Design, Development and Testing of Microbubble Supported Laboratory Scale Dissolved Air Flotation System

By: Daraje Tadale

A Thesis Submitted to the Department of Chemical Engineering, School of Mechanical, Chemical and Material Engineering

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Chemical Engineering (Process Engineering)

Office of Graduate Studies

Adama Science and Technology University

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APPROVAL SHEET

Submitted by:

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This is to certify that the thesis prepared by Daraje Tadele Entitled: "Design, Development and Testing of Microbubble Supported Laboratory Scale Dissolved Air Flotation System" and submitted in partial fulfillments of the requirements for the Degree of Masters of Science In chemical engineering (process engineering) complies with the regulations of and meets the accepted standards with respect to originality and quality.

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We, the undersigned, members of the board of examiners of the final open defence by Daraje Tadale, we have read and evaluated his thesis entitled "Design, Development and Testing of Microbubble Supported Laboratory Scale Dissolved Air Flotation System" and examined the candidate. This is there for to certify his thesis work and has been accepted in partial fulfillment of the requirements of the degree of masters of science in chemical engineering (process engineering) complies with the regulation of the university.

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DECLARATION

I, Daraje Tadale, author of the thesis, “Design, Development and Testing of Microbubble Supported Laboratory Scale Dissolved Air Flotation System” hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name: Daraje Tadale

Signature: ---

Date of Submission: ---------------------------------

This thesis has been submitted for examination with my approval as a university advisor.

Name: Dr. Tatek Temesgen

Signature: -------------------

Date: -------------------------

Place: Adama Science and Technology University, Ethiopia

September, 2020

DEDICATION

This MSc thesis is dedicated to my beloved families, Tadale Zegeye and Wagaye Kebede and to my wife sisay leta, who kept me in your prayer and love.

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First and foremost, I would like to thank God for giving me health and patience to accomplish this thesis work. I would like to acknowledge my advisor Dr. Tatek Temesgen for his endless efforts, comments, proper supervision of the thesis and sharing the manuscript through my thesis. His knowledge and hands on experience in chemical engineering discipline has added greatly to the depth of information provided by this thesis. Next I would like to thank Akaki polytechnic college who helps us in manufacturing of the lab scale DAF system.

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LIST OF ABBREVIATION

MB	Microbubble
CB	Conventional bubble
DAF	Dissolved air flotation
WW	Wastewater
MBG	Microbubble generator
MBF	Microbubble flotation
CBF	Conventional bubble flotation
DO	Dissolved oxygen
RTD	Residence time distribution
TS	Total solid
TSS	Total suspended solid
TDS	Total dissolved solid
CATIA	Computer aided three dimensional interactive application
kla	Volumetric mass transfer coefficient
EF	Electron flotation
HP	Horse power
H	Head
UV/Vis	Ultra violet visible
NTU	Nephelometric turbidity unit
3-D	Three dimensional

ABSTRACT

Microbubble-based methods, in recent times, have been widely used for purification of water and wastewater. Microbubbles have several physicochemical properties, which make them eminently suitable for wastewater treatment. Size of bubble which has an inverse relation with pressure is one of the important parameter in the separation process of fine particles/solids. There are various DAF systems with different bubbling mechanisms and bubble types. In this study, the pilot high rate DAF system of laboratory scale is developed and tested. The system was evaluated by comparing its efficiency for both microbubble and conventional bubbles generation. The size of bubble generated was analyzed by image analysis software following the photographic bubble size measurement techniques. The mean diameter of bubble generated was found to be 32 µm. The generated bubble was tested for suspended solid removal of pulp wastewater, deinking and aeration system and the result of the conventional and microbubble generation system was checked. The efficiency of microbubble generated was greater by 20% in suspended solid removal and 60% kla increase in aeration system than conventional bubbles.

Keywords: wastewater treatment, microbubble, conventional bubble, dissolved air flotation, microbubble generator, aeration and deinking.

1. INTRODUCTION

1.1. Background of the study

Water is very important resource for human life for day today activity, including agriculture and industrial applications. Along with the increase in population and industrialization, the amount of water used and wastewater produced increased and become a serious problem in the global context, especially in the developing countries.

In Ethiopia, the population has been rapidly growing and the projection shows that it steadily increase from 83.7 million in 2012 to 133.5 million in 2032 and will reach 171.8 million in 2050, by which it will be double in 83 years [1]. The gradual increase of industries in turn increased the demand of treated water and generation of wastewater. Some of industries in the country have their own wastewater treatment plant, but it is not effective since they use old and conventional treatment processes. Most of these treatment units mainly remove large particles and dissolved organic materials from raw water [2].

In general, three forces are driving the wastewater treatment market: increasing industrialization, which currently required strict standards for the disposal of effluent to preserve the environment, increasing water costs that encourage water-saving measures its reuse and recycling, and the production and recovery of increasingly advantageous value-added by-products. Therefore, improving the efficiency of wastewater treatment systems highly targets at these three goals of preserving environmental quality, reducing cost and resource recovery.

Conventional wastewater treatment systems consist of a combination of physical, chemical, and biological processes. These processes mainly focus on operations to remove solids, organic matter and nutrients from wastewater. These systems are categorized as preliminary, primary, secondary, and tertiary and/or advanced wastewater treatment based on their degree of treatment and focus of waste to be treated.

Flotation and aeration technologies are of the old treatment technologies which emerged as new area of research and improvement to increase efficiency in a primary wastewater treatment unit. The main focus in these technologies arises from the target of reducing high pressure consumption for bubbling or air mixing in conventional systems. Therefore, study on bubble has received due attention and most of the current researches focus on areas including improvement of bubble generation systems, characterization and enhancement of their properties as well as applications.

Flotation is used as solid/liquid and liquid/liquid separation. It is a known process, widely used separation technique for wastewater treatment specifically for materials less dense than water and fine particles [3, 4], dye removal [5], fermentation and micro-oxygenation of wine[3], algae removal [6], etc. The method of producing bubbles gives rise to different types of flotation processes, namely, electrolytic flotation, dispersed air flotation, and dissolved air flotation [3]. The high and true separation of solids from liquid, following the development of high rate dissolved air flotation (DAF) system makes flotation the most important and widely used in water and wastewater treatments. With this, researchers showed that flotation has high potential to separate pollutants for high rate processes with low detention periods (meaning smaller tank sizes, and relatively low investment costs compared to conventional systems); thicker sludge and scum than in sedimentation or gravity settling [7, 8].

Bubbles are gas-filled cavities within liquids and mainly it has three components: the gas phase, the interface shell and aqueous/ liquid phase [8]. The size of bubble is one of the properties that determine the efficiency of solid/liquid and liquid/liquid separation in wastewater treatment processes. Bubble size is grossly categorized as milli-bubble or conventional bubble, microbubble and nanobubble. Milli-bubbles are bubbles in the range of 10^2-10^4µm; microbubbles are bubbles in the size range of 10^0-10^2 µm while bubbles under the size of 10^0µm are classified as nanobubble [9].

In dissolved air flotation, bubbles are used to separate suspended particles from liquids by bringing particles to the upper surface of liquids. The main process in flotation is the solid–liquid and liquid-liquid separation using bubbles and the floatation system consists of air and water supply, bubble generation system and flotation chamber. To the knowledge of the authors of this thesis, most of the water and wastewater treatment technologies existing in Ethiopia are conventional systems that utilize high energy. Almost all of the systems are designed and constructed by foreign companies. Therefore, the focus of this study is in developing high rate dissolved air flotation system by designing low pressure assisted microbubble generator. To achieve the main goals of this research, a pilot laboratory scale floatation unit, which is equipped with a hydrodynamic microbubble generation system and which apply a splitting mechanism was designed and manufactured. The comparison of bubbles efficiency from the microbubble generator was compared with bubbles from conventional stone diffusers.

1.2. Problem Statement

In Ethiopia, wastewater is discharged from different sectors and most of it ends up in to running rivers resulting in surface water pollution. To preserve and keep the environment clean, there is a limitation of having treatment plants with advanced technology. In general, the research tried to address the issues of:

- Limitation/absence of design skill for advanced wastewater treatment technologies in Ethiopia.
- Replacing conventional wastewater treatment units by designing microbubble based high rate DAF system which has high separation efficiency.
- Possible minimization of high pressure consumption of existing microbubble generation units.

In Ethiopia, there are limited advanced wastewater treatment systems. Some of them exist in industries and most of these treatment plants use conventional systems of floatation and/or aeration. The flotation and aeration units in these conventional systems are not efficient because of the application of large bubbles (mill bubbles) which have low residence time in the aqueous system or use of mechanical systems which need high energy. For example the wastewater treatment plant in Adama Science and Technology University uses agitation process for aerating large volume of wastewater, which results in consumption of high power. The use of high energy has been the main challenge that used to inflate the operation cost of aeration. This problem has been solved by application of microbubbles. But these systems are not well introduced in the Ethiopian context. Moreover, the issue of designing and construction is always limited to foreign companies due to lack of local expertise in the area. Therefore, this study is assumed to contribute a strong base for starting local design and development of flotation and aeration systems that are assisted by microbubble. In addition to developing microbubble assisted floatation/ aeration system, it also focuses on addressing the current research gap of decreasing the high pressure need in microbubble generation chambers. therefore, this study focused on designing high rate DAF unit, which has several advantages over conventional flotation, including: reduction of flocculation time, use of less size of flotation tank which in turn reduces the total cost and high efficiency of pollutant removal by increasing hydraulic loading rate. Moreover, comparative analyses were done with other designs done by other researchers.

1.3. Objective of the study

1.3.1. General objective

The main objective of the study was to design, develop and test a lab scale microbubble supported high rate DAF system and compare it with conventional bubbling.

1.3.2. Specific objectives

- To design low pressure based microbubble assisted DAF system.
- To determine the size of bubble generated.
- To test the efficiency of the MB flotation in comparison to conventional flotation systems.
- To test the efficiency of MB aeration capacity in comparison to Conventional bubbling system.

1.4. Significance of the study

The study tries to accomplish one of its kind works in the development of a DAF system in lab scale for demonstration purpose. It contributes a strong baseline on how to develop a dissolved air flotation unit and providing information for professionals and researchers as well. The designed lab scale dissolved air flotation unit will serve the chemical engineering department as a teaching material for unit operation and water treatment courses. The equipment can be used as a teaching instrument for aeration process applying MB. The system can be used as a starting point for other researchers for experiments on application of MBs for purification of stagnant water area and the removal of algae from rivers and lakes which might cause many negative impacts on human and aquatic animals.

1.5. Scope and limitation of the study

The study includes design and manufacture of MB based DAF system, size determination of the generated microbubble, testing the effect of different operating parameters on the generated bubble size, testing and comparing its efficiency with conventional bubble system. Other properties of microbubble like: rising velocity, zeta potential, and other were not studied. The microbubble generator system was manufactured using locally available material. The biggest challenge was the difficulty of finding a lab scale pump and flow measuring devices for the system to be built in the local market. Moreover the skill and design understanding of the local workmanship was the main challenge that the researchers should overcome to finalize the prototype. Despite these challenge the researchers tried to manage adopting an industrial scale pump and flow meters to build a DAF system. On top of this the availability and cost of materials that can be used in characterization of bubble and/effluent analysis and manufacturing materials of the designed microbubble generator were a limitation for this study.

2. LITERATURE REVIEW

Bubbles are produced using any gas that is not highly soluble in liquid. However, in actual practice, air is the gas most commonly used because of its easy accessibility, safe nature, and less expensiveness.

Bubbles exist in different shape and size in a bulk liquid. The different size categories and properties have been studied for over half a century by different researchers. In 2017, researchers adopted a standard for bubble size range after an extensive review of related articles. Accordingly, the bubble types are categorized in to milli-bubbles which are bubbles in the range of 10^2- 10^4μm; microbubbles are bubbles with size in the range of 10^2-10^0μm and bubble sizes below 10^0 μm were classified under nanobubble [9].

2.1. Fundamental properties of microbubbles

There are various characteristics of microbubble that makes them attracting in different current and future technologies like: removal and/or recovery of ions, spilled oil, wasted pulp and paper, deinking of printed paper and colored water and recycling and removal of pollutants from water and wastewater. Some of the unique and important properties of MB are discussed below.

2.1.1. Bubble size

Microbubbles are bubble types having spherical shape with different researchers suggesting different size range [10, 11]. It is seen that researchers have not reached conformity on the definition of microbubble till 2016. But an extensive review in 2017 by [9] categorized micro bubbles as bubbles in the size range of 10^2-10^0μm. The bubble size directly affects the separation efficiency of solid from liquid by influencing bubble particle collision [12, 13].

2.1.2. Rising velocity

Rising velocity of bubble is one key parameter which affects its property in water [14]. The physical properties of liquid affect the rising speed of microbubbles. Rising velocity of bubble depends greatly on bubble diameter (Fig. 2.1), the density difference or driving force between water and air ($\boldsymbol{\rho}_w$ – $\boldsymbol{\rho}_b$), and dynamic viscosity of water (μ_w). Obviously, conventional (larger) bubbles have greater rise rates than smaller ones, and bubbles rise faster in warmer water

(Fig.2.2). There is evidence that the bubbles in the separation zone are larger than in the contact zone [15, 16].

