water flow rate. The promising concept selection of clear glass material has met the user's need compared to an unfavorable stainless steel column. Transparent acrylic glass Perspex® particularly useful for flow regime see-through investigations using high-speed camera method. Further studies are required to explore the mechanism behind liquid-gas flow interactions by using different types of sparger design.

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