DEVELOPMENT OF AN APPROPRIATE AIR NOZZLE AND AIR SATURATOR FOR THE DISSOLVED AIR FLOTATION AS A SOLID-LIQUID SEPARATION PROCESS IN POTABLE WATER TREATMENT

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by

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LIST OF SYMBOLS AND ABBREVIATION

μm	micrometer
DAF	dissolved air flotation
MUC	Metropolitan Utilities Corporation
CAC	contact adsorption clarification
Fe^{3+}	Ferum (III)
m/h	meter per hour
mg/L	milligram per liter
MLD	million liters per day
kPa	kilo Pascal
$kg/m^2\ h$	kilogram per meter square per hour
$\mu g/L$	microgram per liter
PAC	powdered activated carbon
NTU	Normal turbidity unit
EF	electro-flotation
ECF	electrolytic coagulation/ flotation
DOC	dissolved organic carbon
IAF	dispersed/ induced air flotation
VOC	dissolved /volatile organic compounds
ΔP	difference of pressure on liquid/ gas interface or pressure change across the nozzle
$\gamma_{L/G}$	liquid/ gas interfacial tension
atm	atmosphere
$mN{\cdot}m^{-1}$	mili Newton per meter
m	meter
r	bubble radius
d_{cb}	critical diameter of the bubble nucleus
σ	surface tension or standard deviation
E_{cap}	capture efficiency
E_c	collision efficiency
E_a	attachment efficiency
E_s	stability efficiency
SE	saturator efficiency
η_s	saturator efficiency
PE	air precipitation efficiency
UK	United Kingdom

d_{bubble}	average bubble diameter
μ	dynamic viscosity of water or dynamic viscosity of fluid or population mean
V_{rise}	rising velocity of bubble
$\Delta\rho$	density difference of water and air
g	gravitational acceleration
ρ_2	bubble density
ρ_3	fluid density
PD	plate distributor
SN	spray nozzle
mm	milimeter
LPM	liter per minute
s	second
Q	volumetric flow rate
V_1	average flow velocity in the orifice
V_2	average flow velocity in the distribution channel
N_{Re1}	Reynolds number of the flow in the orifice
N_{Re2}	Reynolds number of the flow in the distribution channel
$C_{s,O2}$	actual mass concentration of oxygen in the water leaving the saturator
$C_{s,N2}$	actual mass concentration of nitrogen in the water leaving the saturator
$C_{a,O2}$	actual mass concentration of oxygen in the water entering the saturator
$C_{a,N2}$	actual mass concentration of nitrogen in the water entering the saturator
$C^*_{s,O2}$	theoretical mass concentration of oxygen in the water that would have attained equilibrium with saturator air at saturator pressure
$C^*_{s,N2}$	theoretical mass concentration of nitrogen in the water that would have attained equilibrium with saturator air at saturator pressure
$C_{m,O2}$	actual mass concentration of oxygen in the water in the measuring apparatus
$C_{m,N2}$	actual mass concentration of nitrogen in the water in the measuring apparatus
$C^*_{m,O2}$	theoretical mass concentration of oxygen in the water in the measuring apparatus
$C^*_{m,N2}$	theoretical mass concentration of nitrogen in the water in the measuring apparatus
°C	Degrees Celsius
C_i	mass concentration of gas *i* in the water
y_i	molar fraction of gas *i* in gas phase
M_i	molecular weight of gas *i*

H_i	Henry's constant of gas *i*
T	absolute temperature
K	degrees Kelvin
p_{total}	absolute, applied pressure
H_{N2}	Henry's constant for nitrogen
H_{O2}	Henry's constant for oxygen
$y_{a.N2}$	concentration of nitrogen in the atmosphere
$y_{a,O2}$	concentration of oxygen in the atmosphere
M_{N2}	molecular weight of nitrogen
M_{O2}	molecular weight of oxygen
p_a	dry atmospheric pressure
p_s	saturator pressure
$y_{m,O2}$	molar fraction of oxygen in the measuring apparatus
$y_{m,N2}$	molar fraction of nitrogen in the measuring apparatus
a_p	air mass
V_p	volume of air
ρ_{air}	density of air
p_a	atmospheric pressure
$\bar{x}$	point estimator of population mean
$\mu_{\bar{x}}$	mean of sampling distribution
$\sigma_{\bar{x}}$	standard deviation of sampling distribution
n	sample size
H_o	null hypothesis
H_a	alternative hypothesis
μ_1	mean population of the first sample
μ_2	mean population of the second sample
D_o	hypothesized difference between two means
n_1	measurements from the first population
n_2	measurements from the second population
ANOVA	Analysis of Variance

LIST OF APPENDICES

PEMBANGUNAN MUNCUNG DAN PENEPU UDARA YANG SESUAI UNTUK PENGAPUNGAN UDARA TERLARUT SEBAGAI PROSES PENGASINGAN PEPEJAL-CECAIR DALAM OLAHAN AIR MINUMAN

ABSTRAK

Objektif kajian ini adalah untuk membangun dan menguji keupayaan muncung dan penepu udara yang telah direkabentuk untuk pengapungan udara terlarut sebagai proses pengasingan pepejal-cecair dalam olahan air minuman. Dua komponen ini mempunyai kepentingan yang tinggi dalam memastikan kejayaan teknik pengapungan udara terlarut. Dua rekabentuk penepu udara telah diuji dan keputusan menunjukkan bahawa penepu udara yang menggunakan plat agihan (PD) mempunyai kecekapan yang lebih tinggi apabila kadar aliran air dipertingkatkan. Faktor tekanan tidak menunjukkan kesan signifikan dalam penentuan kecekapan penepuan udara untuk penepu udara jenis PD. Penepu udara yang menggunakan muncung perenjis (SN) mempunyai kecekapan yang lebih tinggi berbanding penepu udara jenis PD untuk kedua-dua keadaan tekanan yang diuji. Kesan tekanan dalam penepu udara terhadap kecekapan penepuan udara didapati berbeza untuk kedua-dua jenis penepu udara. Untuk penepu udara jenis SN, peningkatan tekanan dalam penepu udara didapati menghindar kecekapan penepuan udara manakala kesan sebaliknya berlaku untuk penepu udara jenis PD. Walaubagaimanapun penepu udara jenis SN telah berjaya dihasilkan di mana keadaan operasi yang optimum (tekanan 500 kPa dan kadar aliran air sebanyak 6 liter per minit) mampu memberikan kecekapan penepuan udara sebanyak 81%. Tiga rekabentuk muncung udara yang telah dihasilkan dan diuji untuk menentukan keupayaannya dalam dua aspek iaitu, kecekapan pelepasan udara dan penghasilan gelembung udara bersaiz mikro. Ketiga-tiga rekabentuk mucung udara di uji dalam keadaan yang berbeza-beza. Parameter yang dikaji adalah nisbah saiz orifis kepada saluran edaran, aliran air tepu dan rekabentuk geometri muncung udara. Keputusan kajian menunjukkan nisbah saiz orifis kepada saluran edaran yang kecil