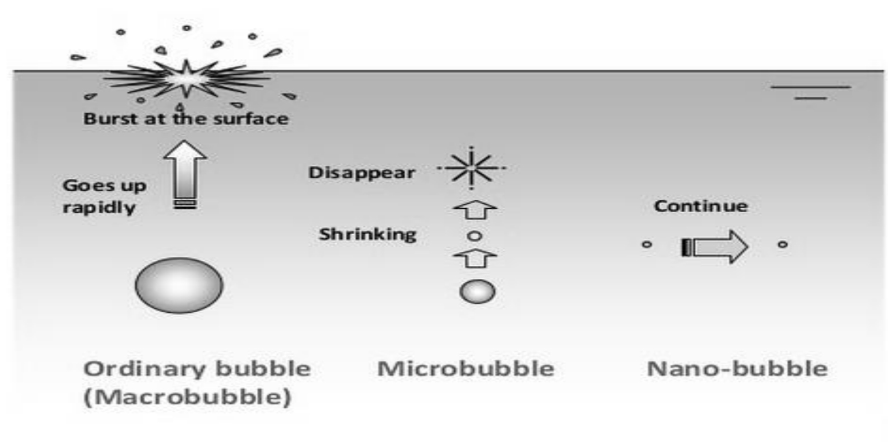


Fig.2.1 Rising properties of different bubble size: source [17, 18]

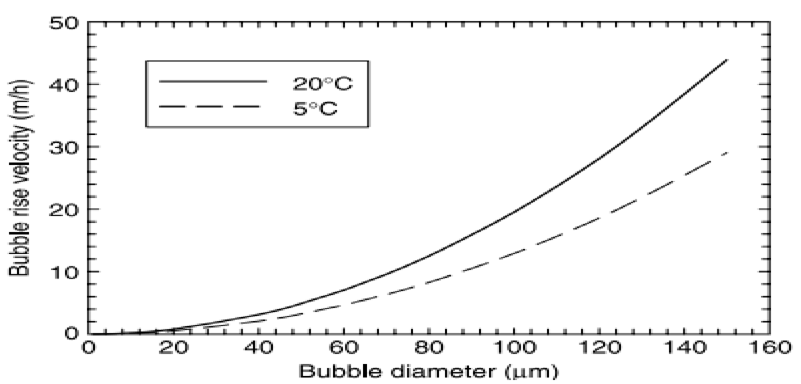


Fig.2.2 Bubble rise velocities as a function of bubble size for 5 and 20 ^{0}C: source [19]

2.1.3. High internal pressure of bubble (self-pressurizing effect)

From Young-Laplace equation, the internal pressure (P) of bubble depends on surface tension (σ) and bubble diameter (BD).

$$P = Pl + \frac{4\sigma}{DB} \quad (2.1)$$

Where, Pl is liquid pressure.

The internal pressure of bubble increases on decreasing the bubble diameter. Decreasing the bubble diameter the partial pressure of the dissolving gas increases and this inturn increases the gas dissolution.

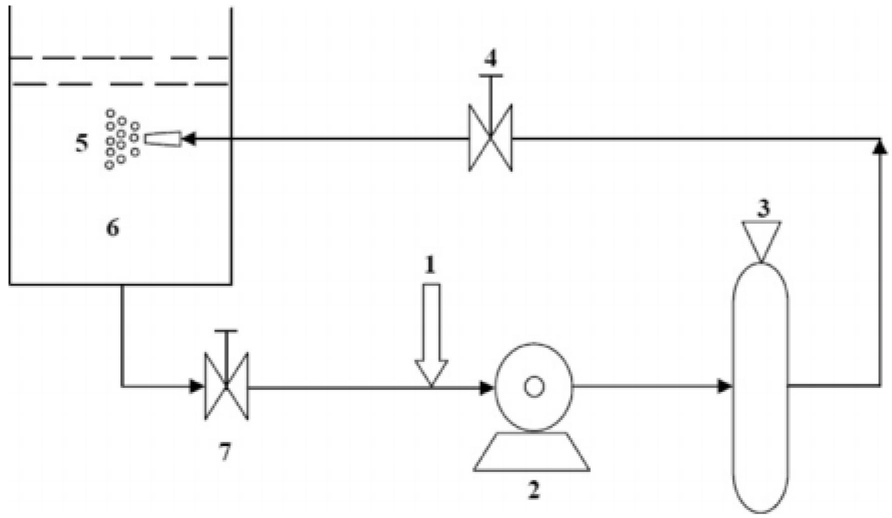
2.1.4. Zeta potential

Zeta potential is an electrical potential of bubble used for the measurement of magnitude of the electrostatic repulsion or attraction between particles and bubbles [11, 20, 21]. It predicts stability of particles in suspension. High zeta potential (negative or positive), of particle shows that they confer stability (the suspension or dispersion will resist agglomeration). Whereas, if the particles have a low potential, then they tend to come closer and will flocculate [11, 22, 23].

Though all the above properties of micro bubble are very important only the size and its corresponding functions are the main concern of this research.

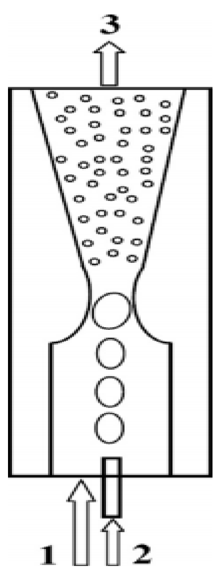
2.2. Micro bubble generation system

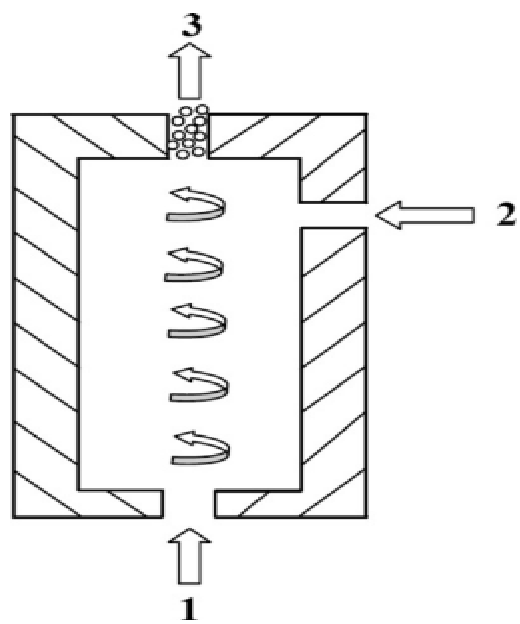
Micro bubbles can be generated by a number of ways. In terms of their mechanisms, microbubble generators are divided as pressurized type, cavitation type and rotating flow type [10, 11]. In pressurized type of microbubble generation system, microbubble is formed when the liquid is saturated with air at an elevated pressure and injected into normal environment with atmospheric pressure through nozzles. In cavitation type, the microbubble is formed when local ambient pressure at point in a liquid falls below the liquids vapor pressure at that point. At this point, the liquid undergoes a phase change, creating largely empty voids termed cavitation bubbles. In rotational flow type (Fig. 2.3 (c)) [27] the microbubble generation initiated by pumping water from the tangential direction into the system and creates vortex on the air drawn into it and the fluid takes air out of the generator with very high rotating velocity, then the air can shred into microbubbles.



(a)

(1: air inlet; 2: pump; 3: saturation tank; 4: reducing valve; 5: microbubbles; 6: water tank; 7: valve)

(b) 

(c) 

(1: liquid inlet; 2: gas inlet; 3: microbubbles)

Fig.2.3 Types of microbubble generators: (a) Pressurization type (b) venturi type (c) rotating flow type. source [11]

Venturi-type generator has been widely used for the generation of micro/nanobubble based on hydrodynamic cavitation mechanism [24-28]. In the Venturi-type generator system, both gas and liquid are passed simultaneously via the Venturi tube to generate the bubble [11, 29, 30]. When pressurized fluid is introduced in the tubular part, the liquid flow velocity and pressure in the cylindrical throat become higher and lower, respectively compared to the inlet section, thus resulting in cavitation [27]. In general, cavitation is the process of formation, growth and shrinkage of submicron bubbles in a solution [31].

[26] generated bubble with a mean diameter of 130-545 nm via Venturi tube based on hydrodynamic cavitation mechanism. [27] were able to generate nanobubble of a mean diameter with less than 50 nm using Venturi tube.

In 2017, [30] generated a microbubble using venturi, and the air came from the air tank, which filled primary with the help of compressor. The microbubble generator developed here was installed vertically and had volumetric flow rates of 10–30 m^3/h and 0–0.12 m^3/h, of water and air respectively. Their experimental results showed that the generated small bubbles had an average size of 0.5 – 0.6 mm, which is relatively larger compare to the standard.

In 2019, [6] generated microbubble with average size of 50µm using natural suction through venturi. Venturi allows air to circulate into the pipe at 20 L/min. Thus, there was no air compressor in this system. They produced bubble size in the range of 30 – 110 µm with micro chamber of diameter 150 mm and length 1200 mm. The system was built on boat to remove algae from Han River in South Korea. However, the system only functioned in pilot scale and could not move.

In all these systems, the pressure in each system dropped below its vapor pressure due to high velocity inside the flow path. Hydrodynamic cavitation in a venture can be well described by Bernoulli's equation which is given by:

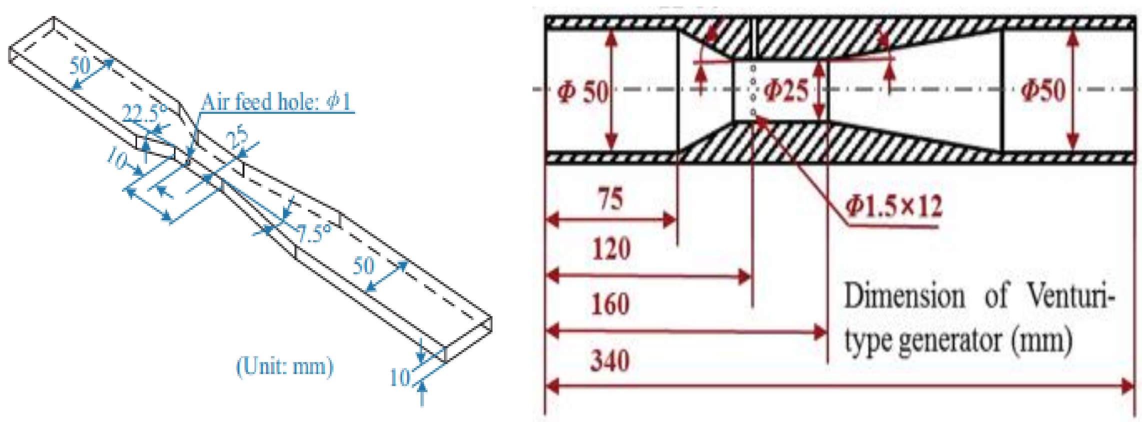
$$p + \frac{1}{2\boldsymbol{\rho v^2}} = c(constant) \tag{2.2}$$

Where, “v” is the water flow velocity, “P” is the pressure, and “ρ” is the liquid density.

2.3. Microbubble generator (venturi) design

A venturi type microbubble generator is the most common and it has wide application in gas – liquid flow system, due to simple structure, robust design, no internal moving part, less maintenance and capability of generating large volume of fine bubbles with mean diameter less than hundred micrometer [32, 33].

A venturi structure consists of three main parts, a converging region, throat and diverging region [30, 32, 33]. A venturi developed by [29, 32] was composed of three sections and the geometrical parameters are shown in figure 2.4 (a) and (b), respectively.



(a) (b)

Fig. 2.4 Configuration of Venturi-type bubble generator (a) rectangular venturi (b) circular [29, 32]

In both figures, the throat section of venturi wall was drilled and air is injected from the compressor tank to the stream, [32]. In figure 2.4 (b), the convergence entrance angles is 7.5° and air is injected through a hole of 1.5mm diameter.

2.4. Bubble size measurement

To determine bubble size, there are numerous intrusive and non-intrusive techniques invented by researchers. Some of the methods are: photographic, acoustic, optical, light scattering, inverted funnel, phase Doppler anemometry, Bayesian magnetic resonance [3].

2.4.1. Photographic technique.

Photographic technique is a method to estimate bubble size with the help of image analysis software. The generated bubbles are captured by a high-speed microscope assisted camera (Fig.

2.5). Columns wall should be transparent so that the high-speed camera can capture the bubbles. A light source can be placed opposite to the camera to get a clear picture of bubbles. The captured images are analyzed by the image processing software to estimate the bubble size. In this technique, bubble size can be measured by manually identifying each of the bubbles, which makes it tedious. Photographic technique is limited to resolve large bubble clusters and captures only those bubbles, which are nearby the wall of the column [3].

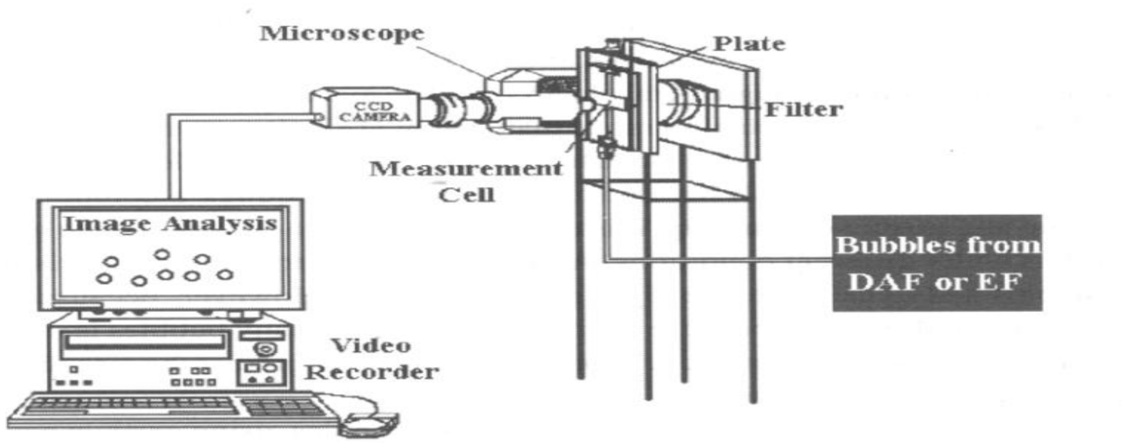


Fig.2.5 Image analysis system: source [34]

2.4.2. Acoustic technique

The acoustic method is based on excessive attenuation of the acoustic wave or scattering, in which sound generated by bubbles are investigated and based on this, an equation is developed between bubble sizes and their natural frequency of oscillation. In this technique, produced bubbles are passed through the acoustic perturbation and at the same time recording and analyzing the response. Bubble size obtained from the acoustic technique is correlated well with photographic technique.

