

**PARTICLE SIZE DISTRIBUTION IN DISSOLVED AIR
FLOTATION PROCESS FOR DRINKING WATER TREATMENT**

By

Jianguo Zhang

A Thesis

Submitted to the Faculty of Graduate Studies

In Partial Fulfilment of the Requirements for the Degree of

MASTER OF SCIENCE

Department of Geological and Civil Engineering

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Of

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Jianguo Zhang © 2004

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Abstract

Algae bloom is the main cause of taste, odor and increased levels of disinfection by-products (DBP) in Winnipeg tap water. Dissolved air flotation (DAF) is effective in removing algae. In this study, a bench-scale continuous DAF unit combined with coagulation and flocculation units was constructed and operated with tap water in Winnipeg at the University of Manitoba. The hydraulic loading rate was 2.2 m/hr, recycling ratio was 8% and saturator pressure was 90 psig (620 kPa). Three different dosages of alum were applied: 41.7 mg/L, 25.5 mg/L and 15.5 mg/L. The coagulation time was 2 minutes and flocculation time was 16 minutes for all three dosages. Besides the regular measurements of turbidity, color, pH commonly conducted in water treatment, the variation of particle size distribution (PSD) in the process was investigated using a microscope and computerized image analysis system.

Test results indicated that when the alum dosage was at 25.5 mg/L, DAF effluent reached turbidity of 0.25 NTU and color of 3.8 TCU, significantly lower than that for raw water. Further addition of coagulant didn't show any benefit for the effluent quality. The mean equivalent diameter of the alum coagulation flocs at this dosage was 36.62 μm , with maximum of 175.98 μm and the minimum of 5.64 μm . About 30.5 % of the particles were smaller than 20 μm , which couldn't be fully removed in the DAF unit and resulted in the effluent turbidity and color.

Compared to the pilot-scale DAF study by the City of Winnipeg, the bench scale unit was operated at lower velocity gradient (240 s^{-1} for coagulation and 40 s^{-1} for flocculation). Such conditions allowed for formation of many pin-flocs (20–30 microns)

good for DAF process while coagulant dosage and mixing energy were lower, which would offer economical savings in the operation of the future water treatment plant in the city of Winnipeg.

It was found that the floated flocs were more compact with increased size compared to those before DAF tank. This was probably further collision and agglomeration occurred during the flotation due to the flocs' size difference.

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Classic analysis system at the start of the experiment;

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Table of Contents

Abstract.....	ii
Acknowledgements.....	iv
Table of contents.....	v
List of figures.....	vii
List of tables.....	ix
List of appendix.....	x
List of abbreviations.....	xi
1.0 Introduction.....	1
2.0 The objective of the thesis.....	8
3.0 Review of the relevant theory and current literatures.....	9
3.1 Dissolved air flotation.....	9
3.1.1 Application of DAF in water and wastewater treatment.....	9
3.1.2 Process mechanism of DAF.....	11
3.1.3 Important parameters for DAF process.....	14
3.2 Particle size distribution (PSD) in water treatment.....	19
3.2.1 Application of PSD in water treatment.....	19
3.2.2 Particle size distribution (PSD) analysis.....	22
3.2.2.1 Particle counter.....	22
3.2.2.2 Microscopic analysis of PSD.....	24
3.3 Coagulation and flocculation.....	24
3.3.1 Background.....	24
3.3.2 Destabilization and coagulation of the algae particles.....	27

4.0 Materials, equipment and methods.....	30
4.1 Bench-scale dissolved air flotation appliance.....	30
4.2 Particle analysis.....	35
4.2.1 Raw water analysis	35
4.2.2 Floc analysis.....	37
4.2.3 Data processing.....	37
5.0 Results and discussions.....	39
5.1 The preliminary study: analysis of Oxford Lake raw water.....	39
5.2 Particle size distribution in the tap water in Winnipeg.....	46
5.3 The effect of coagulation on particle size distribution in the water before and after DAF process.....	49
5.4 Discussions.....	65
6.0 Summary and conclusions.....	68
7.0 Recommendations for future work.....	70
8.0 References.....	71
Appendix	75

List of Figures

Figure-1 Recommended water treatment process design in Winnipeg.....	6
Figure-2 Schematic diagram of a typical DAF process.....	12
Figure-3 Critical diameter of bubbles nucleus for homogeneous nucleation of air in water at 20 °C as a function of the pressure change.....	18
Figure-4 Electrical double layer of a negatively-charged colloid particle.....	25
Figure-5 Schematic of the experimental DAF appliance.....	30
Figure-6 Microscopic image of the particles in the raw water from Oxford Lake.....	40
Figure-7 Particle size distribution in the raw water from Oxford Lake when measured with Image Pro Plus.....	42
Figure-8 Particle size distribution for the raw water from Oxford Lake when measured with Bioquan95 Classic.....	44
Figure-9 Microscopic images of the particles in the tap water in Winnipeg.....	47
Figure-10 Particle size distribution in the tap water in Winnipeg.....	48
Figure-11 Microscopic image of the alum coagulation flocs in the water (alum dosage at 41.7 mg/L).....	51
Figure-12 Alum coagulation flocs' size distribution when alum dosage was at 41.7 mg/L.....	53
Figure-13 Floated flocs' size distribution when alum dosage was at 41.7 mg/L.....	55
Figure-14 Alum coagulation flocs' size distribution when alum dosage was at 25.5 mg/L.....	57
Figure-15 Floated flocs' size distribution when alum dosage was at 25.5 mg/L.....	59

Figure-16 Alum coagulation flocs' size distribution
when alum dosage was at 15.5 mg/L.....62

Figure-17 Floated flocs' size distribution when alum dosage was at 15.5 mg/L.....64

List of Tables

Table-1 Historical raw water quality in Shoal Lake and Deacon Reservoir.....	2
Table-2 Water treatment targets in Winnipeg.....	4
Table-3 Floc particle aggregates' rise velocities for 40 µm bubbles.....	17
Table-4 Operating conditions for the experimental system.....	34
Table-5 General quality of the raw water from the Oxford Lake.....	36
Table-6 Particle size distribution for the raw water from Oxford Lake when measured with Image Pro-Plus.....	43
Table-7 Particle size distribution for the raw water from Oxford Lake when measured with Bioquan95 Classic.....	45
Table-8 Tap water quality in Winnipeg.....	46
Table-9 Particle size distribution for the tap water in Winnipeg.....	49
Table-10 DAF effluent quality when alum dosage at 41.7 mg/L.....	52
Table-11 Alum coagulation flocs' and floated flocs' size distributions when alum dosage was at 41.7 mg/L.....	52
Table-12 Alum coagulation flocs' and floated flocs' size distributions when alum dosage was at 25.5 mg/L.....	58
Table-13 DAF effluent quality when alum dosage was at 25.5 mg/L.....	60
Table-14 Alum coagulation flocs' and floated flocs' size distributions when alum dosage was at 15.5 mg/L.....	64
Table-15 DAF effluent quality when alum dosage at 15.5 mg/L.....	65
Table-19 Comparison of DAF effluent quality under different coagulant dosages.....	66

List of Appendix

Appendix-1 Significance of the difference in particle size for the raw water from Oxford Lake as measured by Bioquant95 Classic and by image Pro Plus system	75
Appendix-2 Significance of the difference in average particle size between the city water in Winnipeg and the raw water from Oxford Lake.....	77
Appendix-3 Significance of the difference in average size between alum coagulation flocs and floated flocs.....	78
Appendix-4 Specification of the heavy duty diaphragm-type injector metering pump...	80
Appendix-5 DAF unit Appliance Photographs.....	81

List of Abbreviations

BACF: Biological Activated Carbon Filtration

DAF: Dissolved Air Flotation

DBP: Disinfection By-products

DOC: Dissolved Organic Carbon

EOM: Extra-cellular organic matter

EPA: Environmental Protection Agency

GACF: Granular activated carbon filter

GCDWQ: Guideline for Canadian Drinking Water Quality

HAA: Haloacetic acid

HLR: Hydraulic loading rate

MGD: million gallons per day

T&O: Taste and odour

THM: Trihalomethane

PSD: Particle size distribution

WTP: Water treatment plant

1. Introduction

The city of Winnipeg's drinking water originates in Shoal Lake, which is located approximately 160 km east of Winnipeg. The water is continuously chlorinated at the Shoal Lake headwork before flowing through a closed aqueduct to the four-cell open-air Deacon Reservoir located in the rural municipality of Springfield, east of Winnipeg. Continuous chlorination at the aqueduct headwork serves four purposes:

- Pathogen control for public health protection
- Control of slime forming on the aqueduct walls, which decreases flow capacity
- Deterrent to the potential of zebra mussels entering the aqueduct, colonizing on the walls, and decreasing flow capacity
- Improvements to taste and odour by oxidizing taste and odour-causing compounds in Shoal Lake water

At Deacon Reservoir the water is re-chlorinated. The water then flows by gravity (plus supplemental pumping when required) to the City's three distribution system reservoirs—McPhillips, MacLean, and Wilkes where chlorine is added for disinfection and taste and odour control before being pumped to the distribution system