(1:1) menghasilkan gelembung udara yang lebih kecil berbanding nisbah yang lebih besar (1:2) untuk ketiga-tiga rekabentuk muncung udara. Kadar aliran air tepu udara yang lebih tinggi (4 liter per minit) didapati menghasilkan gelembung udara yang bersaiz lebih kecil berbanding keadaan aliran air tepu udara yang lebih rendah (2 liter per minit) untuk kesemua rekabentuk muncung udara yang dikaji. Analisis menunjukkan bahawa muncung udara jenis 2 (rekabentuk pemesongan runjung) dengan nisbah saiz orifis kepada saluran edaran 1:1, menghasilkan gelembung udara yang paling kecil (55 μm) pada aliran air tepu udara optimum iaitu sebanyak 4 liter per minit. Kecekapan pelepasan udara untuk kesemua rekabentuk udara adalah dalam lingkungan 84% hingga 87%. Perbandingan keupayaan muncung udara yang direkabentuk dengan satu muncung udara komersial telah dibuat dengan menggunakan kaedah penilaian yang sama. Secara amnya, muncung udara yang direkabentuk menghasilkan gelembung udara yang lebih kecil berbanding muncung udara komersial.

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ABSTRACT

The aim of this research is to develop and evaluate air injection nozzles and air saturators for the DAF process in solid- liquid separation in potable water treatment. These two components are the most critical in ensuring the feasibility and success of the DAF process. The efficiency of the air saturators as well as the performance of the air injection nozzle were evaluated. Two types of unpacked saturators were designed (the unpacked plate distributor (PD) saturator and the unpacked spray nozzle (SN) saturator) and the efficiency of these unpacked saturators were evaluated at different flow conditions. The parameters observed for the unpacked PD saturator were the saturator pressure and flow rate. It was found that the increase of flow rate would lead to the increase of saturator efficiency for the unpacked PD saturator. Saturator pressure however does not have a significant effect towards the unpacked PD saturator efficiency. The unpacked SN saturator showed reasonable efficiency when it was tested at a flow rate of 6 LPM for 500 and 600 kPa saturator pressure. An unexpected trend was observed for the effect of saturator pressure towards the saturator efficiency of the unpacked SN saturator. At lower operating pressure, the efficiency was observed to be higher when compared to higher operating pressure giving the mean saturator efficiency of 81% and 73% respectively. Comparison of the performance for the two saturators showed that the unpacked SN saturator outperformed the PD saturator for the two saturator pressures (500 kPa and 600 kPa) tested at a flow rate of 6 LPM. The optimum operating conditions for the unpacked SN saturator were found to be at 500 kPa saturator pressure and flow rate of 6 LPM giving 81% of mean saturator efficiency. Three designs of experimental air injection nozzles were evaluated in terms of air precipitation efficiency and mean bubble size produced

through injection of supersaturated stream. The first air injection nozzle was a nozzle with one orifice and six distribution channels (equal diameter). The distributing channels are placed at the base of an impinging surface giving a 90° directional change. The distributing channels are located evenly at each mid-section of the hexagonal plane of the nozzle. The orifice was also threaded to increase friction of the traveling stream. The second design employed a conical divergence angle of 90° from the inner distribution channel to the outer distribution channel. The shorter passageway through the distributing channel would give an abrupt release and a quicker expansion of the supersaturated pressurized stream. The third design had 2 directional changes from the orifice to the six distribution channel located evenly at the mid-section of the hexagonal plane of the nozzle. The nozzles were tested on various flow conditions. Several parameters of test were observed to study the effect on the size of bubbles produced. Smaller size ratio of the orifice to distribution outlet were found to produce smaller bubbles for all three nozzle designs for two flow rates tested (2 and 4 LPM). Higher injection flow rate (4 LPM) were found to produce smaller bubbles for all three nozzle designs when compared to a low flow rate injection (2 LPM). The results indicated that the best nozzle design is nozzle type 2 (conical divergence feature) with an orifice to distribution outlet size ratio of 1:1 at a flow rate of 4 LPM produced the smallest mean bubble size (55 μm) when compared to other nozzles. The air precipitation efficiencies for all three nozzles were found to be reasonable (84%- 87%). Nozzle type 2 was later compared to a commercial air injection nozzle at a pressure of 600 kPa and flow rate of 4 LPM. The results indicated that the experimental nozzle produced smaller bubbles compared to the commercial injection nozzle.

CHAPTER 1

INTRODUCTION

Conventional processes of separating solids from liquid in water treatment for clarification purposes like gravity sedimentation is time consuming due to the low surface loading rate. With the demand for a more efficient and rapid process with similar or higher quality output, the flotation process has gained much interest in industrial applications. The benefits of flotation mentioned in many texts include higher throughput, excellent effluent quality, flexibility in design to accommodate unstable raw influent quality and lower cost in construction compared to other processes. Dissolved air flotation is one of the several methods of flotation which has gained much popularity since 1924 in the recovery process of fibers and white water in the pulp and paper industry. Not until 1960's was DAF considered a possible clarification process for potable water treatment in Finland and Sweden (Gregory, 1997).

In the United Kingdom, Dr. Packham prompted the use of DAF for potable water treatment and various studies in DAF were later intensified by the Water Research Centre (Adlan, 1998). Most research in DAF were mainly focused in the optimization of operating conditions and plant design features particularly on processes prior to flocculation, the flow through rate, the recycle rate and pressure, injection nozzle and saturator designs, DAF tank dimensions and deflector plate angles, sludge removal and frequency of scraping (Gregory, 1997).