2.4.3. Light scattering method

Light scattering technique is based on the principle of Mie scattering theory [3]. Intensity of scattered light is related to the radius of the air bubble. Here scattering light intensity is inversely proportional to the radius of the bubble.

2.5. Flotation

Floatation had been one of the basic separation processes in water treatment for many decades [24]. There are different types of flotation; electro flotation, dispersed air flotation and dissolved air flotation [35].

2.5.1. Electro flotation

Electro flotation is the process of separation in which the microbubbles generation system is done by the electrolysis of diluted aqueous, conducting solutions with the production of gas bubbles at both electrodes [36]. At an industrial scale this type of flotation is applied for removal of light colloidal, including emulsified oil, ions, pigments, ink and fibers and it gives cleaned treated wastewater [37]. But the low throughput, the emission of H_2 bubbles, electrode costs and maintenance as well as the voluminous sludge produced make it not preferred in different areas of application.

2.5.2. Dispersed (induced) air flotation

Induce air flotation is occasionally found in wastewater treatment, where relatively large bubbles with diameters of several hundred micrometer are formed by mechanical agitation or sparger air injection [38]. This method, well known in mineral processing, is utilized also in the petrochemical industry, for oil–water separation [36]. However large bubbles lead to poor efficiency on bubble-particle collision.

2.5.3. Dissolved air flotation

The dissolved air flotation is the most important and widely used in water and wastewater treatments. Dissolved air flotation was patented in 1924 by Niels Peterson and Carl Sveen in Scandinavia and its use in the treatment of wastewater and potable water began in the late 1960s [15]. The conventional DAF processes, allowing particles to float by using microbubbles, consist of air and water supply, saturator, and flotation chamber. Thus, traditional DAF requires large flotation tanks and high pressure for microbubble chamber as well as high operating cost.

Here, there are three usable processes of DAF system [39]: full flow, partial flow and re circulated flow. In full/partial flow process of DAF system, all or part of the influents flow through pressure tank and this produce a maximum dissolution of air and it generates a larger amount of bubbles. But, this process consumes high energy and the pumped wastewater may lead to damage of equipment (pumps, valves, and saturator). On the other hand, re-circulation process is the most used type in wastewater treatment and works by re-circulating part of the effluent for pressurizing system.

The DAF systems, [39] built in 1960s with pressurized recycle, examined in Finland and Sweden had hydraulic loading rates of 5–10 m/h. In the late 1990s and in the early 2000s, several companies introduced high rate DAF systems at nominal loading rates of 15–30 m/h and greater, many at 20–40 m/h

In 2018, [40] developed high rate dissolved air flotation for the removal of pollutants from lead-zinc-sulphide ore mill wastewaters. They developed the pilot DAF unit (1.8 – 2.4 m^3/h flow rate) followed an innovative design by enhancing hydraulic loading capacity up to 15 m/h more than double the known value for conventional DAF cells (about 7 m/h).

In recent years, there have been large increases in the hydraulic loading rates in order to improve the conventional DAF system in terms of flotation time, efficiency of pollutant removal, cost of flotation tank as well as operating cost.

2.6. Dissolved air flotation design

A DAF system must be designed to clarify/separate solids or liquid from liquids. However, there are no much clear and proper procedures for designing the DAF system [39]. There is a range of tank sizes with varying rectangular shapes (Fig.2.6) and different arrangements of air nozzles, baffles and depth for removing suspended solids. The key design parameters of DAF system are flow conditions (liquid and air/gas flow rate), configuration of the tank, type of waste treated, air to solid ratio, air pressure, bubble size, etc. To design DAF system some authors start with a loading rate or detention time [35, 40].

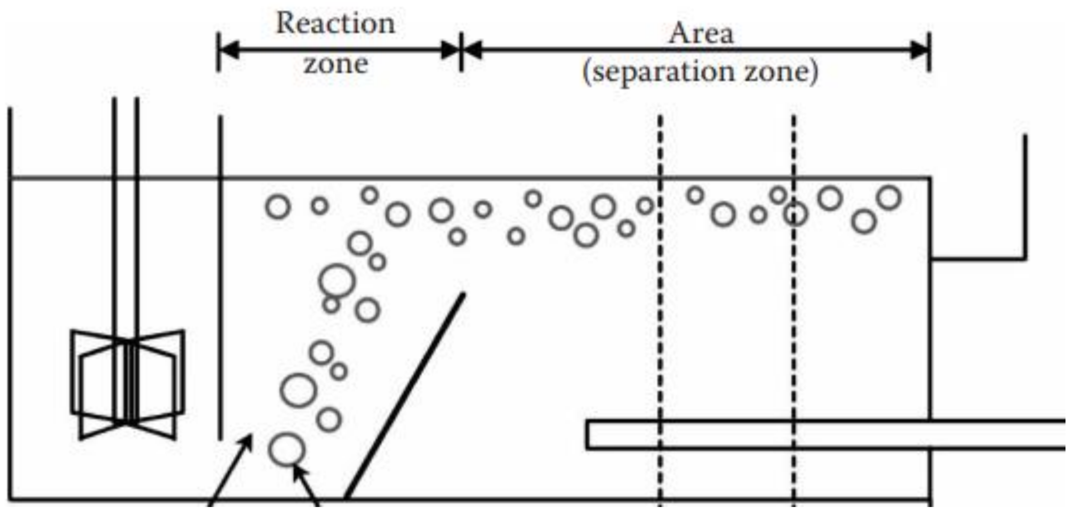


Fig. 2.6 Arrangements in flotation tank: source[35]

The baffle used to facilitate laminar flow at the inlet and reaction zone is angled in the range of 45 – 90 degree [35]. In general different authors [35, 39-41] recommended the following design parameters: ratio of air to solid 0.0005 – 0.3, hydraulic loading rate ≥ 15m/h for high rate and below 15 m/h for conventional, 10 – 60 min retention time, 1 – 7 bar of air pressure and 60^0 angle of baffle in reaction zone.

It is seen that most researchers had made several efforts to develop both efficient microbubble generator and high rate DAF system in different years. The efficiency of separation in high rate DAF system highly depends on the size of its bubbles and its volume. This study worked on designing and developing a high rate DAF system supported by microbubble. The improved, microbubble generator operates at a low pressure of around 2 bars. The rectangular flotation chamber with a straight baffle is used to adjust the loading velocity to the floatation chamber to be in the range of the high rate flotation system. The system is tested for its flow behavior using tracer test and for its functionality for floatation using it for the separation of paper waste and de-inking. Similarly, its application for aeration was checked by measuring the soluble oxygen content in the liquid.

In this research, the recycle process of DAF system was used because of the following advantages:

- Pressurization requires less equipment and thus lower energy consumption.

- Avoids clogging of microbubble generator and pump abrasion.
- Easily assimilated flow changes and/or composition.

3. MATERIALS AND METHODOLOGY

3.1. Materials and apparatus used

The materials used for construction of the DAF tank were acrylic plastic/Plexiglas of 6 mm thickness, Teflon bar of 50 mm diameter for venturi tube and 20 mm for nozzles, metals and aluminum metal sheet for the overall supporting structure of the movable equipment bed.

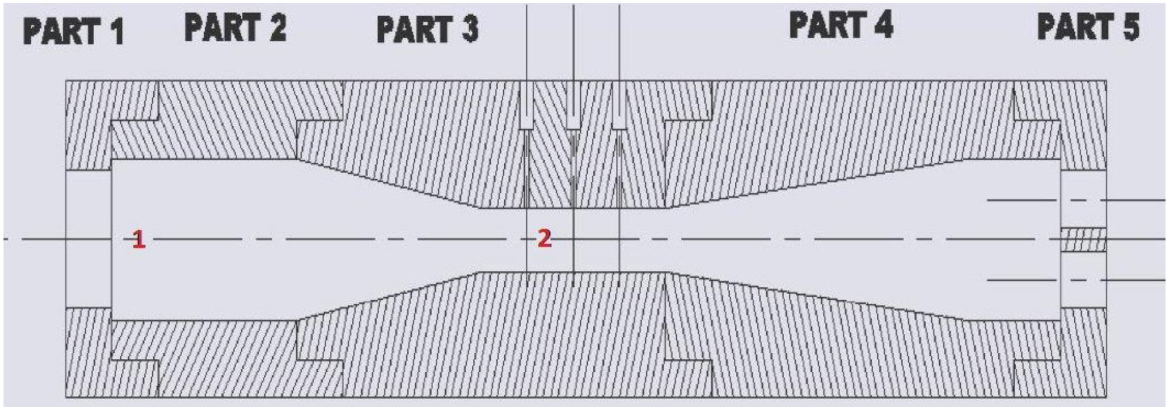
Two centrifugal pumps with a (0.5 HP, 40 m Head and 0.15 HP, 35 m Head) with revolution of 4,900 rpm were mounted to the system for pumping wastewater and recycled water respectively. Plastic pipes with an internal diameter of 25 mm and 4mm were fitted to the overall system as a path of fluid transportation. Fittings (elbows, valves, reducers and unions), to connect one pipe to the other with different sizes were applied. Pressure gauges (10 bar capacity) were mounted to read pressure drop in the pipe flow at the inlet pump, water flow meter (Rota type of capacity 1050 L/h) and air flow meter (capacity 35 L/min) to read amount of air feed were fixed at inlet of the DAF system and the microbubble splitter unit, respectively.

The chemicals used for the overall experiments include tap water as a base, methyl red dye as a surrogate for colour forming chemicals as well as pulp and paper residue for the floating waste.

Digital microscope with 1600X magnification was used for the determination of a bubble size generated by the bubble splitter by capturing image and video of bubbles formed. DO analyzer (REX, JPB-607A) were used for the measurement of dissolved oxygen during the aeration process for the comparison of the effects between the MB and CBs. Turbidity meter (HANNA, HI88703) and UV/Vis digital spectrophotometer (model 371) were used for the measurements of turbidity and color absorbance in a influent and effluent water streams of the flotation tank. Moreover, grinder, oven, digital balance, pH meter and filter papers were used for size reduction of pulp and preparation of synthetic wastewater in the laboratory. .

3.2. Design of microbubble generator (venturi tube)

Venturi tubes have been used to mix air and water for the production of a microbubble in a splitter by splitting. In venturi tube design (Fig. 3.1 (a)), there are four geometrical parameters, including inlet angle, throat length, outlet angle, and diameter of throat and converging region. The pressure is higher at the inlet and then decreases at the throat as the flow velocity increases due to a decrease in area keeping a constant flow rate. When the velocity of liquid in the throttle, (at number 2 of Fig.3.1 (a)) increases, the pressure decrease helps the injection of air to the system with a low pressure supply system. The geometry of designed venturi tube was divided into five parts and their dimensions were given in appendix B.



(a)

(b)

Fig.3.1: venturi tube: (a) drawing of venturi tube and (b) manufactured venturi tube.

In the mathematical model, the physical parameters that were required to form the microbubbles were derived and elaborated:

From Bernoulli's equation (consider region 1&2 of Figure 3.1, (a))

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g h_2 \quad (3.1)$$

With same elevation (h_1=h_2), hence there is no height difference between recycled water inlet and throat of venturi tube; thus the above equation will be:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 \quad (3.2)$$

Recalling continuity equation, $Q_1 = Q_2$ and we have,

$$A_1V_1 = A_2V_2 \quad (3.3)$$

Re arranging eqn. (3.3) and substituting in eqn. (3.2)

$$P_2 = P_1 + \frac{1}{2}\rho V_1^2(1 - (\frac{A_1}{A_2})^2) \quad (3.4)$$

In this experiment, inlet and throat diameter of 25.4 and 8mm and inlet and outlet angles of 12.34^o and 7.5^o were required respectively. Accordingly the pressure in throat section of venturi tube should be less than atmospheric pressure (p_1), and 0.663 atm is taken as a value.

3.3. Design and manufacturing of DAF system

A DAF system has been designed based on empirical values of width to height and length ratio ranges and vice versa. Due to its easy nature of local manufacturing and relatively simple dimensional scale up, rectangular dissolved air flotation tank was selected for this study. The drawing of the DAF system components were prepared using CATIA software based on their calculated dimensions. 3D drawing of the DAF system is presented in Figure 3.2.

The design in this research is supported by mathematical justifications. The high rate flow is usually difficult to adjust in small size or laboratory scale systems but with application of a vertical baffle the speed of the flow to the contact zone is achieved. The system is designed to have four compartments, namely equalization zone, flow adjustment zone, contact zone and separation zone.