The quality of Shoal Lake water as well as the water at Deacon Reservoir meets most of the Canadian Drinking Water Quality Guidelines and has been accepted by the public. Table-1 (Winnipeg Water Consortium, 2002) listed the summarized historical raw water quality information:

Table-1 Historical raw water quality in Shoal Lake and Deacon Reservoir
(1997~2001)

Parameter	Units	Average	Minimum	Maximum	Guideline or Regulations
Shoal Lake Intake					
Turbidity	NTU	1.0	0.35	2.5	≤1.0
pH	units	8.0	7.0	9.0	6.5~8.5
TOC	mg/L	8.9	4	11	No guideline
DOC	mg/L	8.9	3.5	12	No guideline
Alkalinity(total)	mg/L (as CaCO ₃)	79	71	89	No guideline
Hardness(total)	mg/L (as CaCO ₃)	79	66	90	No guideline
Color(true)	TCU	7	<5	15	≤15
Deacon Reservoir Inlet					
Turbidity	NTU	0.80	0.25	1.9	≤1.0
Plankton	Cells/mL	14400	700	114300	No guideline
TTHM	μg/L	113	26	192	≤100
Outlet from Deacon Reservoir Cells 1 & 3					
Turbidity	NTU	0.76	0.25	4.0	≤1.0
Plankton	Cells/mL	19900	790	28500	No guideline
TTHM	μg/L	56	1.5	129	≤100

Water and wastewater department of Winnipeg, 2002 Drinking water quality test results

It was indicated in Table-1 that the water in Deacon Reservoir (also in Shoal Lake headwork) was characterised by moderate to high algae levels, low turbidity and moderate to high total organic carbon (TOC). As a result of chlorination at the Shoal Lake headworks, Deacon Reservoir water contained significant high background levels of disinfection by-products (DBPs). Taste and odour (T&O) events in the distribution system normally coincided with or followed the elevated algae levels in Deacon Reservoir and /or Shoal Lake (Winnipeg Water Consortium, 2001).

T&O is an aesthetic water-quality parameter subject to public perception. As the public's expectations for water quality increase, T&O will be subject to increased scrutiny.

Disinfection by-products (DBPs), especially trihalomethanes (THMs) and haloacetic acid (HAAs) may pose a chronic health risk to consumers and will probably fail to meet future water quality guidelines (Winnipeg Water Consortium, 1998).

Another concern regarding the elevated algae levels is the toxic nature of some of the by-products of algae metabolism (especially blue-green algae). Algae toxins have been detected in surface waters worldwide and although at essentially non-detectable levels in Winnipeg's drinking water, need to be considered in water treatment plant design.

Recently, as water quality guidelines and regulations are becoming more stringent and public water expectations are increasing, the City recognized the need for increased treatment of Shoal Lake water (Winnipeg Water Consortium, 2001).

The city's water treatability issues together with existing and anticipated water quality guidelines and regulations were used to develop water quality targets for water treatment process evaluation. These targets were summarized in Table-2.

Table-2 Water treatment targets in Winnipeg

(Winnipeg Water Consortium, 2001)

Treatment Goal	Specific Parameter	GCDWQ	Pilot Target	Reasons for Pilot Target
Clear water	Turbidity	<1.0 NTU	<0.1 NTU	Future portable regulation: ensures best treatment
Particulate removal	Particles > 2 μ m	NG	<20 particles/mL	Pathogen protection i.e. Giardian /Cryptosporidium
DBP control	TTHMs THAAs	100 μ g/L NG	100 (40) μ g/L N/A (30) μ g/L	Short-term (long-term USEPA regulation)
TOC removal	TOC	NG	40 %	Minimize DBP precursors
T&O control	TON	Aesthetic	Inoffensive /consistent	Level at which T&O should meet public expectations
Algae removal	% removed	NG	Maximize removal	Minimize T&O events and other aesthetic concerns
Color reduction	TCU	15	<5	Value which should meet public expectations
Efficient filter water production rate	UFRV (unit filter run volume)	NG	>200 M ³ / M ²	Balance of filter construction costs, production rate, and wasted backwash water
Filter loading rate	m/hr	NG	>15 m/hr	Minimize filter construction costs
Treatment consistency	Opinion	NG	High degree	Ability to consistently meet treatment goals during changes in raw water quality

NG: no guideline

GCDWQ: Guideline for Canadian Drinking Water Quality

A review of long list of potential water treatment processes by a consultant team to achieve the goals resulted in a short list of two treatment processes to be examined in detail. A pilot-scale water treatment plant (WTP) was designed to test each of the two treatment types to define a state-of-the-art and cost-effective water treatment process for the City of Winnipeg: DAF treatment process and direct filtration process. The pilot plant was fabricated and installed at Deacon Booster Pump Station by the City of Winnipeg. It was commissioned in June 1996 and was operated continuously over 16 months through four different Shoal Lake water quality seasons which provided strong confidence in the recommendations regarding the best water treatment process, currently available, to meet the goals established for the City (Winnipeg Water Consortium, 1998). The DAF treatment process was found to be superior to direct filtration in all the experimental categories investigated. Also, since the DAF process reduced ozone demand and enhanced the filtration process, the pilot program verified that a full-scale DAF water treatment plant was cost-competitive with a direct filtration plant. The DAF process required a smaller ozone facility and filters with less than half the footprint required by a direct filtration plant (Wobma, et. al, 1995)

In the DAF treatment process, raw water was pumped from Deacon Reservoir outlet, prior to chlorination, to the pilot plant. The water was initially treated with coagulants alum, ferric chloride, and polymer aluminum chloride (PACl) in a rapid mix tank and then delivered to a three-stage flocculation tank. The flocculated water entered the DAF tank, and the DAF float layer was continually skimmed off the surface by a mechanical skimming system. The DAF-treated water was pumped to an ozone contactor that flowed into an ozonated water holding tank. The water was then pumped to the filters. The

filtration system composed of four deep-bed filters operating in a rising-head, constant-rate mode. Filter aid chemicals could be added ahead of filters.

Based on the forgoing water treatment goals and the results of the pilot program conducted, a five-step water treatment process was developed and recommended: (1) Alum coagulation and flocculation; (2) Dissolved Air Flotation (DAF) for suspended solids, algae, and organics removal; (3) Ozonation for primary disinfection (including *Cryptosporidium* disinfection) and taste and odor control; (4) Biological Activated Carbon (BAC) Filters as a second (physical) barrier for pathogen removal and organics removal, and (5) Chloramination for disinfection throughout the distribution system (Winnipeg Water Consortium, 2002).

The schematic of the process was shown in Figure-1.

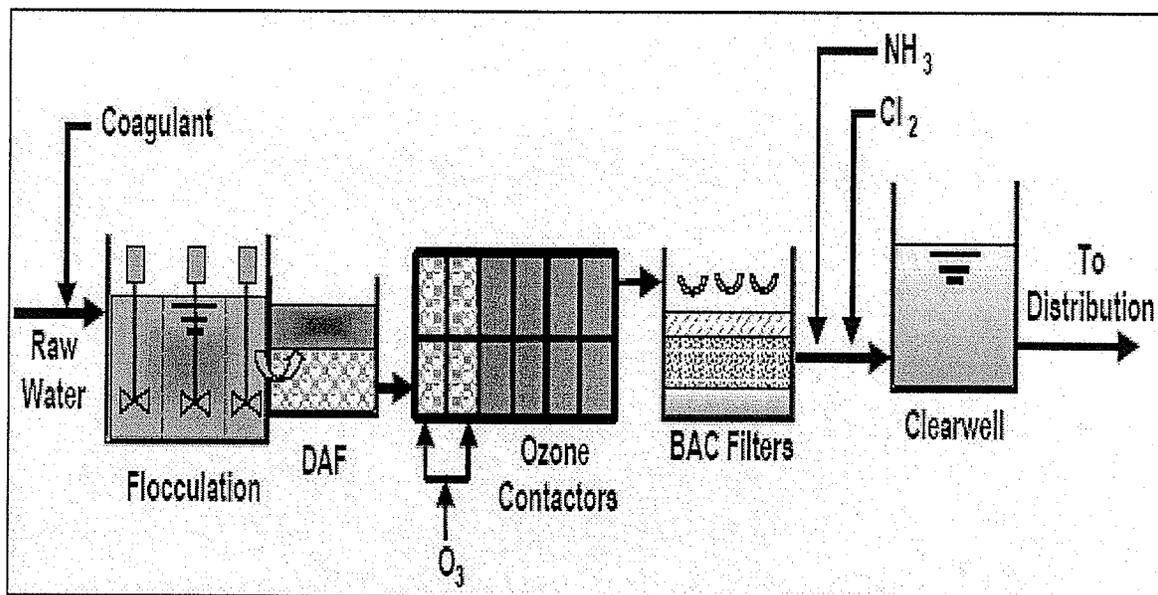


Figure-1 Recommended water treatment process design in Winnipeg
(Winnipeg Water Consortium, 2002)

The recommended four-step treatment process was necessary to meet all the water quality goals established for the City, and it had the additional benefits of providing multiple treatment barriers to maximize the delivery of the key water treatment goals of pathogen removal, DBP control and taste and odor control (Winnipeg Water Consortium, 2002).