The DAF process can be operated in three modes; full-stream pressurization, split-stream pressurization and recycle-stream pressurization. However, only recycle-stream pressurization mode is suitable for potable water treatment as the other modes could be difficult to operate as flocculation and coagulation process are performed prior to flotation. The influent of this two modes has to flow through constrictions such as air injection nozzle or needle valves and would result in break-up of the flocs pre-formed in the prior processes to undesirable sizes for flotation. Four important design criteria in DAF are air-to-solids ratio, hydraulic loading, saturator characteristics and injection nozzle performance (Gochin, 1990).

Packed saturator design criteria have been studied by Haarhoff & Rykaart (1995) with the research emphasis on effects of hydraulic loading and packing depth towards the saturator efficiency. Haarhoff & Steinbach (1997) made a fundamental study on the method for measurement of saturator efficiency with respect to air precipitation efficiency given by different types of nozzles. It was shown that if this parameter was not taken into consideration in the mass balance equation for the determination of saturator efficiency, a significant error in reporting of saturator efficiency would result. Steinbach & Haarhoff (1998) indicated that air composition in saturators would change from start up of operation until reaching an equilibrium state. These phenomena as shown by kinetic modeling by the authors are the result of the differences in solubility of gases in water under high pressure. Studies on the design of unpacked saturators (without packings) have not been found in literature except for pure gas (oxygen) transfers in absorber towers (Vinci et al.,1997). It was shown by the authors that increase of tower height, lowered hydraulic loading rates as well as the use of spray nozzles in absorber towers would encourage higher efficiency in mass transfer of gases. But the study conducted Vinci and co-workers were at atmospheric pressure whereas saturators used in DAF operate under high pressures. From this lack of information, it is suggested that the factors that may affect the performance of unpacked saturators should be studied.

Special orifices are required to promote the generation of desirable sized micro bubbles for flotation. Needle valves and specially designed air nozzles are usually used to generate as well as to encourage air precipitation in DAF tanks. Works of Rykaart & Haarhoff (1995) and Dupre et al. (1998a, 1998b) have identified that several features such as geometrical design, orifice size, presence of an impinging surface, and abrupt release of pressurized supersaturated solution through the a Reynolds tube to simulate air injection nozzles gave promising results in producing micro-bubbles with a narrow size distribution which is desirable to DAF. Rykaart & Haarhoff (1995) studied the behavior of commercially available nozzles with respect to different injection pressures but failed to mention how geometrical features in the nozzle would affect bubble size. This indicated that there were no specific criteria used for the design of DAF air injection nozzles and there is a of information in terms of bubble generation from the use of experimental air injection nozzles.

The aim of this research is to develop and evaluate the performance of the saturator and air injection nozzles for the DAF process. The scope of this study will be limited to laboratory scale as well as indoor operating conditions. The parameters investigated for the performance of the two types of unpacked saturators; the plate distributor and spray nozzle was the air transfer efficiency (saturator efficiency) with respect to various operating conditions (influent flow rate, pressure and temperature). Air injection nozzle performance was evaluated by the parameter of air precipitation efficiency and mean bubble size (diameter) produced.

The results from the saturator test suggested that the use of spray nozzle for the distribution of liquid would greatly enhance the mass transfer between the liquid and gas as compared to the use of plate distributors. The production of fine droplets using the spray nozzle increases the available areas for mass transfers and therefore has a higher efficiency rate. Saturator pressure was also observed to investigate its effect towards saturator efficiency.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction to Dissolved Air Flotation

Dissolved air flotation (DAF) is a solid-liquid separation process used in many industries such as water and wastewater treatment, minerals processing and pulp and paper manufacturing. The principle behind this technique is the introduction or formation of an upward flow of air bubbles. These tiny bubbles will attach to suspended particles, thus giving them a lower density than that of the continuous phase and therefore allowing them to float. DAF is a proven solid-liquid separation technique for drinking water treatment in many European countries and it is an emerging technology receiving much interest due to its high efficiency of solids removal and ease of design (Bunker et al., 1995). Dissolved air flotation is the most commonly applied in flotation process in the field of water treatment. Pressurized water which at first had been supersaturated with air under higher pressure than atmospheric pressure will induce the formation of micro bubbles upon release into atmospheric pressure. These micro-bubbles have diameter ranging from 10 to 120 µm (or less than 100 µm) which is suitable for separating particulate solids and other polluting agents that may be found in water (Edzwald, 1995). This chapter will discuss the history of DAF in the field of potable water treatment as well as its usage in other processes, the advantages and disadvantages of DAF, the theory behind the process as well as the mechanisms involved and finally the methods involved in design and measurements.

2.1 History of DAF in Potable Water Treatment

DAF was first used in the 1960's in South Africa and Scandinavia for drinking water clarification and now it is widely used in Belgium, The Netherlands, France, Asia and Australia (Edzwald, 1995). In Sweden, it has gained widespread acceptance and in Finland 36 water supply plants have used the process within their treatment plant chain (Klute et al., 1995).

In Malaysia, The Metropolitan Utilities Corporation (MUC) holds the concession rights to supply water to Ipoh, Perak from the Sultan Idris Shah II water treatment plant. MUC is a joint venture of several companies including North West Water International of the United Kingdom. The pilot scale study of DAF was later extended to a partial conversion of the plant from sedimentation to DAF (Arnold et al., 1995).

Johnson et al. (1995) investigated several solid-liquid separation techniques in a pilot scale water treatment plant. The study compared effluent water quality, filter production and organics removal by applying DAF, contact adsorption clarification (CAC), inline filtration, and direct filtration for suspended solids removal. Conclusive findings showed that DAF surpassed other treatment processes in all of the categories compared except for CAC. CAC was difficult to scale-up as compared to DAF and furthermore this technology was also expensive and lacked flexibility. Schmidt et al. (1995) and Ferguson et al. (1995) confirmed the ease of design and flexibility of DAF process with good results in particle removal and increased filter runs as compared to direct filtration for potable water treatment.