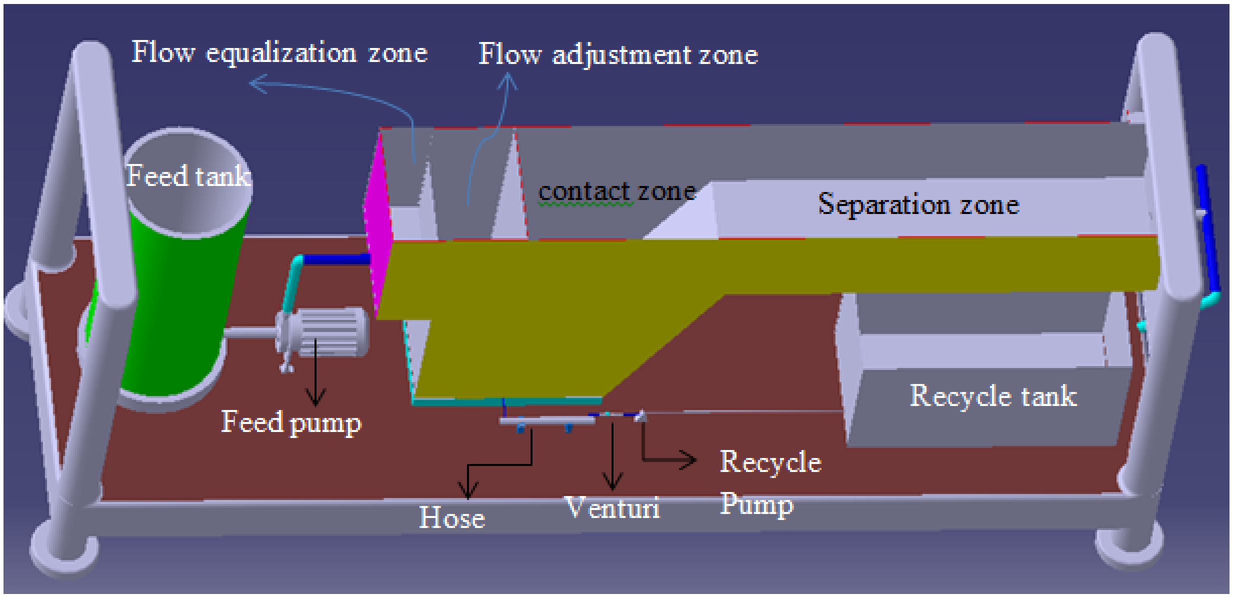


Fig. 3.2: 3- D drawing of DAF system using CATIA software

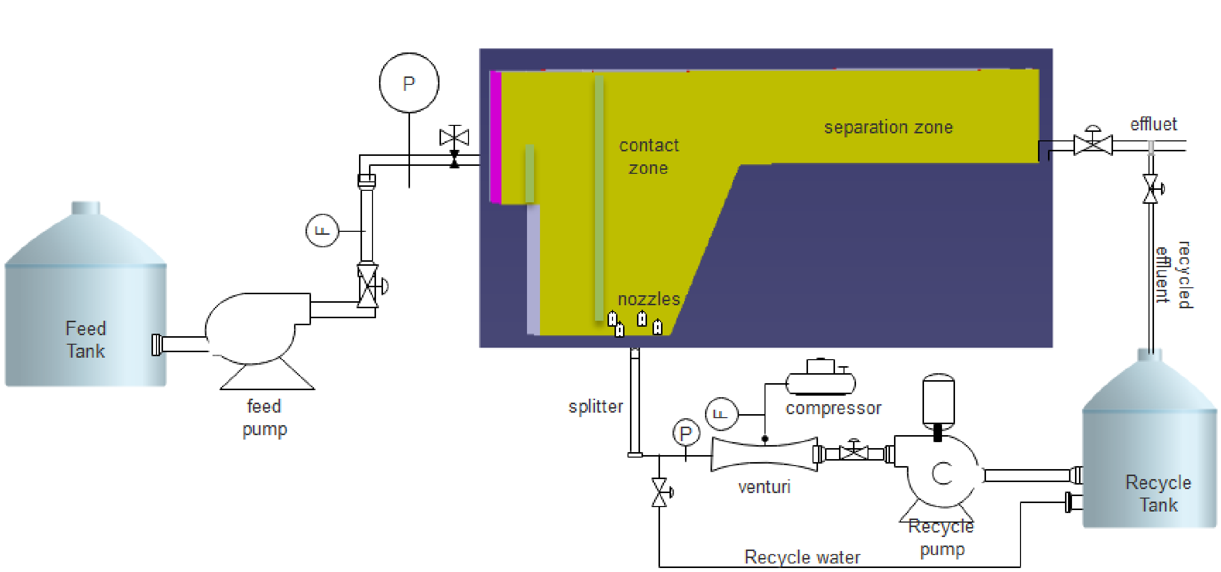


Fig. 3.3: Schematic diagram of experimental lab scale DAF system.

Equalization Zone: is the rectangular tank having a dimension of length, depth and width of 20, 50 and 50 cm, respectively. The advantage of this zone is to reduce the turbulent flow coming from the pipe inlet by distributing over a wide area and homogenize the flow to the flow adjustment zone.

Flow adjustment Zone: is the tank where the well distributed liquid and turbulence flow becomes laminar. It allows the flow to inter the contact region through adjustable baffle opened at 10 cm depth from the bottom or the datum surface of the floatation tank.

Contact zone: is the zone where bubble saturated liquid from MB generation system is introduced and thus, floatation occurs. The floatable suspended solid particles, water and bubbles come together for the first time in the reaction zone to form stable particle/bubble agglomerates which are essential for successful flotation. The compartment has three regions: first rectangular region with a dimension of 40 cm length, 100 cm depth and 50 cm width, triangular region with 35cm base, 60 cm height and 50 cm width and the second rectangular region with a dimension of 35 cm length, 40 cm depth and 50 cm width.

Separation zone: is the zone where a partial mixing occurred and after formation of stable particle/bubble agglomerates in the contact zone, separation of the floated matter takes place in this zone. Sufficient length was required in order to accumulate the floatable solid particles on the upper surface of water, thus the tank is 160, 40 and 50 cm in length, depth and width, respectively. Only 20 cm water depth from the top water table was applied to satisfy the high rate flow range of conventionally existing systems. Unlike the conventional systems, the depth below the 20 cm from the top water table was assumed to be a dead zone and removed to reduce the manufacturing cost of the system. See detail design calculation in appendix A.

Mathematical design of DAF tank

In this research, a DAF tank used for separation of solid/liquid from water was mathematically modeled. The lab scale DAF tank was rectangular in shape with a total length of 250 cm, a height of 100 cm, and a width of 50 cm (total volume of 0.843 m^3). As shown in Figure 3.3 the main wastewater stream interred the tank to the equalization zone via 25 mm diameter plastic pipe from a wastewater feed tank. The wastewater from the equalization tank is passed over a baffle to equally distribute the flow of wastewater into the flow adjustment zone. In the flow adjustment zone the flow must be laminar to reduce the effect of flow of the liquid in the contact zone. Then the wastewater is passed to contact zone where the wastewater and the bubble get in contact and floatation happens. In this zone a portion of the effluent from the DAF system was recycled by a recirculation pump and then mixed with air in the venturi under 2 bar pressure supplied by a compressor. The mixture entered the contact zone via a bank of four nozzles each having a distance of 13 cm from each other. The generated microbubble and the water mixture are conducted vertically by the inclined baffle of 0.7 m in height and at angle of 60^o to the horizontal axis. The mixture inters the separation zone and the water leave the tank through the outlet pipe having the same diameter with the inlet of the DAF system. The floated solid matter was moved to the upper surface and was blocked by an installed stationary 40 degree angled scrapper from vertical axis and submerged 6 cm in to the water from the water level.

A mass balance for a mixture in the flotation tank is calculated by considering perfect mixing. The flotation tank initially operates in fed-batch mode and then operation is changed to continuous mode.

Assumptions

- Incompressible fluid
- Steady state (the system operates at constant volume once it became a continuous operation system)
- Recycle flow is neglected
- Laminar flow in all zones except the equalization tank
- No chemical reaction
- Inlet wastewater flow rate of $1m^3/h$ (Based on the maximum capacity of the flow measuring device at hand)
- Length of baffle in first compartment = 0.15 m
- The same width (0.5 m) for all compartments
- For a high rate flow system, a range of velocity from 15 to 40 m/h in the contact zone is applied conventionally [42] , therefore a velocity of 20 m/h was assumed for the designed DAF operation, at the inlet of the contact zone
- For a high rate flow system, a range of velocity from 2.5 to 26 m/h in the separation zone is applied conventionally, therefore a velocity of 10 m/h was assumed for the designed DAF operation, at the inlet of the separation zone

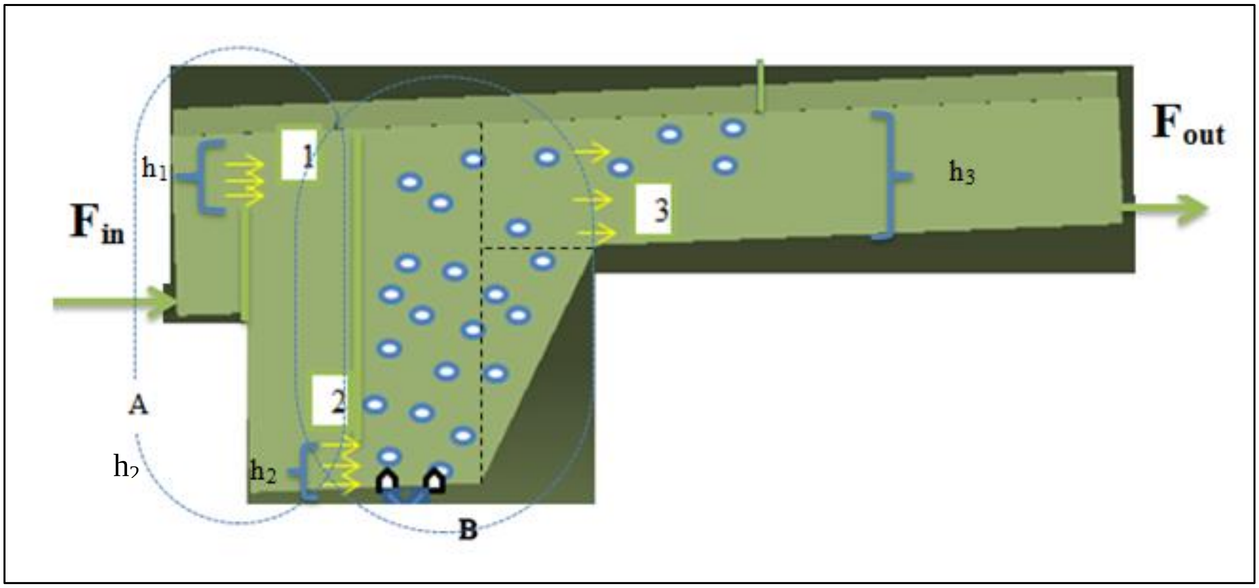


Fig. 3.4: Schematic representation of flow zone boundaries for material balance on DAF system.

The General Material/ Mass flow balance equation for any system with the assumptions given above is given by:

$$\text{mass flow in to the system} - \text{mass flow out of the system} + \text{generation with in the system} - \text{consumption with in the system} = \text{accumulation with the system}$$

Boundary System A, Mass balance between inlet Flow and Flow adjustment zone (between F_{in} and No 2)

$$\rho F_{in} = \rho F_2 = \rho A_2 v_2$$

$$F_{in} = A_2 v_2 \ , \qquad constant\ \rho$$

From the high rate DAF system assumption the velocity (v_2) at point 2 = 20m/h, then

$$A_2 = \frac{F_{in}}{v_2} = \frac{1m^3/h}{20m/h} = 0.05m^2$$

Then, the height of flow at the inlet of contact zone h_2, which is the baffle opening height, is determined from the corresponding area,

$$h_2 = \frac{A_2}{w} = \frac{0.05m^2}{0.5m} = 0.1m$$

From this value the size of 0.1 m depth is assigned for baffle opening on the DAF system

Boundary system B, Mass Balance between the inlet of contact zone and inlet of separation zone

$$\rho A_2 v_2 = \rho A_3 v_3$$

$$A_3 = \frac{A_2 v_2}{v_3} = \frac{0.05m^2 * 20m/h}{10m/h} = 0.1m^2$$

$$h_3 = \frac{A_3}{w} = \frac{0.1m^2}{0.5m} = 0.2m$$

Therefore, the operation water table of the overall DAF system is determined by this height and it has to be 0.2 m high from the base table of the separation system.

Since the system operates at steady state, the total height of liquid (from the ground) in flow adjustment zone and contact zone should be equal.

$$0.5m + 0.15m + h_1 = 0.6m + h_3$$

Where, 0.5m is height of dead zone which, is below flow equalization tank and 0.15m is height of vertical baffle between flow equalization tank and flow adjustment tank. Thus,

$$h_1 = 0.6m + 0.2m - 0.5m - 0.15m = 0.15m$$

$$A_1 = 0.5m * 0.15m = 0.075m^2$$

$$v_1 = {}^{F_{in}}/_{A_1} = {}^{1m^3/h}/_{0.075m^2} = 13.3m/h = 0.0037m/s$$

Reynolds number for pipe flow in feed stream and open channel in the DAF system is calculated as;

Pipe diameter (ID) = 0.0254m

$$A_{pipe} = \frac{\pi D^2}{4} = {3.14 * (0.0254)^2}/_{4} = 0.0005m^2$$

$$v_{in\ pipe} = {F_{in}}/_{A_{pipe}} = \frac{1m^3/h}{0.0005m^2} = \frac{2000m}{h} = 0.56\ m/s$$

$$Re = \frac{\rho v D}{\mu} = \frac{\frac{1000\ kg}{m^3} * 0.56\ m/s * 0.0254m}{0.001\ pa.s} = 14{,}111$$

The calculated Reynolds number shows the flow in the feed pipe is turbulent and therefore the need of applying a baffle to make a flow laminar is very necessary for the system to operate at a low effect of the flow nature.

Reynolds number for open channel [44] is given by:

$$Re = \frac{\rho v (dh)}{\mu}$$

Where, $"dh"\ is\ hydraulic\ radius = cross\ sectional\ area\ (A)/wetted\ perimeter(P)$

At the inlet of flow adjustment zone

$$P_1 = 2h_1 + w = 2 * 0.15m + 0.5m = 0.8m$$

$$dh_1 = {A_1}/_{P_1} = 0.094m$$

$$Re_1 = \frac{\rho v (dh)}{\mu} = \frac{\frac{1000kg}{m^3} *\ 0.0037m/s * 0.094m}{0.001\ pa.s} = 348$$

At the inlet of contact zone

$$P_2 = 2h_2 + w = 2 * 0.1m + 0.5m = 0.7m$$

$$dh_2 = {A_2}/_{P_2} = 0.0714m$$

$$Re_2 = \frac{\rho v(dh)}{\mu} = \frac{\frac{1000kg}{m^3} * \ 0.005556m/s * 0.0714m}{0.001\ pa.s} = 397$$

At the inlet of separation zone

$$P_3 = 2h_3 + w = 2 * 0.2m + 0.5m = 0.9m$$

$$dh_3 = {}^{A_3}/_{P_3} = 0.111m$$

$$Re_3 = \frac{\rho v(dh)}{\mu} = \frac{\frac{1000kg}{m^3} * \ 0.00277m/s * 0.111m}{0.001\ pa.s} = 308$$

Values of Reynolds number calculated above show that the flow is laminar in all three zones fulfilling the assumption of the laminar flow operation to eliminate or reduce the effect of separation.