2. The Objectives of the Study

Dissolved air flotation (DAF) is an effective solid / liquid separation process, and provides excellent algae removal capacity (Kaminski, et. al, 1991).

In the recommended water treatment process in the City of Winnipeg, DAF was chosen as one of the major components of the facility.

Much has been published to describe the application of DAF process for water or wastewater treatment as well as in other fields. However, there are still many uncertainties regarding the mechanism of particle removal in the DAF process. For example, different views have been expressed on the optimum size of the particles to be removed by the DAF process. The size of these particles can be controlled in the coagulation process. Hence the uncertainties are actually about coagulation and flocculation conditions which are optimal for DAF.

The objectives of this study were as follows:

- (1) To investigate the variation of particle size distribution (PSD) in a bench-scale dissolved air flotation process with the city water in Winnipeg;
- (2) To investigate the effect of coagulant (alum) dosage on the changes of PSD, for the changes in PSD have direct effect on the treatment efficiency of dissolved air flotation;

3. Review of the Relevant Theory and Current Literatures

3.1 Dissolved air flotation

3.1.1 Application of DAF in water and wastewater treatment

As early as at the start of the 20th century, dissolved air flotation (DAF) was applied as a method of separating solids in mining industry. A US patent was issued in 1905 for a process using pressurized aeration followed by pressure release (Sulman et al., 1905). Kitchener (1984) referred to a 1907 attribution of H. Norris in which small air bubbles were formed “by supersaturating water with air at several atmospheric pressures and injecting it through a nozzle into a tank.” The use of dissolved air flotation (DAF) as a solids/ liquid separation process in water and wastewater treatment was an alternative to sedimentation for 70 years. Initially this process was applied for removal of materials which had a specific gravity less than water, such as fats, oil, fiber, and grease (Longhurst, et. al, 1987). Today DAF is extensively utilized for a wide variety of water and wastewater treatment applications.

DAF applications were expanded in the late 1960s to potable water treatment in South Africa and Scandinavia (Longhurst and Graham, 1987; Wortel, 1991; Haarhoff and van Vuuren, 1993). DAF is now widely used and has been accepted in these countries as well as in other European countries such as Belgium, the Netherlands, and the United Kingdom. It is also used in Australia and Asia (Edzwald, 1995).

In North America, DAF is regarded as an emerging technology that will become more important because of existing and proposed regulations that require filtration of surface

waters and increased removal of protozoa and cysts, such as *Cryptosporidium* and *Giardia* (Edzwald, 1995).

In December 1998, the US Environmental Agency (EPA) issued two new sets of water regulations: the Interim Enhanced Surface Water Treatment Rule (IESWTTR) and disinfection By-products (D/DBP) Rule. The IESWTR required filtered water turbidities of less than 0.3 NTU and 2-log removal of *Cryptosporidium* by filtration. In addition, the water industry has set a voluntary guideline of 0.1 NTU for filtered water turbidity. The IESWTR is an interim rule and final rule is expected to require even stricter standards for turbidity, *Giardia*, and *Cryptosporidium*. Many newly designed or to be designed water treatment facilities have adopted the regulations in IESWTR. The D/DBP rule requires coagulation as best treatment technology for control of DBP formation by removal of DBP precursors (USEPA, 1998). DAF is more efficient in removing low-density floc produced from coagulation of total organic carbon (TOC) (Edzwald, 1995). DAF has been shown to be particularly effective in removing *Cryptosporidium* Oocysts.

The Millwood Water Treatment Plant in Westchester County, about 60 kilometers north of New York, was commissioned in August 1993. This was the first dissolved air flotation plant in the United States. Currently there are more than 30 water treatment plants in US and Canada using DAF in their operations, with the plant capacity ranging from less than 1MGD to 100 MGD (Edzwald, 1995). More and more water providers in North America are looking into DAF as a pretreatment classification step prior to filtration, because DAF is efficient in removing particles and turbidity, and water facilities can integrate more economical filter designs into new plants. DAF is especially effective in treating supplies with low to moderate turbidities, supplies with natural color,

or with algae problems (Kaminski, et. al, 1991). Furthermore, DAF can be designed at higher loading rates and is more efficient in removing flocs compared to traditional medium-filtration processes (Kaminski, et. al, 1991).

Other advantages that DAF process may offer include: small footprint of facilities, high solids capture particularly of finer solids, rapid start-up, and the ability to withstand changing raw water conditions (Kaminski, et. al, 1991).

3.1.2 Process mechanism of DAF

In a DAF unit, a process water flow (typically 5~10 % of the raw water) is saturated with air under pressure (500~800 kPa). Either clarified or filtered water can be used for the process water. The saturated water (recycle) flow is introduced into the front of DAF tank by means of specialized nozzles or needle valve and consequently undergoes a pressure drop, which results in the formation of small bubbles with diameter between 10~100 μm . These bubbles can attach to the suspended particles and cause them to float to the surface of the water. The floated materials will incorporate into the foam layer, which are physically removed from water using mechanical skimmers or overflow weirs, while the treated water (clarified) passes through the collection devices installed in the bottom of the DAF tank.

Figure-2 showed the schematic diagram of a typical DAF process.

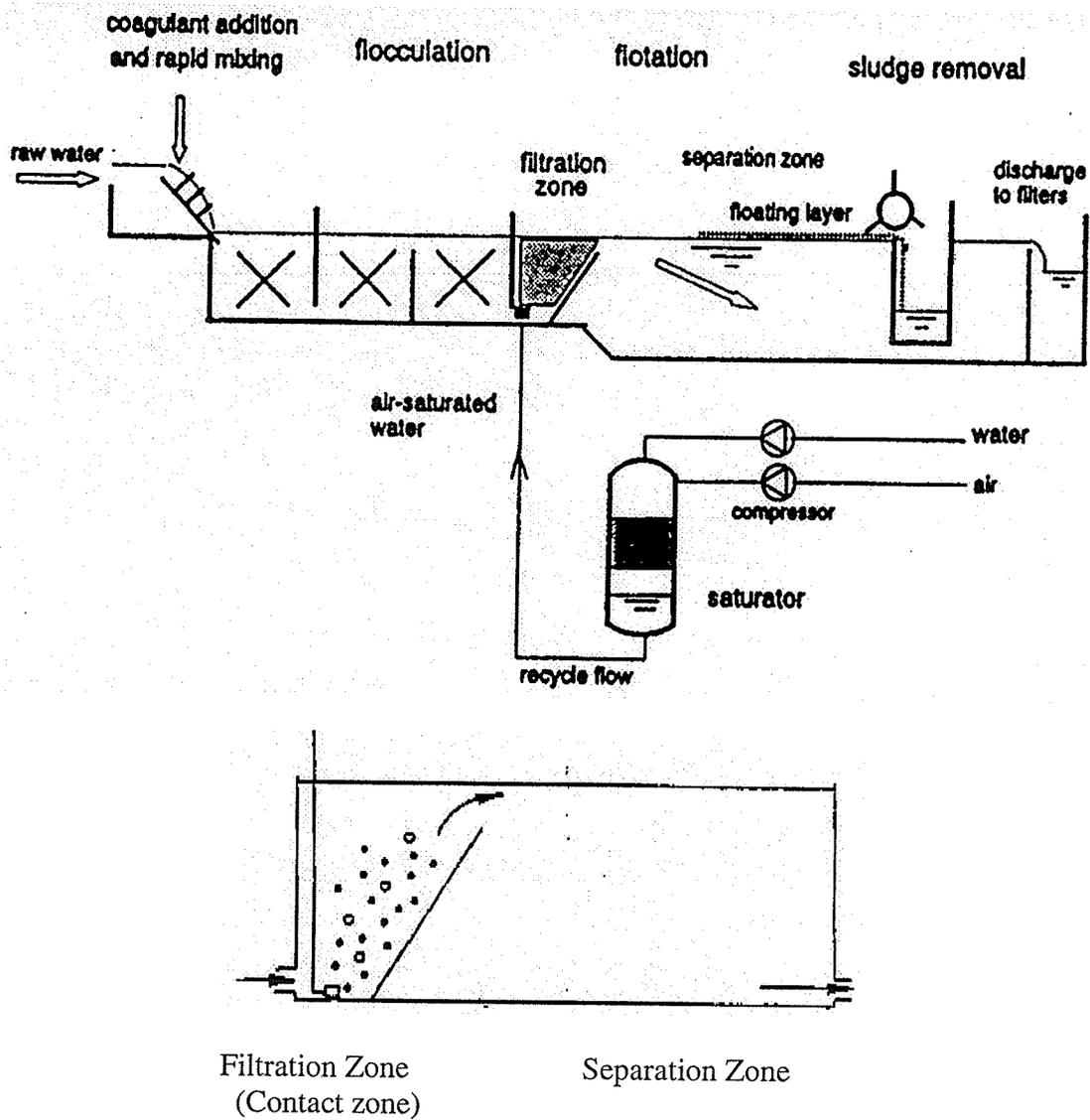


Figure-2 Schematic diagram of a typical DAF process

(Schers, 1991)

The flotation tank can be divided into two zones: filtration (contact) zone and separation zone. The purpose of the filtration zone is to contact and attach bubbles to particles and form bubble-floc aggregates while the purpose of the separation zone is to provide relatively quiescent conditions for particle –bubble aggregates to rise to the surface of the water.