Effects of various coagulation process configurations on the performance of DAF for water clarification in a pilot plant was studied by Klute et al. (1995). The authors performed the investigations at Wahnbach Reservoir, Germany, using Fe^{3+} as the coagulant in the reservoir water. The objective of the study was to investigate the influence of pH and energy input on floc formation. Results indicated that pH of 6.0 and high energy input improved flotation efficiency. It was also indicated that other factors such as reaction time and energy input after polyelectrolyte dosing will also influence overall separation efficiency.

Bunker et al. (1995) further investigated the effects of pretreatment of influent prior to DAF which was performed in the United States. The study indicated that there are other parameters that would influence the efficiency of the flotation process and overall separation efficiency.

O'Connell (1997) reported favorable results of a DAF pilot scale study in Chester Creek, USA in 1985. The removal of turbidity, color, biomass, suspended solids and potential in reducing trihalomethane was indicated to be significantly improved with the use of DAF. The reservoir also experienced seasonal algal blooms which caused disruptions to the conventional plant operations. It was indicated that DAF has been able to cope with the changes without much difficulties. Consistent performance of DAF has shown great potential of conversion from conventional treatment plant to DAF as variations in raw water quality did not have negative impacts on the DAF system compared with conventional sedimentation.

Franklin et al. (1997) presented similar findings with the study of full scale DAF plants in Yorkshire, UK, but indicated much difficulties in the commissioning of the first plant in Blackmoorfoot. The authors elaborated that the problems were due to the design engineers' non familiarity with new technologies such as DAF and lack of experienced technician in the pilot plant. Several treatment plants built later have less compliance failures as design engineers have gathered much practical experience from Blackmoorfoot. All of the treatment plants were able to tolerate extreme raw water conditions due to severe storms and drought conditions with no compliance failure.

2.2 History of DAF for Other Processes

2.2.1 Water Reclamation For Reuse

Offringa (1995) reported that DAF was used in South Africa in many industrial applications with the main emphasis on reclamation of sewage effluents. Only in the late seventies did DAF gain acceptance and popularity in potable water treatment for eutrophied waters. The study also reported the success of reclaiming sewage water for use as underground service water in the gold mining industry. A circular tank was built to handle hydraulic loading of 10 m/h with a recycle of 10%.

A pilot plant was built in 1986 to investigate the removal of phosphorus, soap and emulsified oil before discharge to the river. The hydraulic loading ranged from 7.5 to 10 m/h with air to solids ratio of 0.04:0.08 and alum dosages ranging from 80 to 200 mg/L. A recycle ratio of 5 to 10% was used. The phosphorus removal efficiency varied from 85 to 94% with feed concentrations of 3 to 5 mg/L. Detergents, oils and fats removal was found to be in the range of 30 to 88%. Phosphorus removal from secondary sewage effluent was also studied for possibilities to be used in the cooling system of a uranium enrichment plant (Offringa, 1995). The author reviewed a study in the removal of suspended solids and phosphorus at the Baviaanspoort sewage works in 1993 to meet stringent regulatory requirements for effluent discharge. The 36 million liters per day (MLD) plant treated secondary effluent with effluent quality of 1 mg/L for phosphorus and 5 mg/L for suspended solids. The recycle system consisted of an unpacked saturator that operated at 10% recycle with saturator pressures maintained at 350 to 450 kPa.

Offringa (1995) reported that a treatment plant in Sappi Enstra was designed and commissioned in 1970 to reclaim humus tank effluent from a pulp and paper mill.

The design was based on full stream recycle at 160 kPa using radial flow in a circular tank. It was also reported that the plant was successful in operation at loading rates of 5.2 to 6.7 m/h using alum and polymer dosing without harmful effect on the quality of the products when the reclaimed water was fully used in all sections of the plant.

2.2.1 Sludge Thickening

Offringa (1995) indicated that several activated sludge plants in South Africa have incorporated DAF for sludge thickening. Higher ratios of aerated recycle are required to operate a sludge thickening plant compared to a potable water clarification or water reclamation process. Ratio up to 2:1 is applicable for sludge thickening with hydraulic surface loadings of 2 to 4 m/h and air to solids ratio of 0.02:0.04. Saturator pressures are normally maintained from 400 to 500 kPa. The author also cautioned that solids loading should not exceed 6 kg/m^2 h without flocculants and 12 kg/m^2 h when using flocculants. DAF used in sludge thickening proved to be an effective process with solids capture exceeding 98% with a general feed between 1000 to 5000 mg/L solids. It was also found that it has an advantage in nutrient removal where phosphate is not released from the thickened sludge. Arora et al. (1995) had similar results in the USA as it was found that DAF is an excellent alternative for sludge thickening compared to gravity thickeners.

2.2.2 Industrial Effluent Treatment

The removal of suspended solids in paper mill effluents by DAF was also very successful (Offringa, 1995; Viitasaari et al., 1995; Jokela et al., 1997). DAF in chemical effluent treatment also gave good results as indicated by Odegaard (1995), Arnold et al. (1995), Rubio & Tessele (1997), Rubio et al. (2002) and Zouboulis & Matis (1995). Rubio et al. (2002) had reviewed the application of DAF technologies in the treatment of different types of wastewater from industries in Brazil with high potential results. The authors concluded that DAF may become one of the most promising technologies for wastewater treatment in the future.

Offringa (1995) reported that suspended solids of 200 to 300 mg/L were successfully reduced to 10 mg/L. The plant operated at peak flow rate of 7.5m/h using 85% recycle at 290 kPa. The flotation tank was rectangular in shape and equipped with surface scrapers. Sludge was floated off at a consistency of 2 to 4% solids, collected and thickened to 20% with a filter press. More recent studies made better progress in the understanding of DAF process used in pulp and paper mills. Under proper flocculation conditions, solids removal between 80 to 98% were successfully achieved from feed concentrations of 600 to 6000 mg/L. Air to solids ratios between 0.002 and 0.01 respectively were required for high and low solids content with recycle ratios of 0.1 to 0.25 and saturation pressure of 400 kPa. A comparative study was also conducted to evaluate the efficiency of induced air flotation (IAF) and DAF in the treatment of tannery effluents. It was found that DAF required a pre settling process for high solids loading to achieve acceptable air to solids ratio. IAF was also found to be more suitable for tannery effluent treatment as compared to DAF due to foaming problems associated with DAF. However IAF systems could not exhibit good clarification efficiency as compared to DAF (Offringa, 1995).