Time required, filling the DAF tank at a level of steady process and at constant feed flow rate, $1m^3/h$ is calculated as:

Volume of equalization zone (V_1):

$$V_1 = D * L * W = 0.3m * 0.2m * 0.5m = 0.03m^3$$

Volume of flow adjustment zone (V_2):

$$V_2 = D * L * W = 0.8m * 0.3m * 0.5m = 0.12m^3$$

Volume of Contact zone (V_3) is the volume summation of three regions.

$$V_3 = V_{rectangle\ 1} + Volume_{triangle} + V_{rectangle\ 2} =$$

$$(D * L * W) + \frac{1}{2}(D * L * W) + (D * L * W) =$$

$$(0.8m * 0.4m * 0.5m) + \frac{1}{2}(0.6m * 0.35m * 0.5m) + (0.2m * 0.35m * 0.5m) =$$

$$0.16m^3 + 0.0525m^3 + 0.035m^3 = 0.2475m^3$$

Volume of separation zone (V_4):

$$V_4 = D * L * W = 0.2m * 1.6m * 0.5m = 0.16m^3$$

Total volume of DAF tank (V_T)

$$V_T = V_1 + V_2 + V_3 + V_4 = 0.5575m^3$$

$$Time(min) = \frac{V_T}{F_{in}} = \frac{0.5575m^3}{1m^3/_{hr}} * \frac{60\ min}{1\ hr} = 33.5\ min$$

The time required to fill the DAF system at a level of steady state used to analyze residence time distribution of DAF system.

3.4. Experimental procedures

The MB generation system and DAF system were manufactured in Akaki poly technic college (Addis Ababa) and installed in Adama Science and Technology University of chemical engineering department, based on the dimensions derived from the design calculation. For operational testing of the DAF system the residence time distribution using a tracer test, floatation test using synthetic pulp wastewater, deinking test using methyl red as a surrogate ink and aeration test were done for indirect method for the presence of microbubble generation in comparison to the conventional bubble aeration.

3.4.1. Air bubble generation process

The bubble production system comprised of a various elements. From the DAF system, filled with a designed level of tap water having at a steady state, recycled water was pumped and mixed with air in a venturi tube. Controlled amount of air from a compressor was fed to the throttling section of venturi tube at low pressure. Some of the water and air mixture was allowed to flow back to recycle tank to control the recycled water amount. Finally, the pressurized water - air mixture is released into the contact zone of the DAF system through four 1.5 mm injection nozzles. The generated bubble size is determined before applying on the separation process. In bubble generation system an image was captured in continuous shot using digital microscope as shown in Figure 3.5.

All captured images, using digital microscope were processed through image analysis software named imajeJ. The software was calibrated with known length of lines and set global to analyze other captured images. Images taken in single and continuous shot and the appropriate image of bubble is selected for size determination.

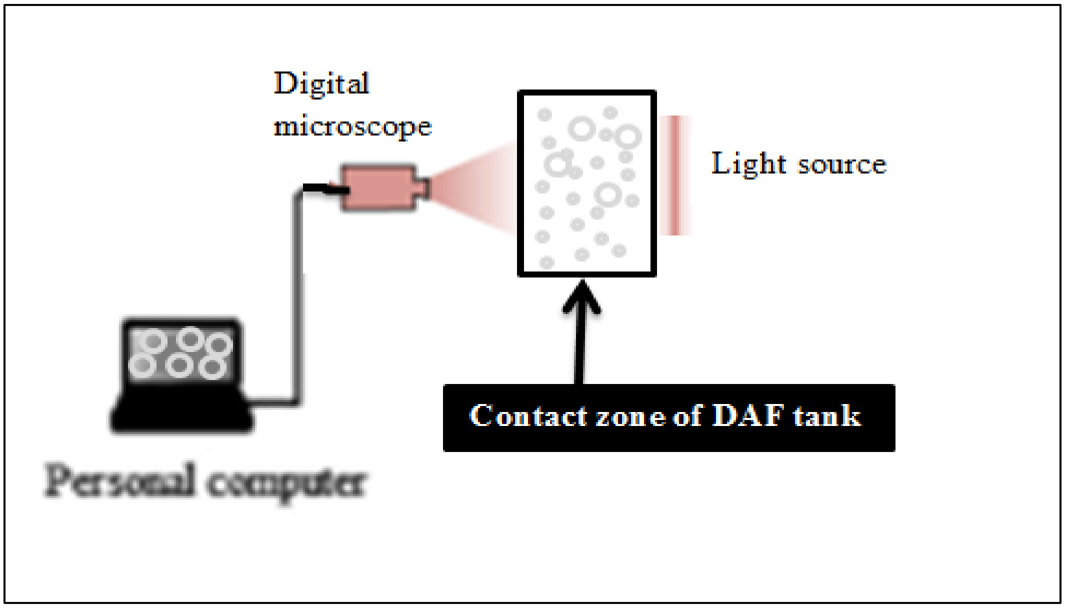


Fig. 3.5: Schematic of bubble image analysis setup

3.4. 2. Raw material collection and preparation of synthetic wastewater

Pulp and paper wastewater were collected from Ethiopian pulp and paper Share Company and tested for its concentration and turbidity. Based on that synthetic wastewater was prepared depending on the properties of the effluent of the company for all the experiments.

Synthetic wastewater was prepared by taking Ethiopian pulp and paper share company effluents as a reference.

Both the total solid and suspended solid concentration was measured to know the proportion of the suspended solid according to the standard procedure of environmental engineering lab manual measurement.

Concentration of solids (total solids) in effluent was determined using gravimetric analysis.

$$Total\ solids\left(\frac{g}{L}\right) = \frac{(w_2 - w_1)g}{sample\ volume(mL)} * 10^3$$

Where, $w_2 = weight\ of\ crucible + weight\ of\ residue$ and

$w_1 = weight\ of\ crucible$

Clean crucible was treated in furnace at 550 ^{0}C for one hour and kept in a desiccant before measurement and w_2 is the measurement taken repeatedly until the weight of sample kept in oven at 105^{0}C become constant. Accordingly, the effluent sample, taken from the company has 20 % total solid weight by volume (0.2 g/L) and turbidity of 52 NTU.

The suspended solids of the effluent also determined using:

$$Total\ suspended\ solids\left(\frac{g}{L}\right) = \frac{(w_2 - w_1)g}{sample\ volume(mL)} * 10^3$$

Where, $w_2 = weight\ of\ filter\ paper + weight\ of\ dried\ residue$ and
$w_1 = weight\ of\ filter\ paper$

The filter paper is rinsed with deionized water and dried under 105^{0}C in oven until the weight is constant before using for sample filter.

W_2 is measured repeatedly until the weight of sample kept in oven at 105^{0}C was constant. Thus, the suspended solid is 0.16g/L of the solution.

For deinking test, ink with methyl red dye which is 1% weight by volume (g/L) and aluminium sulphate (100mg/L) as a coagulant, was applied to surrogate the wastewater contaminated by ink.

3.5. Experimental measurements

All experimental measurements are taken under ambient temperature and pressure before and after the experiments. The following methods or measuring techniques were applied for determination of each parameters used during the overall research period.

Table 3.1 Methods used for analysis in the lab test

Parameters	Turbidity (NTU)	Light intensity (%,)	Dissolved oxygen(mg/L)	pH	TS and TSS
Method/ instrumentation	Turbidity/turbidimeter	Transmittance /UV-VIS spectroscopy	DO meter	pH meter	Gravimetric analysis

3.6. Residence time distribution of DAF system

The flow pattern inside the DAF system is analyzed by the determination of the Residence Time Distribution. It tells the probability distribution of time that solid or fluid materials stay inside the DAF tank in a continuous flow system. In this test, methyl red dye is used as a tracer in a step change test for a continuous system where steady state of bulk flow is reached. The response of the tracer profile in three different zones was detected for both microbubble and conventional flotation systems to observe the comparison of mixing potential of the two bubbling systems. Concentration of samples taken from the three zones was evaluated against the calibration curve shown in figure 3.6. Concentration ratio versus time is plotted and RTD is investigated.

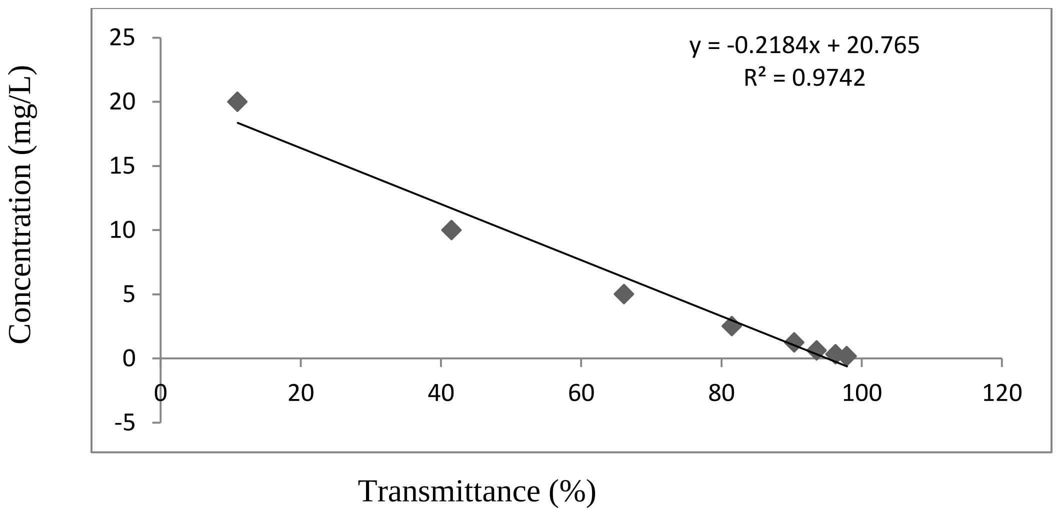


Fig. 3.6: Calibration curve of dilution

4. RESULTS AND DISCUSSION

4.1. Properties of synthetic wastewater

The property of the wastewater from the pulp and paper industry was determined to formulate a synthetic pulp and paper wastewater in the laboratory. The measured properties and the properties of the formulated synthetic wastewater are summarized in Table 4.1.

Table 4.1 Characterization of working liquids

Liquid type	Measurements					
	Turbidity (NTU)	Transmittance (%)	pH	TS (mg/l)	TDS (mg/l)	TSS (mg/L)
Tap water	0.23	100	7.02	-	-	-
Effluent from industry of paper	52	-	7.6	200	40	160
Synthetic wastewater	53	-	7.5	200	42.1	157.9
Inked water	-	14.3	8		-	-

Turbidity of synthetic wastewater was measured after gravimetric analysis of reference wastewater and the value is nearly the same. Most of Solid particles (80%) of the wastewater are suspended solids while the left 20% are dissolved solids. The flotation treatment unit is very important for such type of wastewater.

4.2. Characterization of bubble produced

Captured images at appropriate operating parameters were treated with imageJ following the procedure stated in chapter three. Raw bubble image selected for size analysis is shown in Figure 4.1.