Kitchener and Gochin (1981) listed three possible mechanisms for forming aggregates of bubble and particles: (1) entrapment of performed bubbles in large floc structures (when floc size much larger than bubble size scale); (2) growth of bubble nuclei formation on particles or within flocs and (3) particle collision and adhesion with performed bubbles. Mechanism 1 is more important where large particles or flocs (100's of μm) either already exist or are formed rapidly by high rates of flocculation involving concentrated suspensions. Mechanism 2 probably occurs to varying degrees in most applications. However, it is mechanism 3 that is most important and applicable. This is true given the time scale for the formation of air 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.

No matter what view is taken, there is universal agreement and experimental evidence that two conditions are necessary for favorable flotation: (1) charge neutralization of the particles; (2) production of hydrophobic particles.

Charge neutralization: Addition of appropriate dose of chemicals (coagulant) is the major method for charge neutralization of the particles in the water. Flotation is not successful without coagulation. It was reported that flotation performance was improved by nearly two-log reduction in algae cells and reduction in turbidity if properly pre-coagulated (Edzwald, 1995).

Hydrophobic particles Bubble adhesion or attachment to particles requires hydrophobic particle surfaces (Gochin and Solari, 1983) or hydrophobic spots on particles. For many particles, hydrophobicity is increased by simply reducing the negative charge. Other particles such as freshly precipitated or amorphous $\text{Al}(\text{OH})_3$ have polar surface groups

that bond water making them hydrophilic. This hydrophilic effect may also be reduced by charge neutralization.

3.1.3 Important parameters for DAF process

Hydraulic loading (overflow) rate It is often regarded as a design parameter for DAF. Hydraulic loading rate (HLR) is an important factor that affects clarification in DAF unit. Historically, DAF have been designed with hydraulic loading rate of 5~10 m/hr. These loading rates stemmed from DAF experiments in Scandinavian countries and the United Kingdom. In the United States and other countries, higher HLR became feasible due to differences in water quality and pretreatment. For example, a large DAF facility was built in Fairfield, CT with a HLR of 15 m/hr. Edzwald and his co-workers (1991) reported through their bench-scale and pilot plant tests that DAF treatment facilities may be designed and operated with HLR as high as 30~40 m/hr depending on water temperature, quality and pretreatment.

Bubble concentration and size Air bubbles are released in the flotation tank by dissolving air under pressure (typically 65~90 psig) into the recycle flow, typically 5 to 12 percent of the raw water flow, and then lowering the pressure by release of the recycle water to atmosphere pressure through needle valves or specially designed nozzles.

The air supplied for flotation can be described in terms of the recycle ratio or percentage (R_r), the air bubble number concentration (N_b), and bubble volume concentration (Φ_b).

The recycle ratio is defined as

$$R_r = Q_r / Q_0 \quad (1)$$

Where: Q_r : the recycle flow

Q_0 : the plant flow

The recycle ratio is a rough indicator of the air supplied. It doesn't account for saturator efficiency, pressure and water temperature. However, it is an operating and design parameter used in practice.

The air bubble number concentration (N_b), and bubble volume concentration (Φ_b) are fundamental parameters relating to particle-bubble collisions. They are calculated from the following equations:

$$C_{sat} = f P_t / H_{air} \quad (2)$$

C_{sat} : saturated mass concentration of air in saturator recycle water;

Where f : the saturator efficiency;

P_t : the total air pressure of the saturator (i.e., gauge pressure plus one atmosphere);

H_{air} : Henry's law constant (4.18 Pa/ mg/ L at 20 °C)

$$C_r = [(C_{sat} - C_a)R_r - k] / (1 + R_r) \quad (3)$$

$$\Phi_b = C_r / C_{sat} \quad (4)$$

$$N_b = (6\Phi_b) / (\pi d_b^3) \quad (5)$$

Where: C_r : the mass of air per unit volume of water.

C_{sat} : the air concentration remaining in solution at atmosphere pressure;

k : flotation tank influent flow saturation factor given by $(C_a - C_0)$, where C_0 is the mass air concentration of the influent flow;

d_b : the density of air saturated with water vapor (1.19 mg/ cm³ at 20 °C)

Φ_b : bubble diameter;

Normally higher concentrations are obtained with increasing recycle ratio or increasing saturator efficiency.

Rising velocity In DAF process, the bubble-particle aggregate rise velocity is determined by (Edzwald, 1995)

—Stoke's equation for laminar flow condition ($Re < 1$)

$$V_{st} = g(\rho_w - \rho_a)d_a^2 / (18\nu\rho_w) \quad (6)$$

—Adjusted Stoke's equation for laminar-turbulent flow condition ($1 < Re < 50$)

$$V_{st} = g^{0.8}(\rho_w - \rho_a)^{0.8}d_a^{0.4} / (10\nu^{0.6}\rho_w^{0.8}) \quad (7)$$

Where ρ_a : the bubble-particle aggregate density;

d_a : the bubble-particle aggregate diameter;

ρ_w : water density;

ν : water viscosity at specific temperature;

g : the gravity;

v_{st} : Stokes' velocity (rising velocity);

To determine the rise velocity of the floc particle-bubble aggregates require calculation of ρ_a and d_a . These equations are shown as follows.

$$\rho_a = (\rho_p d_p^3 + B_n \rho_b d_b^3) / (d_p^3 + B_n d_b^3) \quad (8)$$

$$d_a = (d_p^3 + B_n d_b^3)^{1/3} \quad (9)$$

where B_n : the number of the bubbles attached to a floc particle;

d_p : the particle diameter

ρ_p : particle density

d_b : bubble diameter

When the temperature is kept constant under given flow condition, the form of the Stoke's equation depends on the floc particle and bubble size. While in DAF process, when the saturator pressure and recycle ratio are kept unchanged, the rise velocity of the particle-bubble aggregates is mainly dependent on the floc particle sizes.

Table-3 shows the particle –bubble aggregate rise velocity for 40 µm bubbles (Edzwald, 1995).

Table-3 Floc particle aggregate rise velocities for 40µm bubbles

Floc Particle Size (µm)	Number of Bubble Attached (Bn)	Rise Velocity (m/hr)
5 (Crypto)	1	3.1
10 (Giardia)	1	3.1
20	1	3.0
	2	4.9
50	1	2.1
	2	3.9
100	1	1.0
	2	2.2
	10	10.4

Calculation of bubble size The process of bubble formation involves two steps: nucleation and growth. In a supersaturated system of clean water the large pressure difference across the nozzle produces bubble nuclei spontaneously according to the thermodynamic principle of minimizing the free energy change. Assuming air is an ideal gas, the critical diameter of the bubble nucleus (d_{cb}) for homogeneous nucleation is

$$d_{cb} = 4 \sigma / \Delta P \quad (10)$$

where σ is the surface tension

ΔP is the pressure change across the nozzle

Figure-3 showed the critical diameter of the bubble nucleus as a function of the pressure change (Edwards, 1995)

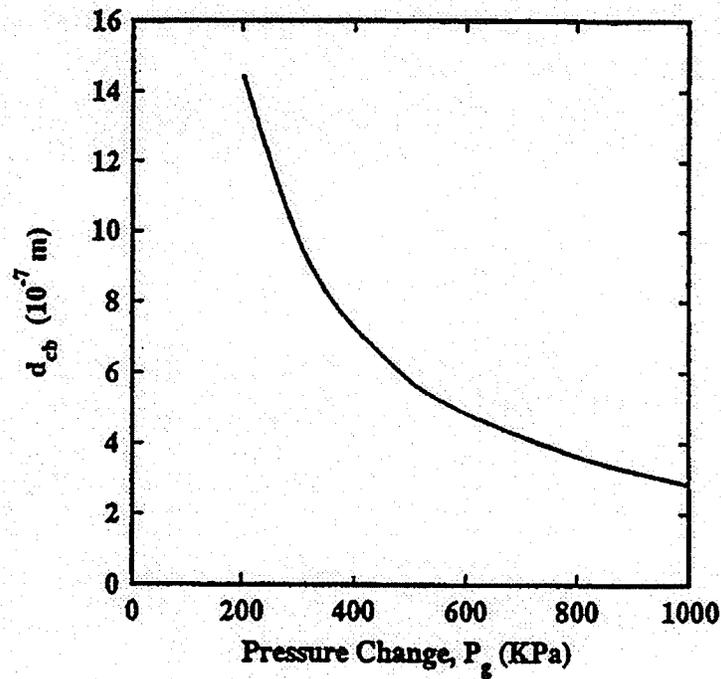


Figure-3 Critical diameter of bubbles nucleus for homogeneous nucleation of air in water at 20 °C as a function of the pressure change

Smaller nuclei were formed at higher pressure changes. In a heterogeneous system, minimization of the free energy change was made easier by bubble formation occurring on particle nuclei or other surfaces containing scratches or crevices. The nuclei grew into bubbles in the second step. Measurements of bubbles sizes for DAF systems indicated that bubbles maintained a steady state size range of 10 to 40 μm (Takahashi et al., 1979). The steady-state bubbles' size depended on the saturator pressure and injection flowrate

(Takahashi et al., 1979). The injection flow or recycle flow must provide a rapid pressure drop and be sufficient to prevent backflow and bubble growth on pipe surfaces in the vicinity of the injection system. Higher pressures produced smaller bubbles, but there was a diminishing return in reducing the bubbles size. Additional bubble growth might occur as the bubbles rise in the flotation tank due to a decrease in the hydrostatic pressure or by coalescence. Both of these had negligible effects on small bubbles formed in DAF systems (Takahashi et al., 1979).