2.2.4 Eutrophic Water Treatment

Serious complications involving the operation of conventional treatment plants were realized when eutrophication of surface waters occurred (Offringa, 1995; Vlaski et al. 1997; Markham et al. 1997; Franklin et al. 1997; Fouche & Langenegger, 1997; Finlayson, 1997; Slatter et al. 1997). Offringa (1995) reported that raw water drawn from the Harbeespoort Dam for treatment in Schoemansville treatment works, South Africa, were constantly affected by algal bloom particularly *Microcystis* throughout the year. Chlorophyll ‘a’ averaged at 25 μg/L but exceeded 100 μg/L at times. It was also explained that frequent occurrences of taste and odor problems in the initial treatment plant that consisted of pre-chlorination and settling followed by slow sand filtration prompted the conversion of the settling tanks into flocculation units and DAF units. This modification resulted in the doubling of the capacity of the treatment plant. Powdered activated carbon (PAC) was added at concentrations of 8 to 10 mg/L when required and was later removed by DAF. With the success in Schoemansville, a small treatment plant was later constructed for a small community in Kosmos, South Africa. This plant has utilized DAF for the water clarification process with a maximum flow rate of 1.2 MLD and hydraulic loading of 6m/h. The recycle rate was fixed at 9% with saturator pressure of 400 kPa. Turbidity as low as 0.3 NTU was achieved prior to sand filtration (Offringa, 1995). Lake Nsese, South Africa, had similar problems of high turbidities and high concentrations of chlorophyll ‘a’ and color indicating organic pollution and eutrophic conditions. DAF was proved to be the most suitable treatment in pilot scale investigations. A full scale plant was later built and commissioned in 1984. The plant was subjected to unusual severe floods which resulted in turbidities exceeding 200 NTU. Studies of the plant concluded that it could only deal with raw water turbidities up to 80 NTU (Offringa, 1995). It was also suggested that high rate pre clarification was needed to safeguard for future occurrences of high floods. The flotation units were designed for hydraulic loadings up to 7.1 m/h using a saturator pressure of 560 kPa and a recycle rate of 10%.

2.3 Advantages and Disadvantages of Flotation

Flotation technique has distinctive advantages over conventional gravity settling for the removal of low density particles which have a tendency to float. Flotation techniques are classified based on the methods of producing bubbles. Flotation can be integrated with raw water and wastewater-treatment schemes in the following ways (Féris et al., 2000):

1. As a pre-treatment unit before primary sedimentation, a rougher-flash unit;
2. As a primary treatment unit before secondary treatment units, such as bio-oxidation lagoons in wastewater treatment;
3. As a unit process for the removal of contaminants not separated by other processes. Examples can be identified in the removal of metal ions from dilute solutions of the ions and in the selective separation of valuable ions;
4. As a unit process for sludge thickening.

Klute et al. (1995) reported that the parameters involved in ensuring the success of the flotation process were air to solids ratio, bubble-volume concentration, nozzle design, contact time and hydraulic load. The authors have demonstrated the importance of optimizing of coagulation process prior to DAF with an extensive investigation on pH effects, coagulant concentration, and mixing and flocculation intensity in a pilot plant. Bunker et al. (1995) indicated that the selection of coagulant should be based on water temperature and raw water characteristics such as particle concentrations and types and the concentration and nature of natural organic matter.

For many applications of flotation in the wastewater treatment field, it is more efficient to use micro-bubbles generated by nucleation of dissolved air, rather than the dispersed air method used for minerals as demonstrated by Zouboulis & Matis (1995). Flotation offers process advantages over sedimentation, including better treated water quality, rapid startup, high rate operation, and thicker sludge. DAF is considered not only an alternative to sedimentation plants, but also a clarification method to improve filtration (O'Connell et al., 1997)

In dissolved air flotation (DAF), water is saturated with air under pressure (higher than 3 atmospheres) and passes through a nozzle where bubbles are formed and released into the flotation chamber at atmospheric pressure. The water becomes supersaturated with air and air precipitates out from the solution in the form of tiny bubbles. In industrial scale, the supersaturated water is forced through needle-valves or special orifices, and clouds of micro-bubbles are produced just down-stream of the constriction (Gochin, 1990).

Because of the relatively small tank area and volume required in DAF installations compared with traditional settling plants, the capital cost is generally low. The total cost is largely determined by non-process factors, such as site conditions and costs of building works. The main disadvantage of DAF is the high-energy consumption compared to coagulation sedimentation-filtration plants. However, local circumstances could also play a major role in terms or energy costs. Treatment cost comparisons should also take into consideration of the effluent quality and also additional process advantages (Zabel, 1985; Féris et al., 2000).

2.4 Flotation Techniques.

2.4.1 Electro-flotation (EF)

The mechanism of micro bubble generation is by the electrolysis of diluted aqueous, conducting solution with the production of gas bubbles at both electrodes. This method is usually applied at industrial scale for the removal of light colloids such as emulsified oil from water, ions, pigments, ink and fibers from water (Rubio et al., 2002). Advantages reported are high clarity of treated effluents and disadvantages included low throughput, emission of hydrogen bubbles, high electrode and maintenance costs and massive sludge generation rate. Electrolytic coagulation/ flotation (ECF) system has been reported using reversible polarity aluminum electrodes where aluminum ions are released from anodes, inducing coagulation, and hydrogen bubbles generated from the cathode, enabling flotation of the flocs. It was also reported that laboratory scale tests using ECF reactors perform better than conventional aluminum sulfate coagulation when treating synthetic colored water. Results showed that 20% more dissolved organic carbon (DOC) was removed using electro-coagulation for the same aluminum doses (Rubio et al., 2002).

2.4.2 Dispersed (induced) Air Flotation (IAF)

An air injection system with the integration of a high-speed mechanical agitator will produce bubbles essential for the flotation process. This technology uses the suction of air (from lowered pressure) from centrifugal force developed from the rotation of the agitator. Gas is introduced at the top and the liquid become fully intermingled and, after passing through a disperser outside the impeller, form a massive amount of bubbles of size ranging from 700-1500 μm diameter. This method is well known in the mineral processing industry as well as in the petrochemical industry for oil-water separation (Gochin, 1990).