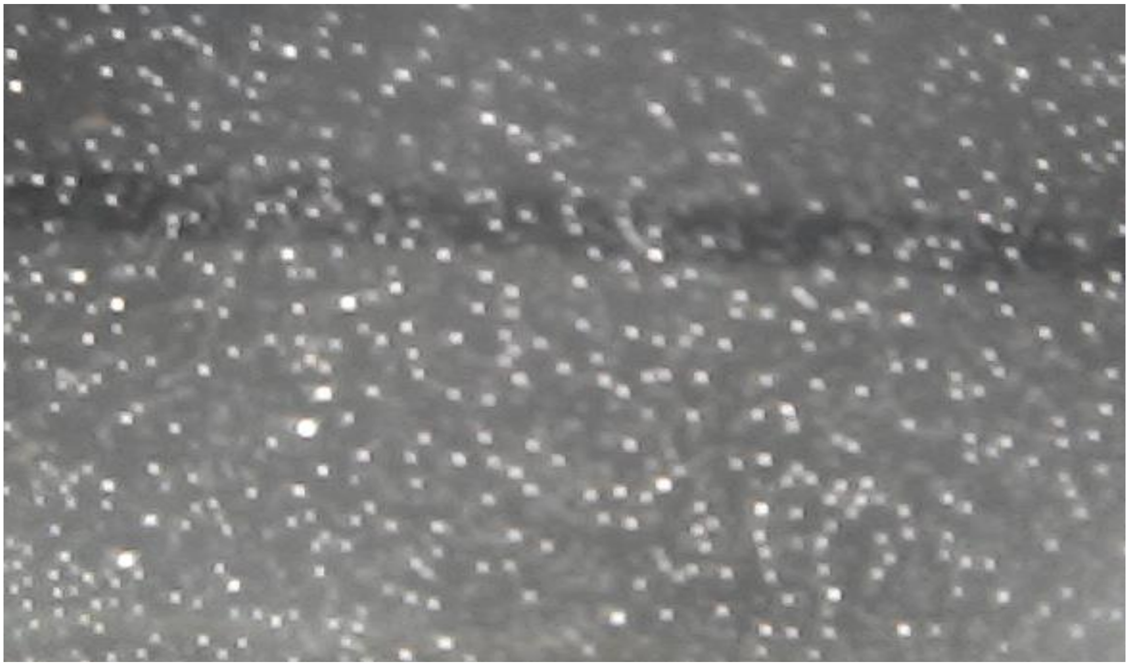


Fig. 4.1: Raw images of bubble for size analysis

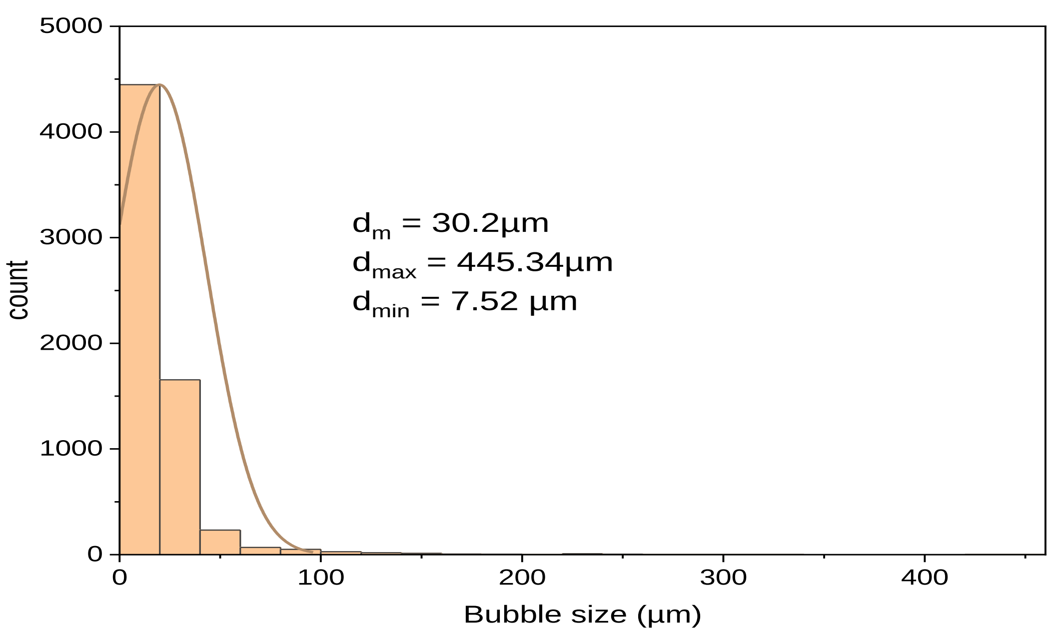


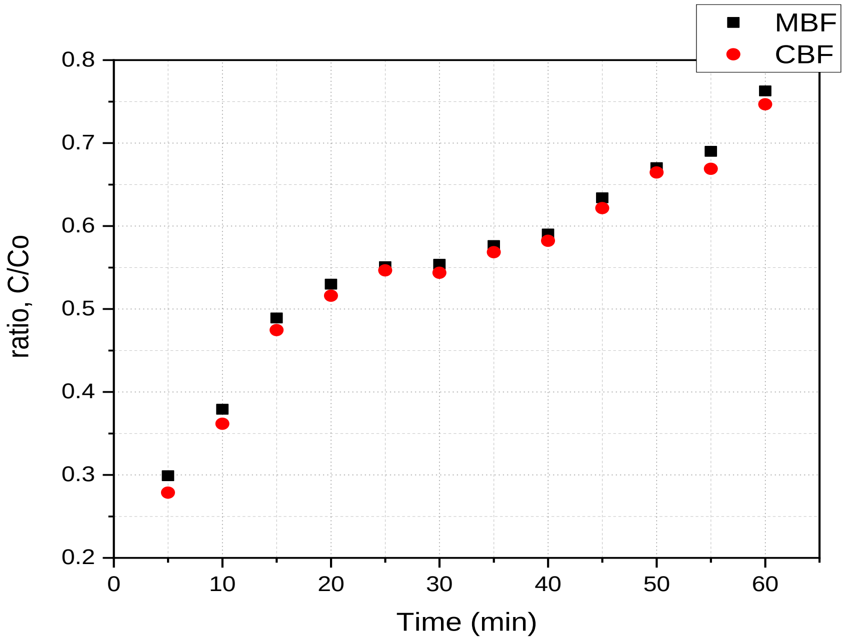
Fig. 4.2: Size distribution of bubbles

The bubble size analysis suggested a size distribution in the range of 7.52 – 445.3 μm with a mean diameter of 30.2 μm (Fig 4.2). But, the majority (70%) of bubbles was between 8 and 20 μm in diameter while 99% were smaller than 100 μm. The result found can be consistent with the results of researchers [9] adopted a standard for microbubble size range in the context of dissolved air flotation system. Moreover, the researchers believe that the accuracy of the bubble measurement must be improved to include bigger bubbles by reducing the fast motion of bigger bubbles.

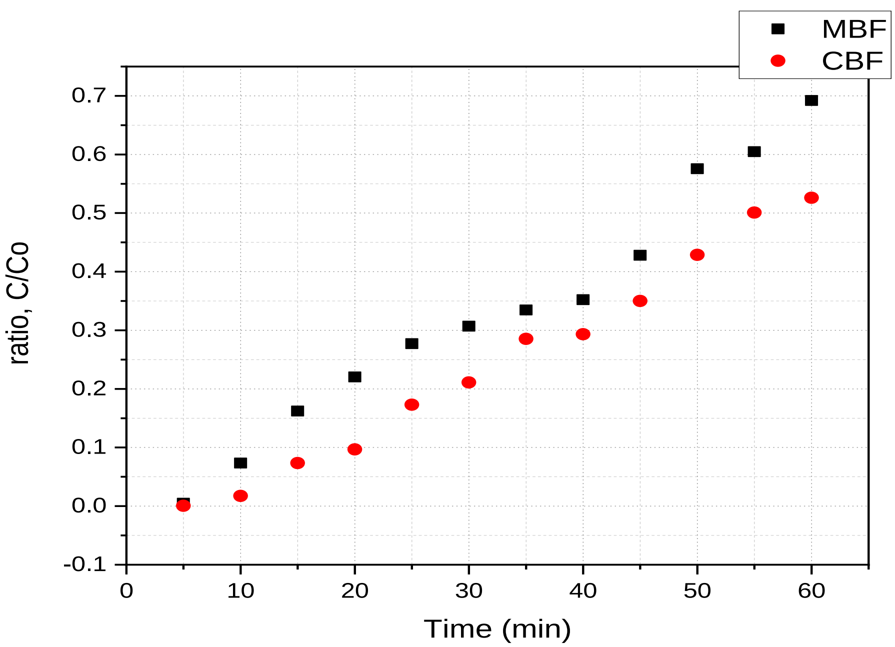
4.3. RTD analysis of DAF system

The experiments are numerically analyzed with regard to the designed total volume of DAF tank in three zones, namely, flow adjustment, contact and separation zones for both microbubble and conventional bubble flotation. The flow behavior in both microbubble and conventional flotation times was determined with same flow parameters of 3 L/min air flow rate and 1000 L/hr. wastewater feed flow rate. From the experiment (Figure 4.3), the mixing time of flotation for microbubble floatation system is shorter than the conventional flotation in all the three zones. For microbubble flotation, the ink concentration ratio reached 59 %, 35 %, and 30 % in the flow adjustment, contact and separation zones, respectively within the first 40 minutes. Whereas for conventional flotation the ink concentration reached 58%, 29% and 15% in the flow adjustment, contact and separation zones respectively with in the same time of 40 minutes. In the flow adjustment zone the concentration ratio of the ink is almost the same in the entire operation time (Figure 4.3 (a)). A slight increment by the MB generated system is may be because of a backflow of MBs to the flow adjustment zone.

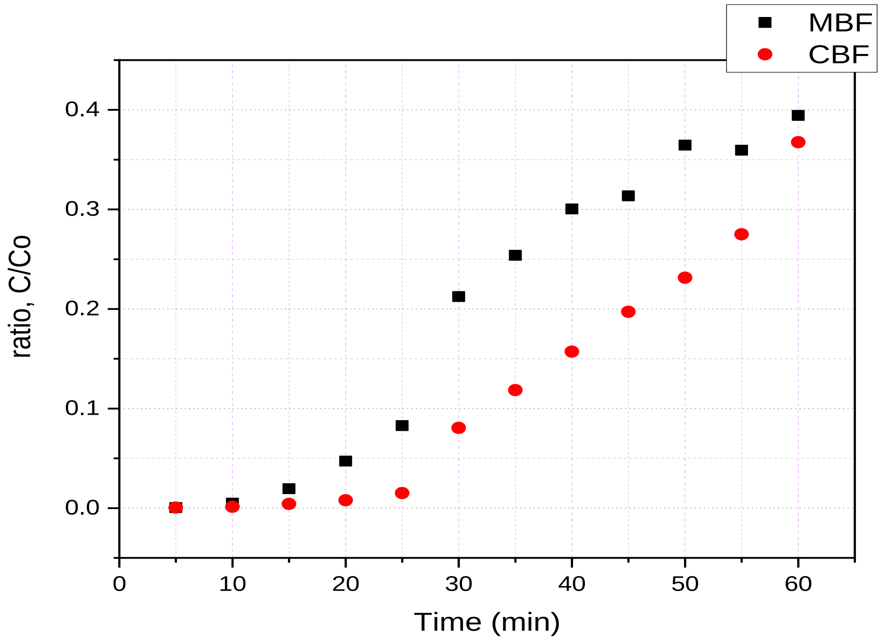
In contact zone and separation zone (Figure 4.3(b) and (c)) there was a significant difference in percentage of ink concentration ratio. This indicates the microbubbles generated highly facilitated the mixing of the flow after the wastewater gets in contact with the generated bubble. This is an indication of the possibility of MBs ability in improving the hydraulic mixing efficiency in the system.


MBF
CBF
0.8
0.7
0.6
0.5
0.4
0.3
0.2
ratio, C/Co
0
10
20
30
40
50
60
Time (min)

(a)


MBF
CBF
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
ratio, C/Co
0
10
20
30
40
50
60
Time (min)

(b)



(c)

Fig.4.3 Residence time distribution for both microbubble and conventional flotation system in (a) laminar zone (b) contact zone (c) separation zone.

4.4. Characterization of effluents

The turbidity of effluents from both microbubble and conventional bubble flotation tests were determined using turbidimeter measured in nephelometric turbidity units (NTU). The turbidity test for effluents of both MB and conventional flotation is performed with the same air and wastewater flow rate of 3 L/min and 1,000 L/hr. respectively. The samples were taken after 40 minutes flotation assuming that at least more than 60 % of the fluid is replaced and the value was recorded for one hour (Figure 4.4). For the same residence time, the turbidity value of conventional flotation effluents is much more than the MB flotation effluents. This high value of turbidity indicates the presence of more dispersed and suspended solids leaving the system with the effluent without being floated. This result shows that the MB floatation system developed has a better suspended solid separation efficiency compared to the conventional bubbling system.

Fig. 4.4: Pulp wastewater treatment process during the experiment

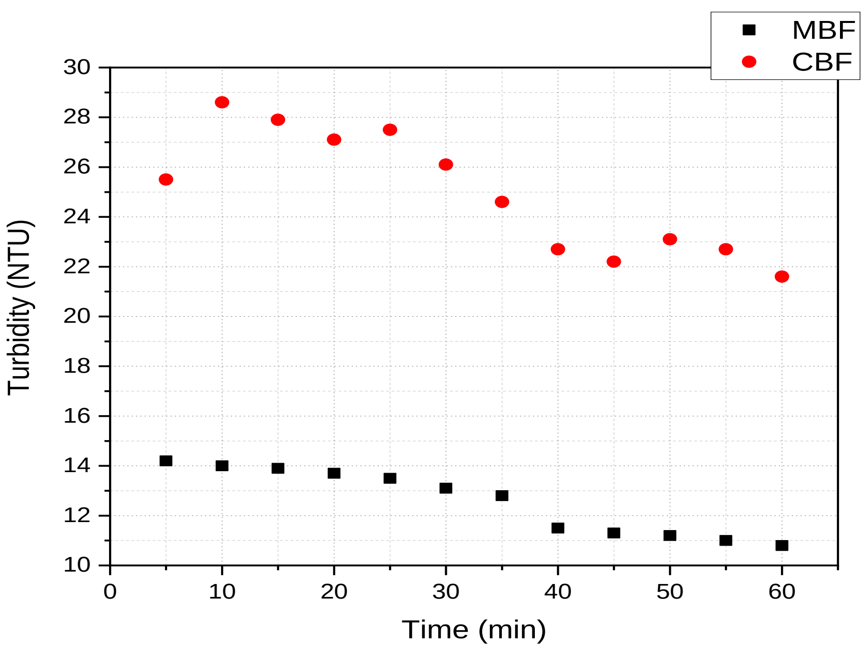


Fig.4.5: Turbidity of both MBF and CBF effluents

In deinking process a dyeing wastewater with a coagulant of Aluminum sulphate (100mg/L) was treated in both MBF and CBF. The experiments were performed at same conditions of 3L/min air flow rate, 1000 L/hr. wastewater flow rate and 20 minutes of flotation time. For the same residence time, Figure 4.5 the transmittance value of microbubble flotation effluents is much more than the conventional flotation effluents and the initial value of transmittance for both MB and CB flotation were not the same. This indicates that the smaller the bubble sizes, the more methyl red dye was removed and the shorter time the process takes. It also is an indicator for the presence of microbubbles. The ink degradation could be a result of oxidation by the OH radicals formed on the surface of the microbubbles.