According to the theory of single-collector collision efficiency, in a DAF unit, the particle-bubble collision efficiency is composed of four parts: diffusion efficiency, interception efficiency, gravity settling efficiency and inertia efficiency. The interception efficiency is good for floc particles between 10 to 100 μm . Actually the optimum particle size range for DAF is between 20 to 30 μm (Edzwald, 1995). Another report by Hanjing (1991, 1997) showed that most efficient bubble-particle collision was achieved when the flocs' size is close to the bubble size. Only efficient bubble-particle collision will result in efficient removal of particles in water, thus improving the effectiveness of the DAF process.

3.2 Particle size distribution (PSD) in water treatment

3.2.1 Application of PSD in water treatment

Many of the contaminants of concern to the water industry either are particulates or are associated with particles, such as clay and silts, inorganic metals, biological contaminants including bacteria, virus and algae (Wiesner and Mazounie, 1989).

Furthermore, particulate matter has been shown to shield organisms from disinfectants. Therefore, removal of particles from water and wastewater is regarded as a major concern and one of the most important goals for environmental engineers through out the twentieth century (Lawler, 1997). The processes carried out in water treatment plants consist of a sequence of steps, which are designed to remove a large percentage of the suspended solids from the raw source water. These steps include some or all of coagulation and flocculation, sedimentation or flotation, filtration, disinfection. The technology, practical operation and results of all these processes are intimately linked with particle size distributions. Plummer(1996) reported up to 20 to 50 fold increases in the time required for inactivation of particle-associated coliforms depending not only on types of disinfectant, but also on the size of the particles.

Currently, turbidity is the most widely used indicator of the concentration of the particles in water. Turbidity is a measure of the scattering of light by particles suspended in an aqueous medium. The deflection or scattering of light is related to a number of optical phenomena that in turn depend on the concentration, size, and the shape of the particles as well as the wavelength of the incident light, the angle of observation, the optical properties of the particles, and the refractive index of the suspending medium (Kerker, 1969). While valuable, the measurement of turbidity has some limitations. It is only a gross and indirect indicator. Turbidity measurement is not sensitive to small particles, especially those in the size range of *Girdia* cysts and *Cryptoridium*. Furthermore, low turbidity of the treated water does not necessarily indicate the absence of particles in the water (Gorczyca & London, 2003).

With more stringent regulations proposed for water treatment, it has become more critical that we learn more about the particulate materials present in water. More information than turbidity is required for choosing, evaluating and optimizing the treatment processes.

Particles in the water usually have several properties that influence their behavior in water and have direct relation with the treatment efficiency. These properties include size, shape, density, surface charge, settling rising velocity and porosity. In suspensions of interest in water treatment practice, there is a distribution of particle sizes, a variety of shapes, a range of densities, etc. The heterodispersity with respect to some of these properties is still beyond our ability to measure or account for.

However, size distribution is reasonably understood and is of primary interest.

Understanding particle removal requires understanding of particle heterodispersity, especially with respect to size (Lawler, 1997). Particle size distribution (PSD) allows more accurate simulations of filtration models and better understanding of filter performance (Kaminski, Vescan, and Adin, 1997). PSD analysis can provide a more sensitive measurement of the particles in the water and as such, can be a very valuable analytical tool for the evaluation of the treatment processes. It provides a better means for selecting, and subsequently optimizing processes compared to traditional water analysis.

With the aid of computerized image analysis systems as well as statistical software, such as SPSS or SAS, the particle size distribution can be measured and processed accurately. A joint mathematical and experimental approach of studying the changes in PSD in

particle removal processes will surely lead to greater insight to these processes (Lawler, 1997).

3.2.2 Particle size distribution (PSD) analysis

There are mainly two methods being used to analyze the particles in water: particle counters and microscopy analysis.

3.2.2.1 Particle counter

When a particle counter is used for PSD analysis for suspensions of water or wastewater, an electrical signal is created for every particle in the sensing zone. The signal is related to the particle size; As each particle passes through the sensing zone, the signal is created, sized and counted. The sizing is done in increments—all signals within a certain range are counted as equal, resulting in a discrete rather than continuous distribution. The distribution (number of counts in each range of signal sizes) is interpreted as the particle size distribution, when the relationship between the signal size and particle size is known. That relationship is dependent on the methodology of the instrument. Light blockage, electrical zone sensing, and laser light scattering are all used, and each has a different relationship between signal size and particle size (Lawler, et. al, 1983)

Light blockage: The particles in a flowing sample actually block part of a light beam, and a pulse, proportional to the projected area, of the particle, is generated on a photodiode.

Electrical zone sensing: This procedure involves diluting the sample in an electrode solution, and passing it between two electrodes. A constant voltage is passed between the

electrodes, and the particles passing through the sensing field produce a change in electrical resistance, which is proportional to the particle volume. This volume measurement is then converted to particle size and concentration values.

Laser light scattering: The sample is placed in a beaker, which a rotating laser strikes, producing forward light scatter. The diameter of the conical section striking a photo-detector is related to particle size.

In the instruments, the discrete size distribution increments are large. The resulting information is sufficient for plant operation. Application of particle counter for particle size distribution analysis is quick, easy, and economical. However, the small number of data points on a distribution curve may be easily misinterpreted. As each particle counter has a pre-set range for the particles. Particles which sizes fall outside the range are not reported and hence, the data and curve is not complete. When investigating a malfunctioning slow sand filter in North Caribu in Northern Ontario, Gorczyca & London (2003) found that the particle counter was not able to identify the particles less than $2\mu\text{m}$ and larger than $15\mu\text{m}$, which were the primary causes which lead to high turbidity and malfunction of the slow sand filter.

It is reported that a recently developed dynamic particle counter by Brightwell Technologies Inc. may be used to measure the PSD from optical images of the suspensions (Brightwell, USA, 2003). The technique used in this counter is quite similar to the microscopic analysis.

3.2.2.2 Microscopic analysis of PSD

In this method, a computerized image analysis system is used to observe and measure the particles in the water. The particles are isolated in the sample to be observed under the microscope. The images captured from the microscope can be readily recorded and saved in a computer. The images captured then can be analyzed and measured through the image analysis software installed in the computer. The measured data are processed by means of statistical software, such as SAS or SPSS. A continuous size distribution curve can then be attained. Compared with the size distribution obtained from the particle counter, the measured size range is much broader and more extensive. Further more, other characteristics of the particles can be observed and studied. Thus this method is more effective.

3.3 Coagulation and flocculation

3.3.1 Background

Surface water generally contains a wide variety of colloidal particulate impurities that may cause the water to appear turbid or may impart color. Colloidal particles normally range in size between 0.001~1.0 micrometer (Adamson, A. W., 1990). They are so small that they will not settle by gravity and can pass through most common filtration media. A typical colloidal particle is comprised of two layers: (1) A fixed layer of oppositely charged ions adsorbed to the colloidal surface and (2) a diffuse layer of a mixture of charged ions as is shown in Figure-4 (Adamson, A. W., 1990). A shear surface separates the fixed and diffuse layers and defines the mobile portion of the colloid. The competing

forces (electrical attraction and diffusion) spread the charge over the electrical double layer and keep the colloidal solution stable (Sawyer, et. al, 1994).