2.4.3 Dissolved Air (pressure) Flotation (DAF)

Micro-bubbles are formed as a result of pressure reduction of water pre-saturated with air at pressures higher than atmospheric. Féris et al. (2000) indicated that the minimum pressure for DAF to occur is 3 atm. Supersaturated water is forced through needle-valves or special orifices, and milky solution of micro-bubbles are produced just down-stream of the constriction.

DAF was first introduced in 1924 by Peterson and Sveen for the recovery of fibers and white water in the paper industry and later in 1960's, this technique was widely accepted for the treatment of potable water and wastewater. Since then DAF has been used in many applications including

- Clarification of refinery wastewater, wastewater reclamation,
- Separation of solids and other undesirable substances in drinking water treatment plants.
- Sludge thickening and separation of biological flocs,
- Removal/separation of ions,
- Treatment of ultra-fine materials
- Removal of organic solids, dissolved oils and VOCs (dissolved toxic organic chemicals)
- Removal of algae, 5-7 µm *Giardia oocysts,* 4-5 µm *cryptosporidium oocysts*, humic water treatment, algae from heavily algae laden waters (Féris et al., 2000).

2.5 Removal Mechanisms by Flotation

The removal of ions from water which is one of the most vital issues relating to environmental problems today is theoretically possible through different flotation techniques. The principal techniques are precipitate flotation, gas aphrons flotation, foam flotation, adsorbing particulate flotation and ionic flotation (Rubio et al., 2002).

2.6 Principles of Bubble Formation and Size Distribution

Bubble formation can be separated into two main categories; that is the reduction of free energy of the system resulting in the appearances of the bubbles thus considered spontaneous in the thermodynamic sense; and the increment of free energy into the system resulting in bubble formation (Lubetkin, 1994).

Microscopic air bubbles in DAF are produced by injection of pressurized supersaturated water into a flotation tank using specially designed air nozzles or needle valves. The phenomenon of desorption of dissolved gas with the formation of bubbles is often called cavitation in the broad sense of the term, i.e. the formation of “gaseous cavities” in a continuous liquid medium. It can also be called nucleation of bubbles. By analogy with the mechanism of precipitation of solid substances, the expression dissolved gas precipitation is also used to describe the phenomenon of transformation of air in supersaturation from liquid phase to gaseous phase (Klassen & Mokroussov, 1963). Two kinds of bubble nucleation can be distinguished depending on whether the gas precipitation takes place in a homogeneous phase (in the liquid phase) or the heterogeneous phase (on solid surfaces). These can also be referred as homogeneous precipitation and heterogeneous precipitation (Klassen & Mokroussov, 1963).

2.6.1 Mechanism of Homogeneous Precipitation

In homogeneous precipitation or nucleation, bubbles are formed in a medium free from foreign bodies or surface. The thermodynamic drive for the phase change is the excess of chemical potential of the liquid phase as compared with that of the vapor

(Lubetkin, 1994). This thermodynamic drive may arise from the alteration of temperature or alteration of pressure.

Most workers in one way or the other think unmistakably that the formation of bubbles at the time of release is linked to a mechanism of homogeneous precipitation of dissolved gas in supersaturation in the liquid phase for DAF. Takahashi et al. (1979) were among one of the earliest to conduct a fundamental study on bubble formation in dissolved DAF. The bubbles observed, rapidly generated after the pressurized water had gone through the nozzle, might be formed by the diffusion and the grouping of dissolved gas molecules within the continuous liquid phase. Laplace's equation determines the equilibrium conditions of such bubbles:

$$\Delta P = \frac{1 \cdot \gamma_{L/G}}{r} \qquad (1)$$

where ΔP is the difference of pressure on either side of the liquid/ gas interface (atm); $\gamma_{L/G}$ is the liquid/ gas interfacial tension ($mN \cdot m^{-1}$) and r is the radius of the bubble (m).

The existence of a stable bubble with an infinitesimal radius is linked to an infinitely high difference in pressure on either side of the liquid-gas interface. Therefore the formation of a bubble by homogeneous precipitation requires a pressure decrease which also must be infinite (Dupre et al., 1998a). In practice, when gas-saturated water is progressively released, a minimum but finite difference in pressure is necessary to generate bubble nucleation.

Large pressure difference across the air injection nozzle produces bubble nuclei spontaneously according to the thermodynamic principle of minimizing the free energy change (Edzwald, 1995). Assuming air as an ideal gas, the critical diameter of the bubble nucleus (d_{cb}) for a homogeneous nucleation is given by the equation below.

$$d_{cb} = 4\sigma/\Delta P \quad (2)$$

where σ is the surface tension and ΔP is the pressure change across the nozzle. Figure 2.1 shows the critical diameter of the bubble nucleus as a function of the pressure change.

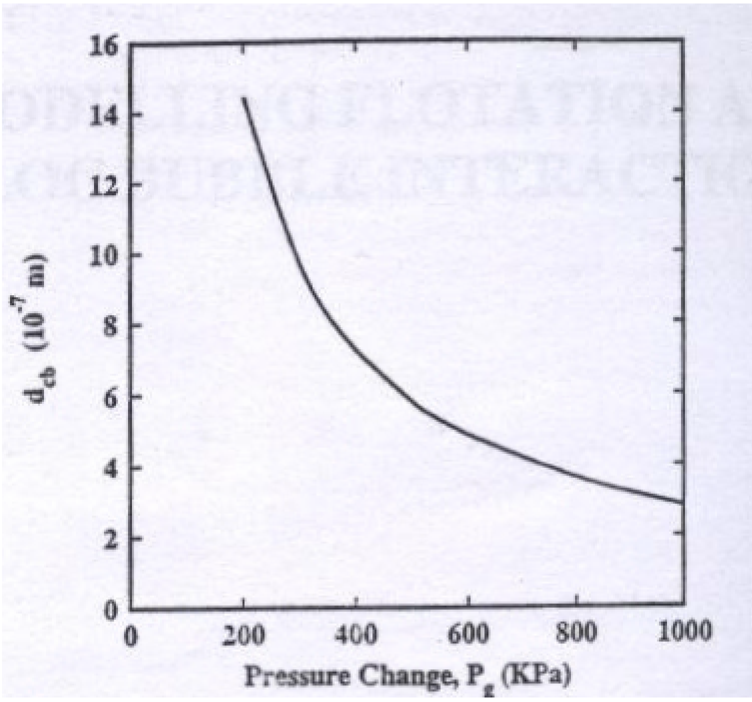

Figure 2.1: Diameter of bubble nucleus as a function of the pressure change. (Source: Edzwald, 1995)