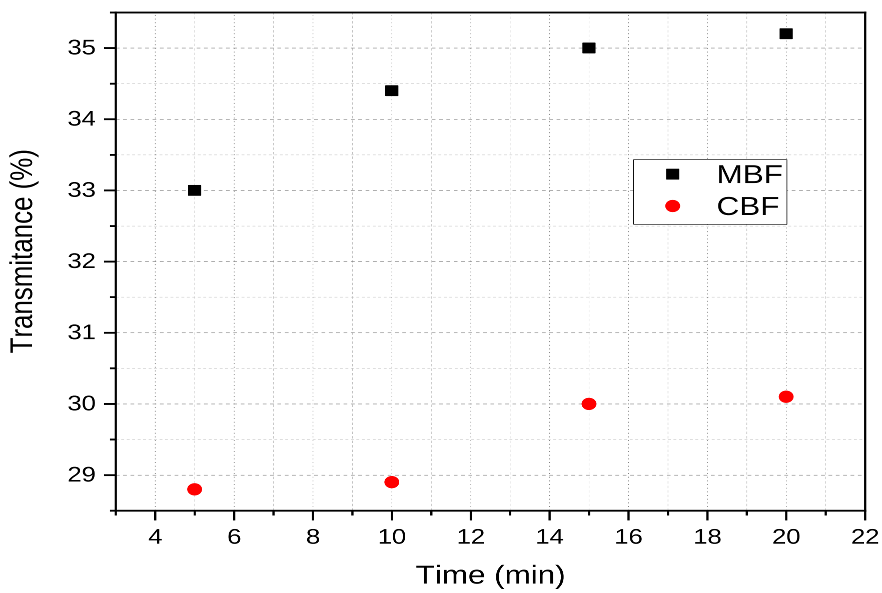


Fig.4.6: Color removal efficiency of both MBF and CBF

4.5. Aeration Efficiency improvement using MB application

Aeration is a mass transfer process between the gas and liquid systems. Its contribution in water treatment systems is very crucial in the reduction of the possibility of becoming septic nature of most treatment systems. Comparison of the mass transfer efficiency between two bubbling systems could be an indirect indicator for the production of finer bubbles. A system with fine bubbles can produce high mass transfer efficiency that the system operating with big size bubbles because of a potential of fine bubbles in increasing the mass transfer surface area compared to big bubbles. For the aeration process, the volumetric mass transfer coefficient *(kla)* is the indicator for the efficiency of a given system. The value was obtained from the measurement of DO concentration using the mass transfer model [43] with the corresponding temperature of water in the tank. A comparison between the two systems was done to see the variation of the *kla*.

$$\frac{dc}{dt} = k_l a(C^* - C)$$

$$\ln\left(\frac{C^* - C_L}{C^* - C_o}\right) = -K_L a.t$$

Where, t is the aeration time, C_L is the DO concentration at any time t, C^* is the equilibrium DO concentration in the liquid phase, and C_0 is the DO concentration at the initial point. In experiments with microbubble aeration, the initial DO concentration was 8.6 mg/L. However, in 20 minutes, the DO concentration reached a stable condition of 18.7 mg/L. In the case of the conventional aeration, the initial DO concentration was 8.5 mg/L and reached at a concentration of 13.7 mg/L in same time taken for microbubble aeration. The difference between the two aeration systems is plotted with concentration versus time as shown in Figure 4.7. The concentration of DO increase in the microbubble aeration compared to the conventional bubbling is an indication for the higher aeration potential of MB application in aeration.

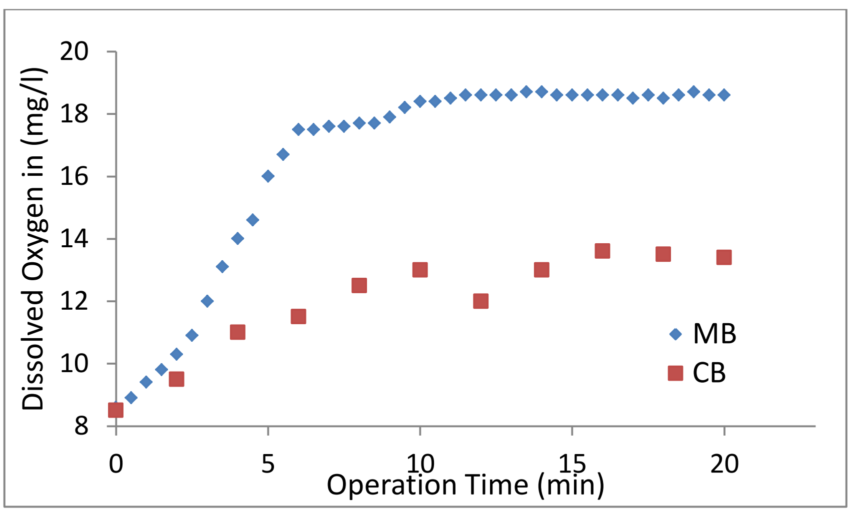


Fig. 4.7: Dissolved oxygen measurement for both MB and CB aeration

Curve fitting was done for the Normalized DO data versus time graph to determine the *kla* of each aeration system and the results found are presented as shown in Figure 4.8 and Figure 4.9. The result shows that the value of the kla for MB was found to be 0.3 while the result for CB is 0.175. The *kla* value was increased by almost 60 %, because of the reduction in bubble size caused by generation of MB. This difference between the two aerations is significant indicating the increment of the aeration surface area to volume ratio in the MB system compared to the CB system. High kla value in microbubble aeration system shows that, high volume of aeration tank used for conventional system can be replaced by small volume using microbubble aeration which, in turn reduces the cost of the aeration tank.

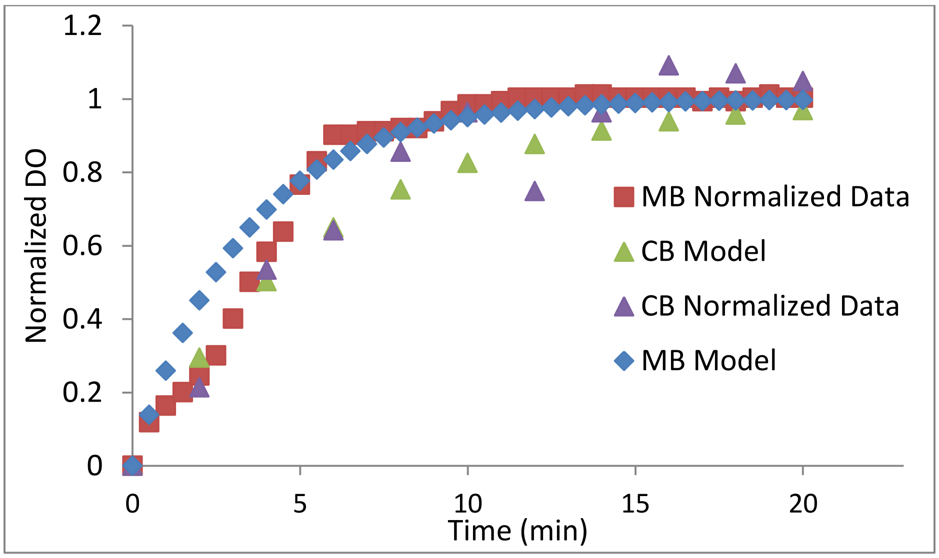


Figure 4.8: Curve fitting of Normalized DO measurement for both MB and CB aeration for *kla* determination

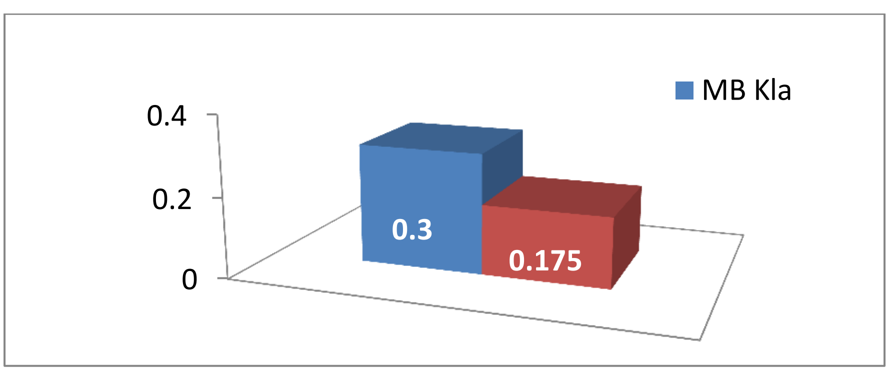


Figure 4.9: Comparison of kla between MB and CB aeration systems

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study answers the main objective of the research including, designing, manufacturing and developing a lab scale DAF system for demonstration. In this study, flotation assisted by microbubble was developed and compared with conventional/large bubble systems produced using stone air diffusers. The developed microbubble generation system produces large volume of bubbles within the range of microns size and this confirm the successful work of the study. Bubbles produced in small size had indicative separation efficiency in pulp wastewater, flotation which reduces a turbidity by 79.6% while in conventional is 59.2%. In dyeing wastewater the transmittance increases from 33% to 35% and 29% to 30.1% in microbubble flotation and conventional flotation, respectively under same conditions for a 20 min operation. The slight difference with transmittance value of the first percentage may be because of color removed by microbubble during the replacement process of water in the tank. The comparison between the two bubbling system also tested in aeration process for same condition and the DO concentration of the tap water, which initially were about 8.6 mg/L and 8.5 mg/L, increased to high values, 18.7 mg/L and 13.7 mg/L in microbubble and conventional bubble aeration, respectively.

5.2. Recommendation

Due to unavailability of appropriate devices and time consumed for manufacturing the lab scale DAF system, the scope of this work was limited.

In this thesis work indicative work has been done to show the significant potential of microbubble for wastewater treatment because of the separation ability, collision efficiency with suspended solids and relatively low rising velocity with conventional bubble. The significant reduction of turbidity value and an increase of transmittance of effluents make this work valuable and successful.

However in present work there are some studies that need further investigation: these include, the effect of solid particle size on separation efficiency of microbubble, effect of recycled water amount on the production volume of bubbles, effect of varying amount of air supplied on the bubble size, effect of coagulant type and concentration on separation efficiency with support of microbubble, the nozzle number and its configuration in reaction zone. Based on the started study, researchers can further expand the study on the recommended areas. Finally, the modeling of the designed system can further be upgraded and optimized using software programs.

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APPENDIXES

Appendix A. Sizing of DAF tank

- Incompressible fluid
- Steady state (the system operates at constant volume once it became a continuous operation system)
- Recycle flow is neglected
- Laminar flow in all zones except the equalization tank
- No chemical reaction
- Inlet wastewater flow rate of $1m^3/h$ (Based on the maximum capacity of the flow measuring device at hand)
- Length of baffle in first compartment = 0.15m
- the same width (0.5m) for all compartments
- For a high rate flow system a range of velocity from 15 to 40 m/h in the contact zone is applied conventionally [42] , therefore a velocity of 20 m/h was assumed for the designed DAF operation, at the inlet of the contact zone
- For a high rate flow system a range of velocity from 2.5 to 26 m/h in the separation zone is applied conventionally, therefore a velocity of 10 m/h was assumed for the designed DAF operation, at the inlet of the separation zone
- Retention time of contact zone (t) = 1.2 min = 0.02 hr.
- Retention time of separation zone = 19 min = 0.2hr.
- Depth to width ratio = 0.2 – 0.6

1. Contact zone

Taking depth to width ratio of 0.2

$$Depth(D) = width(W) * depth\ to\ width\ ratio = 0.5 * 0.2 = 0.1m$$

$$Area(A) = D * W = 0.05m^2$$

$$Design\ hydraulic\ loading\ rate\ (v_{design}) = {design\ flowrate(F_{in})}/{area} = 20m/h$$

$$Volume\ (V) = F_{in} * retention\ time = \frac{1m^3}{h} * 0.02hr = 0.02m^3$$

$$\text{length (L)} = \frac{\text{volume}}{\text{A}} = \frac{0.02m^3}{0.05m^2} = 0.4m$$

$$rising\ velocity\ of\ particle(v_{ris}) = \frac{Depth}{t} = \frac{0.1m}{1.2min} = 0.0833m/min$$

2. Separation zone

Taking the same width with contact zone and 0.6 depth to width ratio

$$Depth(D) = width(W) * depth\ to\ width\ ratio = 0.5 * 0.6 = 0.4m$$

$$Area = 0.4m * 0.5m = 0.2m^2$$

$$loading\ rate = \frac{design\ flowrate}{area} = \frac{1m^3/h}{0.2m^2} = 5m/h$$

$$Volume\ (V) = F_{in} * retention\ time = 1m^3/h\ * 0.32h = 0.32m^3$$

$$\text{length (L)} = \frac{\text{volume}}{\text{A}} = \frac{0.32m^3}{0.2m^2} = 1.6m$$

The effective depth, D_{ef} to travel a rise rate which calculated in contact zone within the specified detention time (t = 19 min) is estimated,

$$D_{ef} = rising\ velosity * retention\ time = \frac{0.0833m}{min} * 19.2min = 1.59m$$

In a given flotation time (19 min) the particles/bubbles can move around 1.59m vertically and thus we can fix the total height to 1m in order to collect and accumulate the scum efficiently on the surface of the water.