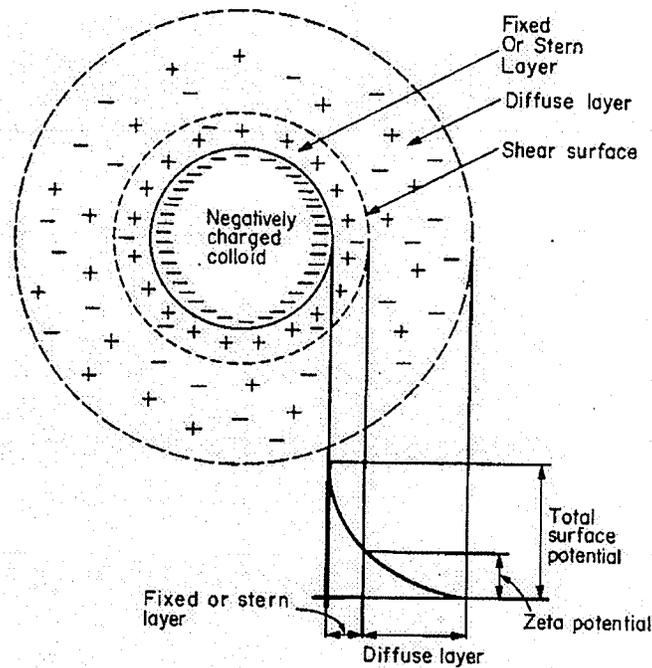


Figure-4 Electrical double layer of a negatively-charged colloid particle

(Adamson, A. W., 1990)

To be removed, individual colloids must aggregate and grow in size. Chemical agents (coagulants) can be used to promote colloid aggregation by destroying the forces that stabilize colloidal particles. The process of destroying the stabilizing forces and causing aggregation of colloids is called chemical coagulation. Two distinct steps will occur in the process of coagulation: particle destabilization followed by particle transport to promote collisions between the destabilized particles.

Particle destabilization can be achieved by four mechanisms: (1) double-layer compression, (2) adsorption and charge neutralization, (3) enmeshment in precipitate, and (4) inter-particle bridging (Sawyer, et. al, 1994). In chemical coagulation, destabilization is induced by the addition of suitable chemical coagulant and particle

contact is ensured through appropriate mixing devices. Coagulant dosages cannot be calculated but must be determined experimentally, usually by a simple jar test. However, a jar test result will usually indicate an optimum efficiency at a lower dose than that needed for actual plant operation. Hence, adjustments have to be made with the jar test result when full-scale applications are needed.

The coagulants most commonly used in water treatment are based on iron (III), aluminum (III) and polymers (cationic and anionic).

In a typical water treatment plant, there are two independent mixing systems used for coagulation: rapid-mixing and slow-mixing (flocculation). The function of a rapid – mixing unit is to provide complete mixing of the coagulant and raw water. It is known that destabilization and early stages of floc formation occur during rapid mixing. Proper design of rapid-mixing units can optimize these processes, resulting in a reduced coagulant demand and improved aggregation in subsequent flocculation units. However, completely mixed units can't provide uniform mixing because of flow and mass rotation of water (Sawyer, et. al, 1994). As a result, some portions of the water may have a high concentration of chemicals, while others may have a low concentration. The existence of non-uniform mixing is more of concern when hydrolyzing metal ions are used as coagulants. If destabilization by adsorption is desired, non-uniform mixing will be quite undesirable. Destabilization will be poor in areas of low chemical concentration because of insufficient adsorption and low chemical potential. Destabilization will also be poor in areas of high chemical concentration because over-adsorption and charge reversal. Once reversal occurs, continued mixing will not improve the situation for the adsorption process is essentially irreversible (Sawyer, et. al, 1994). Hence, the completely mixing

units are being replaced by in-line blenders, which were found to be very efficient rapid-mixing units (Hyde, et. al, 1977). Contacts between destabilized particles are essential for aggregation to occur. These contacts can be achieved by three separate mechanisms: (1) thermal motion, (2) bulk liquid motion (stirring) and (3) differential settling (Sawyer, et. al, 1994). To attain these goals, there must be velocity gradients in flocculation basin high enough to promote aggregation. Typical velocity gradients in flocculation tank vary from 20 to 80s⁻¹ (Camp, 1968). However, if it's too high it is possible that the flocs will be sheared apart. If flocs are ruptured by shearing, re-aggregation is more likely to occur for iron (III) and aluminum (III) flocs than for polymer flocs because the polymer segments, once detached by mixing, may fold back and re-stabilize the particles. The detention time is also very important as it determines the amount of time that particles are exposed to the velocity gradient and thus a measure of contact opportunity in the basin. A detention time of 30 minutes is commonly used for flocculation design (Sawyer, et. al, 1994).

3.3.2 Destabilization and coagulation of the algae particles

Almost all surface water contains algae. DAF process is especially efficient for algae removal. However, algae particles may be initially stable in water due to 1) electrostatic interactions because of surface charge producing diffuse electrical double layers 2) hydrophobic effects because of adsorbed water or algae cell surfaces 3) steric effects due to adsorbed macromolecules or extra-cellular organic matter (EOM). Ives (1959) described the electro-kinetic properties of algae and the significance of algae surface charge in coagulation and flocculation. He showed that algae were electronegative for all

pH conditions investigated of pH 2.5 to 11.5. While surface charge was an important property of algae affecting its stability as a particulate suspension, other factors, such as extra-cellular organic matter (EOM), may also be important. Algae can excrete EOM such as polysaccharides, pectins, lipoproteins, and polyamino acids. The amount and structure of EOM adsorbed on algae surfaces or released to the bulk solution depended on algae type and growth phase (Luse et al., 1985; Benhardt and Classen, 1991) The EOM may cause stability because of steric effects or may aid flocculation through inter-particle bridging depending on the ionic strength and calcium concentration.

Edzwald et al (1990) have presented a conceptual model describing particle removal by dissolved air flotation (DAF) process. The model prescribed that good particle-bubble attachment and hence effective flotation required conditions in which particles had to be destabilized, i.e., became hydrophobic and had little or no surface charge. These requirements were the same as destabilization of particles for flocculation and settling, and for filtration. The experimental data for separation of *Cyclotella* by DAF from Wachusett Reservoir (Edzwald and Wingler, 1990) indicated that particle removal (turbidity and $\log N/N_0$) does not occur without coagulant addition.

However, in the case of flocculation before DAF, different opinions existed as to the optimum coagulant dosage, flocculation time and floc size. For example, some researchers emphasized that long flocculation is not needed and pin-floc sizes between 10~30 μm are most favorable (Edzwald, et al., 1992). In this study, the flocculation time of 5-15 minutes was enough and chemical dosage as low as 10 mg/L was sufficient.

Other studies, however, emphasized that larger flocs are preferred (Tambo et al., 1995). In the pilot water treatment study conducted in Winnipeg, it was reported that for warm

water (temperature between 15 and 22 °C), alum dosage of 40 mg/L combined with LT22 (polymer) of 0.025 mg/L and H₂SO₄ of 25 mg/L was recommended while for cold water (temperature lower than 5 °C), alum dosage of 65 mg/L combined with LT22 of 0.025 mg/L was recommended. Under cool fall weather (temperature between 5 to 15 °C), an alum dosage of 60 mg/L was required to reach the treatment goal: turbidity less than 0.1 NTU through DAF and deep-bed filter (Winnipeg Water Consortium, 1998). The difference in coagulant dosage was large. There is a need to understand what the optimum size of the floc is and associated with it, the coagulant dosage for DAF process.

4. Materials, Equipment and Methods

4.1 Bench-scale dissolved air flotation appliance

The bench-scale DAF appliance in the laboratory was composed of two parts: pre-treatment unit and DAF clarification unit, as was shown in Figure-5.

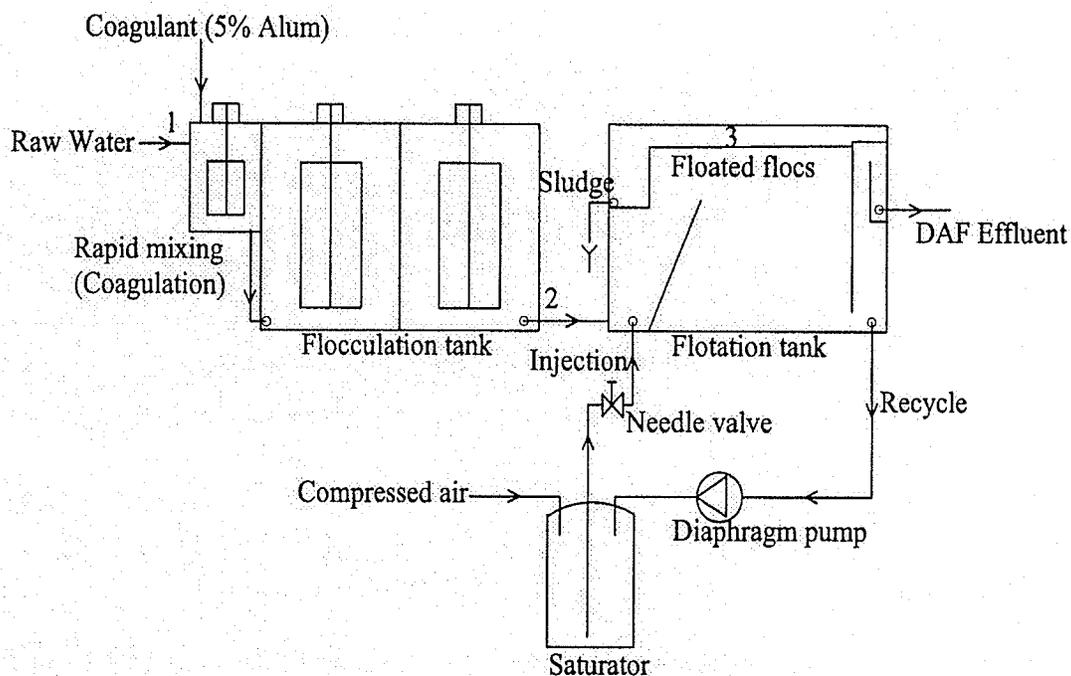


Figure-5 Schematic of the experimental DAF appliance

The pre-treatment unit included chemical (coagulant) addition, rapid mixing (coagulation), and slow mixing (flocculation). It consisted of a three-chamber unit: the first chamber for coagulation and another two (same dimensions) for flocculation.