On this basis, Rykaart & Haarhoff (1995) suggested that at the time of release, bubbles form in the nozzle by the precipitation of dissolved gas in the pre-existing nucleation centers. However, in a pure environment, concentrations of dissolved gases in water are always too low to enable spontaneous bubble formation. Indeed, the nuclei formed re-dissolve before they become big enough to be stable. Thus, in the study carried out by Kitchener & Gochin (1981) on the mechanisms involved in a nozzle, the latter was simulated by a glass tube with a restriction (Reynolds tube) fed with distilled water free of insoluble impurities. The formation of a cloud of micro-bubbles can be observed at the exit of the tube when the initial water pressure was sufficient for a phenomenon of ultrasonic cavitations to occur. They were of the opinion that ultra-sounds may permit the creation of vapor cavities in which dissolved gas would precipitate. Nevertheless, the supersaturation pressure used in flotation (400 to 600 kPa) is not sufficient to create a phenomenon of ultrasonic cavitations with ordinary nozzles (Dupre et al. , 1998a). Such cavitations are not normally observed at the time of the nucleation of micro-bubbles formed by the release of "ordinary" pressurized water. In fact, the pressurized water used in DAF for water treatment are not of similar quality as pure water. It contains all kinds of soluble compounds and particles in suspension. These soluble compounds considerably reduce the minimum pressure drop necessary for homogeneous nucleation.

2.6.2 Mechanism of Heterogeneous Precipitation

This mechanism of precipitation accounts for most if not all of the bubbles formed in DAF. The fact that water used in DAF contains soluble impurities in the raw influent would allow the stabilization of gaseous micro-cavities. The duration of these micro-cavities would then be sufficient to generate the formation of stable bubble nuclei. Edzwald (1995) indicated that in a heterogeneous system, minimization of free energy change is made easier by bubble formation occurring on particle nuclei or on other surfaces containing scratches or crevices. The author also indicated that smaller nuclei are formed at higher pressure changes. The degree in which bubbles are easier to precipitate or nucleate depends solely on two parameters; the contact angle of the gas/ solution/ solid surface and the geometry of the nucleation site (Lubetkin, 1994).

2.6.2.1 Gas Precipitation at the Surface of a Solid: Pure Heterogeneous Precipitation

The solid compounds contained in water to be treated using DAF can favor heterogeneous precipitation at the liquid-solid interface. The gas molecules in solution diffuse to a solid surface, going through the external layer of its hydration film (Klassen & Mokroussov, 1963). The higher the surface hydration (hydrophilic), the more difficult it is for the gas molecules to go closer to the solid surface as more time will be required. That is why air bubble precipitation on a solid surface is all the more difficult when the surface is hydrophilic. However, in the case of hydrophobic particles, it is easier for the gas molecules to move the water molecules at the solid surface than to separate water molecules from one another. Thus, air bubbles will then form at the liquid-solid interface (heterogeneous precipitation) much more easily than in the liquid phase (homogeneous precipitation).

2.6.2.2 Gas Precipitation in Pre-existing Micro-bubbles (or bubble nuclei) at the Solid Surface: Homogeneous–like Precipitation

Air can be mechanically trapped in small or tortuous capillary spaces of the solid surfaces. These gaseous nuclei are privileged sites for dissolved gas precipitation in supersaturation. When the release occurs, these microscopic nuclei can become bigger and form micro-bubbles. This kind of heterogeneous precipitation is more likely to occur than pure heterogeneous precipitation (Carr et al., 1995).

However Dupre et al. (1998b) observed that bubbles formed only after the release zone contrary to Kitchener & Gochin (1981) and therefore no ultrasonic cavitation was ever detected in their experiments. The authors redefined the mechanism of bubble formation involved in the release zone as ‘a mass precipitation of dissolved gas in supersaturation’. In their experiment, gas pockets formed at the end of the release zone in low turbulence Reynolds's tubes and the appearance of bubbles is a result of the bursting of these gas pockets. In stronger hydrodynamics turbulence induced conditions, the bubbles formed within the turbulent zones. Therefore their opinion states that the formation of big undesirable bubbles in DAF was caused by the mechanism intervening in the release zone. It was also indicated in their study that the geometry of the nozzle (conical divergence angle in the release zone) has a great influence towards the bursting mechanism of the gas pockets and on the formation of small bubbles with a restricted size distribution desirable for DAF. The authors also observed that the surface energy of the release zone has an influence towards the mechanism of bubble formation. Dupre et al. (1998b) claimed that if the nozzle has hydrophobic surface, it will result in the formation of bubbles by heterogeneous phase.

2.7 Bubble Size and Influence of Various Parameters

Takahashi et al. (1979), De Rijk et al. (1994) and Dupre et al. (1998a) studied bubble sizes in DAF systems with results indicating that the range of bubble size is from 10 to 120 µm with a reasonable average estimate of 40 µm at steady state. Takahashi and co workers observed that the steady state size of the bubbles depends heavily on the saturator pressure and injection flow rate. Higher flow rates produce smaller bubbles and it becomes constant at the maximum flow rate with respect to nozzle design. Dupre et al. (1998a) indicated that nozzle geometry has a strong influence towards bubble size distributions. The bubbles were larger when the nozzle constriction was long (gradual pressure release). The authors explained that the injection flow must provide a quick pressure drop and sufficient to prevent backflow and bubble growth on pipe surfaces in the vicinity of the injection system. It was also observed that higher pressures produce smaller bubbles, but at pressures above 500 kPa, the increase of saturator pressure will not have a significant effect on bubble size (De Rijk et al., 1994).