Table A1. Dimension and parameters of contact and separation zone of DAF tank

Type	Variables						
	Depth (m)	Width (m)	Length (m)	Flow rate (m^3/h)	Rising velocity (m/min)	Area (m^2)	Effective depth (m)
Contact zone	0.1	0.5	0.4	1	0.0833	0.05	1.59
Separation zone	0.4	0.5	1.6	1	0.052	0.2	

Appendix B. design of venturi tube

Assumptions

- Inlet flow rate = flow rate of feed pump, 25 L/min ($4.167 * 10^{-4} m^3/s$)
- No height difference between the water inlet and throat
- Pressure at inlet (P_1) = atmospheric pressure, 1atm
- Internal diameter = 25.4 mm for inlet and 8 mm for throat section of venturi
- Density of water ($\boldsymbol{\rho}_w$) = 1000kg/m^3

Taking the recycle pump flow rate, assumed above the velocity in the converging region (v_1) and throat tube is calculated from equation 3.3:

$$V_1 = \frac{Q_1}{A_1}$$

$$V_1 = \frac{Q_1}{A_1} = \frac{4.167 * 10^{-4} m^3/s}{5.065 * 10^{-4} m^2} = 0.823\ m/s$$

Where, $A_1 = \pi r_1^2 = 3.14 * (0.0127m)^2 = 5.065 * 10^{-4} m^2$

$$A_2 = \pi r_2^2 = 3.14 * (0.004m)^2 = 5.02 * 10^{-5} m^2$$

Taking atmospheric pressure at point 1 of figure 3.1(a) which is = $1.013*10^5$pa then the value of p_2 is evaluated using equation (3.4).

$$P_2 = 1.013 * 10^5 pa + \frac{1}{2} * \frac{1000kg}{m^3} * (0.823m/s)^2 (1 - (10.081)^2\ )$$

$$= 6.72 * 10^4 pa \sim 0.663 atm$$

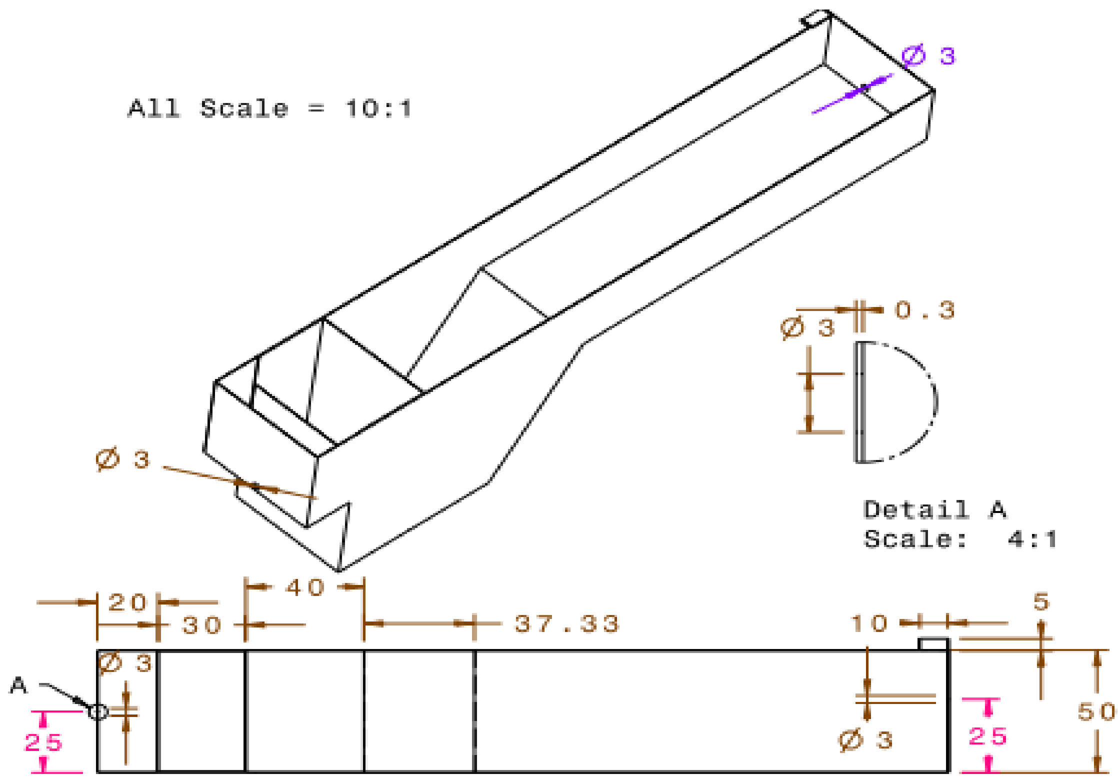
$$V_2 = \frac{A_1 V_1}{A_2} = 5.065 * 10^{-4} m^2 * 0.823 \frac{m}{s} / 5.02 * 10^{-5} m^2 = 8.294\ m/s$$

Table B1. Configuration of venturi tube

Param eters	D_1 (m)	D_2 (m)	A_1(10E-4) (m^2)	A_2(10E-5) (m^2)	V_1 (m/s)	V_2 (m/s)	P_1 (atm)	P_2 (atm)	Length (m)

Value	0.0254	0.008	5.065	5.02	0.823	8.294	1	0.663	0.226

Appendix C. Drawing of DAF tank and venturi



All dimensions are in mm and the thickness of material is 0.6 mm

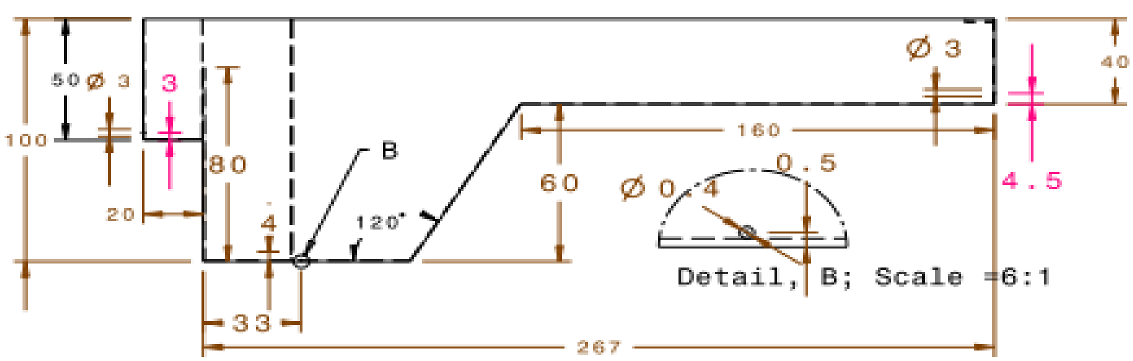
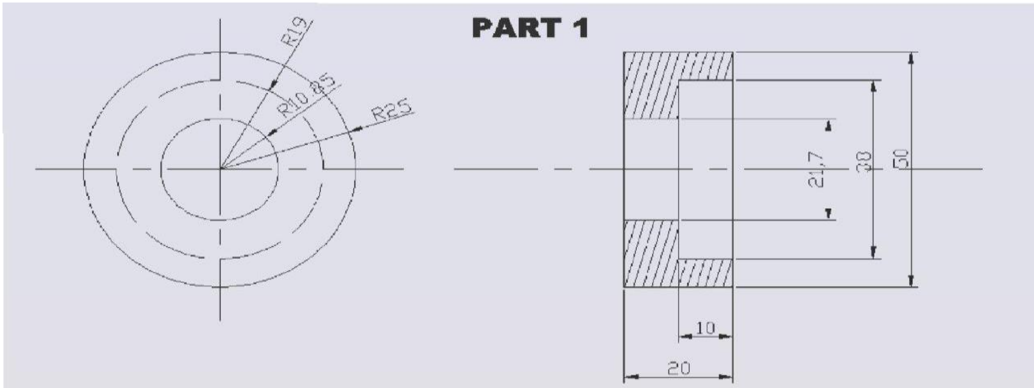
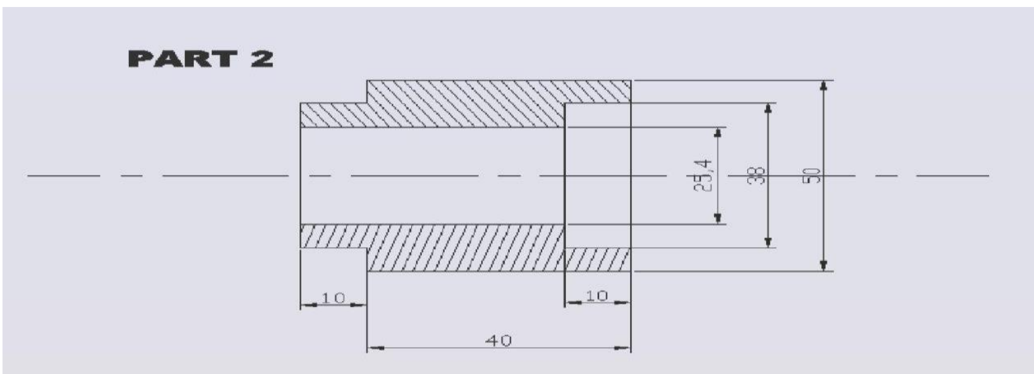
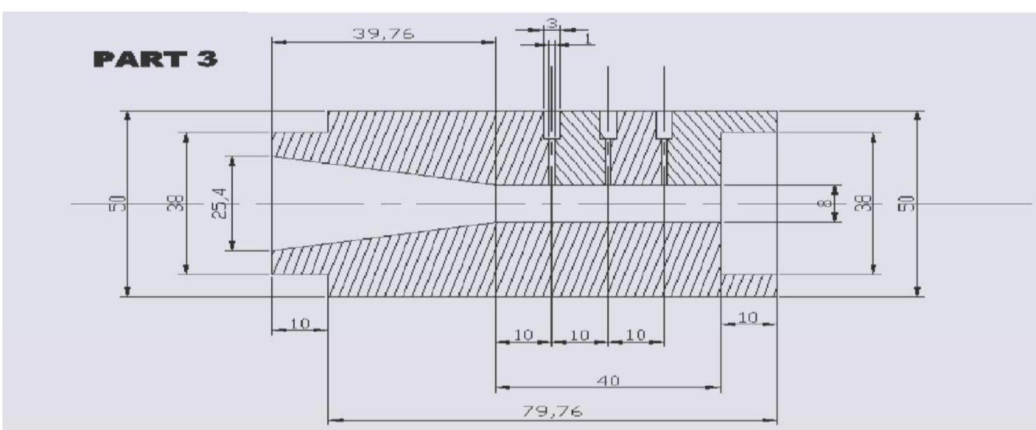
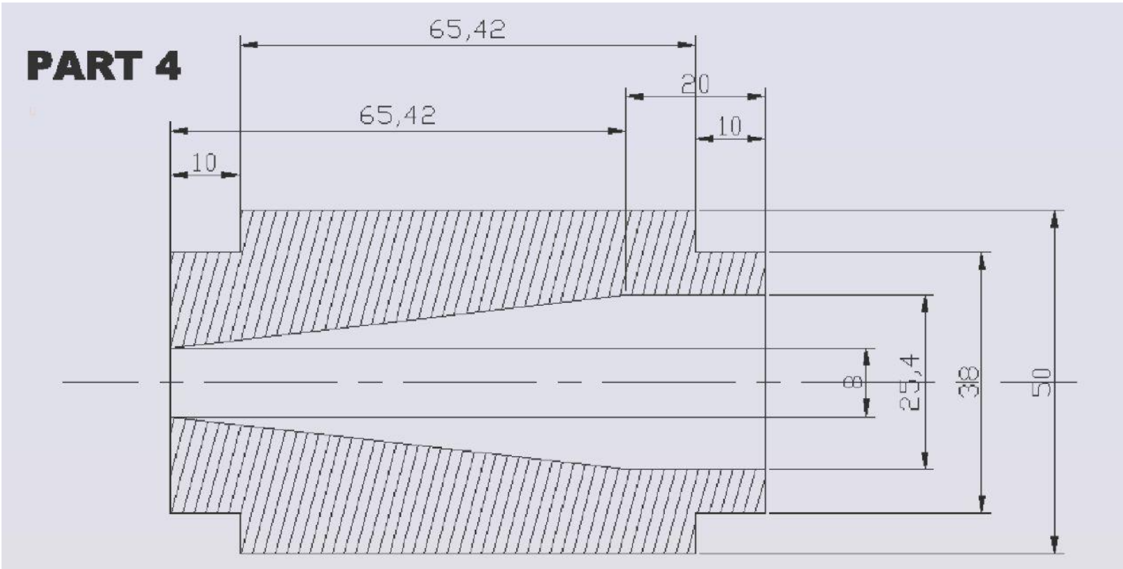


Fig. C1: Drawing of DAF tank


PART 1
R19
R10,85
R25
21,7
38
50
10
20


PART 2
25,4
38
50
10
10
40


PART 3
39,76
3
1
50
38
25,4
8
38
50
10
10
10
10
10
40
79,76



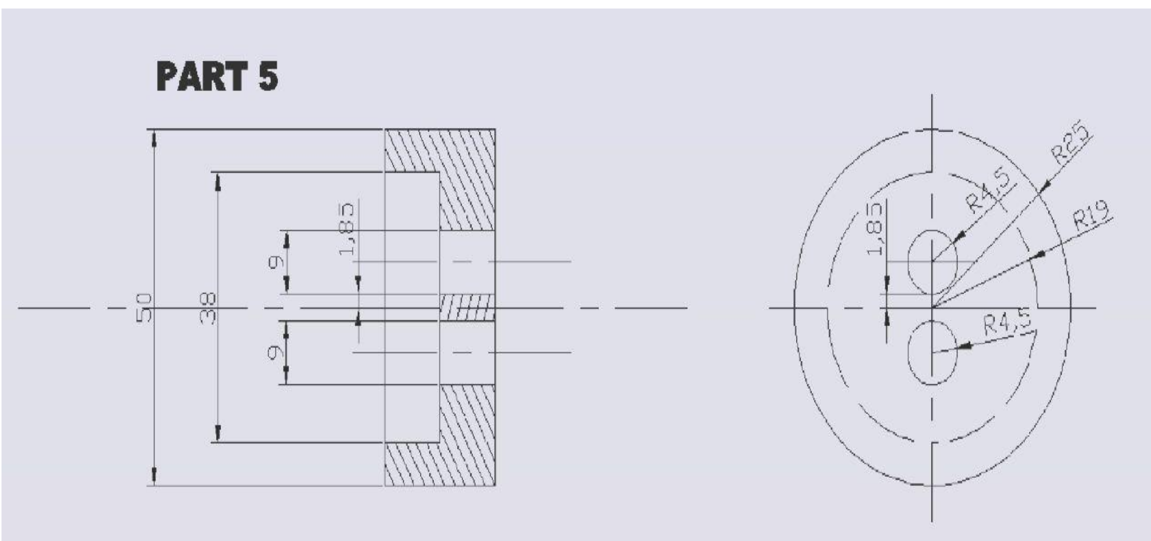


Fig. C2: Drawing of venturi tube

Appendix D. lab work image

Fig. D1: Synthetic wastewater preparation and treatment process

Fig. D2: UV/Vis test of dyeing wastewter