The dimensions for the three chambers were as follows:

Coagulation chamber: width \times length \times height = 10.2 cm \times 10.2 cm \times 24.2 cm

The depth of water in running unit: 19.3 cm.

Each Flocculation chamber: width \times length \times height = 10.2 cm \times 20.4 cm \times 44.2 cm

The working depth of water in flocculation tanks: 39.0 cm.

The coagulant solution (5 g/L Alum, $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) was added to the first chamber through siphon. The relationship of the injecting speed and the dosage was calibrated in advance before the test was run. Then the coagulated water flowed sequentially by gravity into the following two flocculation chambers, where flocculation took place.

The rapid mixing (coagulation) was conducted with a paddle speed of 300 rpm for 2 minutes, while slow mixing (flocculation) was set with paddle speed of 30 rpm for 15.8 minutes (7.9 minutes for each flocculation chamber). Many plants using DAF in Europe were built with long flocculation times of 20 to 30 minutes, which resembled that in conventional water treatment using settling. Edzwald et. al. (1991) reported that long flocculation period were not necessary prior to DAF. Usually flocculation time of 5 to 20 minutes was recommended. In this test, total flocculation time of 16 minutes was applied.

In all experiments, only alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) was used as coagulant under room temperature (15~20 °C). The concentration of the coagulant solution is 5 %.

At the start of the experiment, a jar test was done to select the optimum dosage of coagulant (alum). Five one-liter beakers were filled with one liter of tap water in Winnipeg. Then add alum solution (5 %) to the five beakers above until the concentrations inside reached 15, 25, 35, 45, and 55 mg/L respectively, with coagulation time of 2 minutes, mixing speed of 300 rpm, and flocculation time of 30 minutes, and mixing speed of 30 rpm.

The temperature of the tap water varied between 7~11 °C. The dosage was adjusted depending on the treatment efficiency and the floc size data measured by image analysis system.

The DAF unit was composed of a DAF tank, a saturator, a heavy duty diaphragm-type injector metering pump and a needle valve (3/8”).

The dimension for the DAF tank was as follows: width × length × height = 10.2 cm × 49.4 cm × 43.1 cm.

The water depth when running was 38.5 cm. The average separation area was 279.5 cm².

The saturator was a two –gallon stainless steel pressure tank (Alloy Products Co., USA), with some pre-fabricated screwed connectors on the top.

The heavy duty diaphragm-type injector metering pump (Omega Ltd., USA) was used to recycle and boost process water into the saturator. The specifications of the pump were listed in Appendix-4.

A needle valve was used mainly to control the recycle flow rate in the pipe and to release the pressure thus creating lots small bubbles. It was also used as diffusers. The needle valve was manufactured by Marsh Instrument Co. (model No. of N1512-26).

All parts were connected using polyethylene tubing with quick connectors (3/8”).

The post DAF effluent was used as the process water and was recycled by the diaphragm pump to the saturator vessel. The water and the clean air were mixed in the saturator and pressurized to 90 psig (620 kPa), and then were released through the needle valve into the front of the DAF tank. Tons of small bubbles were created which then attached to the flocs contained in the flocculated water entering the DAF tank. The bubble-floc particle

agglomerates rose to the surface of the water by flotation. The floated materials were skimmed off manually every 15 minutes.

The clean air was provided from the pipeline compressed air and was adjusted by the control valve installed in the inlet. The saturator pressure was kept around 90 psi, which was slightly higher than what was reported by other papers to ensure the creation of smaller bubbles.

All operational parameters in the experiment were established with reference to the experience of similar bench-scale DAF appliances. Due to the equipment limitation the hydraulic loading rate for DAF tank was set 2.2 m/hr. The recycle ratio was set at 8 percent.

A total of three experimental runs were conducted on the bench-scale DAF system. Each time the experiment was run consecutively for about four hours. The coagulant dosage was adjusted depending on the PSD test results measured from image analysis system, all other operational parameters were kept unchanged.

In about one hour from the start when the operation became stable, samples were collected at the locations 2 and 3 (as indicated in Figure-5) for analysis and comparison of particle size distribution and DAF effluent. The sample at location 2 was collected from the sample cock installed at the bottom of the 2nd flocculation chamber close to the outlet while the sample at the location 3 was directly drawn from the floated flocs using a big-mouth pipette. It was reported earlier that there was little difference with regard to the particle number and their volume for the sample after flocculation and that entering the DAF tank (Edzwald, et. al, 1992). Hence in this study, the sample collected from the

outlet of flocculation tank (location 2) was representative of the sample entering the DAF process.

The DAF effluent was tested for the turbidity, colour, and pH every 30 minutes during each test run. The samples for particle analysis were collected once only when the best DAF effluent quality was reached during each test run.

The operating conditions for the DAF system were summarized and listed in Table-4. As comparison, the data of the pilot-scale study by the City of Winnipeg were also listed in the table.

Table-4 Operating conditions for the experimental system

Parameter	Experiment			Pilot study result from Winnipeg *
	1	2	3	
Raw water flow rate (L/ hr)	61.5			~20,000
Raw water temperature (°C)	7~11			4~15
Alum dosage (mg/L)	41.7	25.5	15.5	60
Coagulation time (minutes)	2			In-line mixing
Flocculation time (minutes)	16			10
Velocity Gradient in the flocculation tank G (s^{-1})	39.6			40-100
DAF hydraulic loading rate (m/hr)	2.2			20
DAF saturator pressure (psi)	90			70~80
Recycle ratio (%)	8			10

4.2 Particle Analysis

4.2.1 Raw water analysis

Preliminary study The goal of the preliminary study was to investigate the quality and particle characteristics of the raw water from the Oxford Lake in northern Manitoba.

Oxford House is a First Nation community located along the Eastern shoreline of Oxford House Lake at the mouth of Hayes River, 950 kilometers North of Winnipeg.

In the past the water from the Oxford Lake was chlorinated only before delivery to the people in the community and for other public utilities. Recently a water treatment plant was built, which used dissolved air flotation as its main unit and is now successfully operated. The water treatment process in the Oxford House WTP was similar to the process proposed by the City of Winnipeg:

Raw water (from Oxford Lake) → Coagulation / Flocculation →
DAF → Filtration → Effluent

Therefore, it was anticipated that the investigation of the raw water quality of the Oxford Lake would be useful to the research to be conducted for DAF experiment with the city water in Winnipeg (Fernandes, 2003).

The sample was measured by two different image analysis softwares: Biquant95 Classic (Bimetrix Inc.) and Image Pro Plus (Media Cybernetics Inc.). The results of the preliminary study were used to compare the two image analysis softwares before making a decision on purchasing one of the systems for use in this and future relevant study in the Environmental Engineering Laboratory at University of Manitoba.

The water sample was collected in Oxford Lake and then couriered to the Environmental Engineering laboratory at the University of Manitoba. The raw water sample was received on February 28th, 2003. Water turbidity, color, pH, and alkalinity were presented in Table-5:

Table-5 General quality of the raw water from the Oxford Lake (February 28th, 2003)

Source of the Water	Turbidity (NTU)	Color (TCU)	Alkalinity (C _a CO ₃ mg/L)	pH	TOC (mg/L)
Oxford Lake	0.8	23.0	90	7.1	9.6
GCDWQ ¹	1.0	15.0	N/A	6.5~8.5	NG ²

¹Guidelines for Canadian Drinking Water Quality

²NG: No guideline

The initial test results indicated that the water from the Oxford Lake had low turbidity of 0.8 NTU and high color of 23 TCU. The water from the Oxford Lake had similar qualities to that of Shoal Lake water (table-1).

The low turbidity of 0.8 NTU indicated that the size of the particles in water was probably very small and their concentration was quite low.

Slides preparation In water samples with low turbidity, it was difficult to have a representative number of particles in a few drops. To increase the particles' concentration in the sample, the following procedure was applied: a clear container was filled with about 10 liters of the water sample, covered and put aside in the laboratory under room temperature for 20 hours, during which most of the particles causing the water turbidity and color would settle to the bottom of the container (Gorczyca & Ganczarczy, 1996).

Following the settling period the water at the top of the container was carefully decanted,

leaving about one liter of sediment concentrate at the bottom. The concentrated sample was centrifuged at 5000 rpm for 15 minutes and the water at the top in the vials was carefully decanted, leaving about 1 ml of the concentrated sample at the bottom. A drop of the concentrated water sample was pipetted and put on a microscope slide. Once it became dry the particles in the water sample were left on the slide, and the slides were sealed with a slide epoxy (permount) for sample preservation (Gorczyca and Ganczarczyk,1996).