Dupre et al. (1998b) reported that another study was carried out by Wang & Ouyang (1994) with longer nozzles than those of Takahashi and co workers. It was reported that the bubbles formed were bigger when the nozzle is longer. Thus the latter suggested that bubble size distribution is connected to the degree of turbulence caused by the passage of the liquid flow through the nozzle. They were of the opinion that with the higher degree of turbulence, the faster the mass transfer from liquid to the gas phase and this would result in smaller and higher number of bubbles. Dupre et al. (1998b) attempted to study bubble formation in constrictions with respect to several identified parameters. In the first series of test, it was found that conic divergence in hydrophilic Reynolds tubes used in the experiment has a great effect on bubble size. Results indicated that when divergence angle was increased, the fraction of bigger bubbles (500 µm) would decrease. The authors concluded that this phenomenon was attributed to the increased turbulence that encouraged bigger bubbles to burst into smaller ones. The author also reported that the same trend occurred for hydrophobic tubes but indicated that the influence of the conic divergence angle was less clear. The second series of the test involved the use of chemicals such as polyelectrolytes. Dupre and co workers indicated that the use of polyelectrolytes generally produces bubbles with smaller diameters, but when the chemical substance of the polyelectrolytes were taken into account, the influence was much more complex. Surfactants would lower the water/air interfacial tension, encouraging the bubbles to burst. The addition of small amount of ethanol has shown to produce more micro bubbles. In contrast, the electrolytes would reduce the electrostatic repulsion forces and thus has encouraged bubble coalescence. The authors in their opinion indicated that the choice of material used in the fabrication of nozzles should not be based on mechanical resistance and cost alone as it would have influence in the production of micro bubbles. It was also in their opinion that the key parameter in the design of DAF nozzles are in the nozzle geometry. Nozzle designs should also have a wide spectrum of application from the size distribution of bubbles produced (Dupre et al., 1998b). Additional bubble growth may occur as the bubbles rise in the flotation tank as a result of decrease in hydrostatic pressure or by coalescence. Both of these have negligible effects on the small bubbles formed in the DAF systems (Takahashi et al., 1979). Small bubbles found in DAF systems rise as rigid spheres under laminar flow conditions and obey Stokes law. Larger bubbles have higher rise velocities and exist as ellipsoids or spherical caps (Edzwald, 1995).

2.8 Bubble Particle Interactions

Kitchener and Gochin (1981) gave three possibilities of attachment mechanisms for bubbles and particles aggregates formation. They are as follows:

1) Entrapment of preformed bubbles in large floc structures (floc size exceeds bubble size).
2) Growth of bubble nuclei formation on particles or within flocs and
3) Particle collision and adhesion with preformed bubbles.

The first mechanism is more important where larger particles or flocs (100's of µm) either already exist or are formed rapidly by high rates of flocculation involving concentrated suspensions. The second mechanism probably occurs to varying degrees in most applications; however, it is the third mechanism that is most important and applicable. This is true given the time scale of less than 1 second (Rykaart & Haarhoff, 1995) for the formation of the bubbles from supersaturated recycle water injected into the flotation tank with pressure changes of 4 to 6 atm and given its many applications in treating dilute suspensions. This is not to assume that all the supersaturated air comes out of the solution instantaneously. It is noted that some air does leave the solution slowly and heterogeneous nucleation will be a factor in bubble formation, especially in applications using clarified water as the recycle water (Edzwald, 1995).

2.9 Bubble-particle Attachment Process

For attachment to occur, the liquid film between the particle and the gas bubble that have collided must thin and rupture, followed by expansion of the three phase contact to form a wetting perimeter.

Dai et al. (1999) indicated that the attachment of a hydrophobic particle to a gas bubble is one of the sub-steps of bubble-particle interaction in flotation. After colliding with the suspended particles, the rising bubbles will attach to the surface of the particles and form stable bubble-particle aggregates or agglomerates. These aggregates or agglomerates will then rise to the surface of the flotation cell. This particle-bubble interaction can be best described by three independent sub-steps: collision, attachment and stability. The effectiveness of the whole bubble-particle capture is represented by the product of the probability or efficiency of each sub-step given by the following relationship;

$$E_{cap} = E_c \, E_a \, E_s \qquad (3)$$

where E_{cap}, E_c, E_a and E_s are the capture, collision, attachment and stability efficiencies, respectively. The capture, collision and attachment efficiencies are defined as the fraction of particles captured by a bubble, the fraction of particles colliding with a bubble, and the fraction of colliding particles which actually attach to the bubble surface, respectively.

Attachment efficiencies have generally been obtained indirectly from experimental capture efficiency data coupled with theoretical particle-bubble collision and stability models (Yoon & Mao, 1996). Compared with collision models, the number of attachment models is limited. Furthermore, these attachment models depend on quantities that are not easily measured (Yoon & Mao, 1996). One of these quantities is the induction time which is defined as the time for the liquid film between the particle and the bubble to thin and rupture and for the three-phase line of contact to expand until an equilibrium value is obtained. Only recently attempts have been made to measure directly the induction time or calculate the contact time and link this to the induction time (Stechemesser & Nguyen, 1999).

Bubble-particle attachment occurs when the bubble-particle contact time is longer than the induction time. The contact time is related to the bubble-particle collision. If a particle impacts on the bubble surface with enough kinetic energy so as to cause considerable deformation of the bubble surface, the colliding particle then rebounds from the deformed surface due to the elastic energy of the deformed part of the surface. For particles smaller than 100 μm particle rebound on an immobilized bubble surface has been neglected because their kinetic energy is too small to distort the bubble surface. After impact, these particles slide along the bubble surface. Although the contact time is defined as the sum of the impact time and the sliding time, the contact time for small size or low density particles mainly refers to the sliding time as the impact time is much smaller than the sliding time (Rubenstein, 1995). Therefore, researchers have concentrated on sliding time models (Wang et al., 2002) and most attachment efficiency models are based on the relative magnitude of the induction time and the sliding time (Wang et al., 2002). It has been realized for some time that surface forces between particle and gas bubble played a very important role in bubble-particle attachments.

2.10 Theory of Flotation

Flotation may be defined as the transfer of a solid from the body of a liquid to the surface by way of bubble attachment (Rubenstein, 1995). Gochin (1990) describes ‘flotation’ as a generalization for a number of processes known collectively as