4.2.2 Flocc analysis

Alum flocs collected from flocculation tank and DAF tank, were larger than the particles in raw water. A wide-mouth pipette was used to withdraw 1 ml of the water sample from the sample port at the flocculation chamber (at sample port 2) and then rapidly transferred it to a petri-dish, with addition of 8ml of liquefied 1.5 % agar solution. All the particles and flocs in the sample were embedded in agar, and could no longer move easily to contact with other particles and flocs in the sample. The agar-solidified samples were stored inside a refrigerator with temperature of about 1 °C to prevent any changes in the samples until their analysis the following day (Gorczyca and Ganczarczyk, 1996).

4.2.3 Data processing

The image analysis system was composed of an optical microscope coupled with a high-resolution video monitor, a high-resolution digital camera, a digital terminal box used to connect the parts above, and a computer system installed with Image Pro- Plus analysis software. The prepared slides or agar-embedded dishes were observed under laboratory

microscope using objectives of appropriate magnification times. The video-images observed could be captured and saved in the computer for further analysis and measurements. The geometric characteristics for the particles in water, such as projected area (cross-sectional area), shape factor, etc. could be measured using Image Pro Plus system.

Objectives with magnification 10 and 40 were used to observe the slides and those with magnification 4 and 10 were used to observe the agar-embedded dishes.

The equivalent diameter was the diameter of a circle having the same projected area as the particle image, and was calculated as follows.

$$\text{Equivalent Diameter} = (4 * \text{Projected area} / \pi)^{1/2} \quad (11)$$

5.0 Results and Discussions

5.1 The preliminary study results

In the preliminary study, the Oxford Lake water sample was measured with two different image analysis softwares: Bioquant 95 Classic and Image Pro Plus. The results were compared statistically.

In the preliminary study, the slides prepared from the water collected in the Oxford Lake were observed under microscope using the objectives with magnification of 10 and 40. The images captured were then analyzed first using the Image Pro-Plus system and then using another image analysis software Bioquant95 Classic for comparison of the two image analysis systems. Figure-6 showed the images of the particles in the water under the microscope.

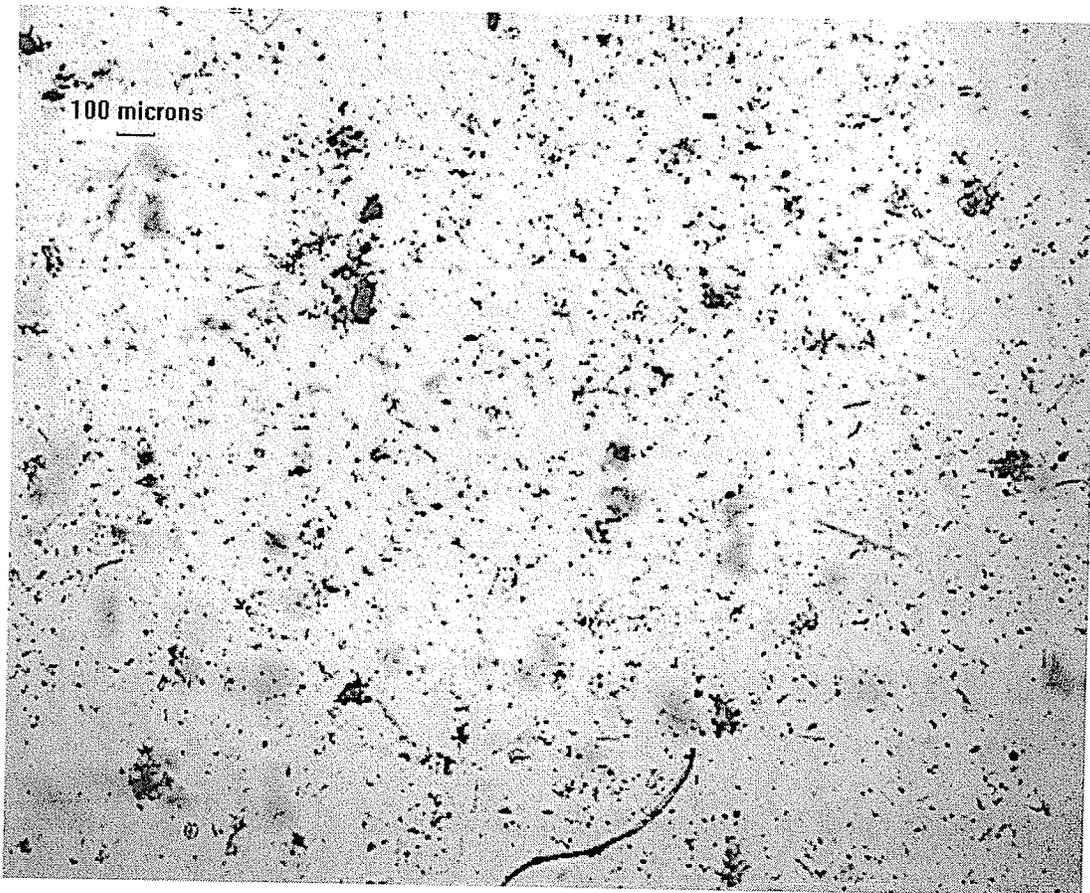


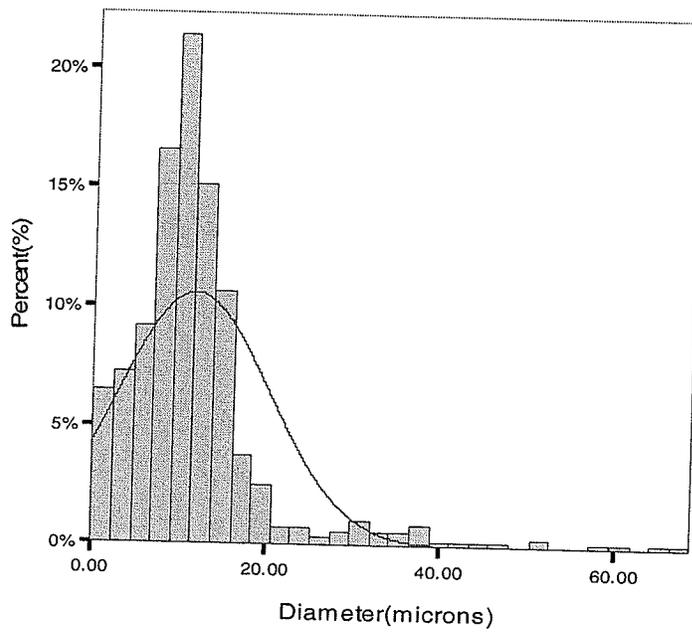
Figure-6 Microscopic images of the particles in the raw water from Oxford Lake

The microscopic images indicated that most of the particles in the raw water from the Oxford Lake appeared as discrete and small particles. The PSD results indicated that 92.4 percent of the particles had the equivalent diameter smaller than $20\mu\text{m}$, with the peak occurring at $11.52\mu\text{m}$ and minimum of $1.35\mu\text{m}$. Dr. Katherine Londry, a staff member of the Department of Microbiology and Mr. Paska, a Ph D student of the Department of Botany confirmed through microscopic analysis that the particles appeared in the water sample were mainly diatoms and other algal cysts.

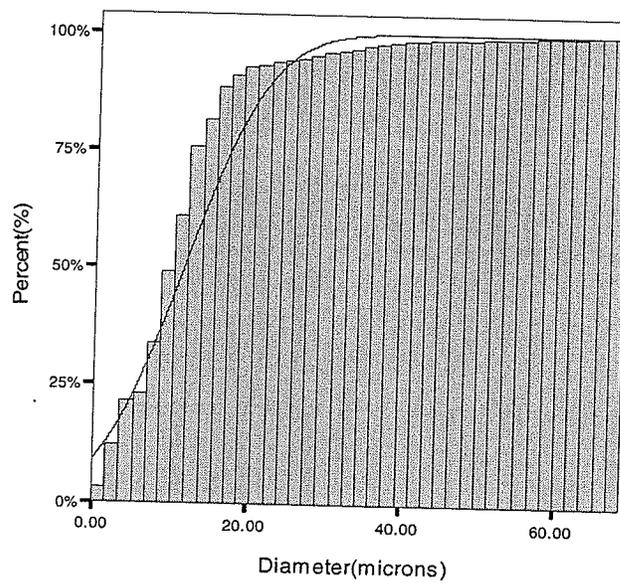
From the microscopic image, it was found that the particles with larger diameter ($>20\mu\text{m}$) were grouped small particles—they were probably formed from “natural

agglomeration” after static settling and concentration: some of the small discrete particles were stuck together and formed the particle groups, as were clearly shown in figure-8 (b) and (c), with the maximum size was 68.66 μ m,

Figure-7 showed the differential and cumulative particle size distribution curves from the data when measured with Image Pro-Plus software. Table-6 listed the summary of statistics for the test result.



(a) Differential PSD



(b) Cumulative PSD

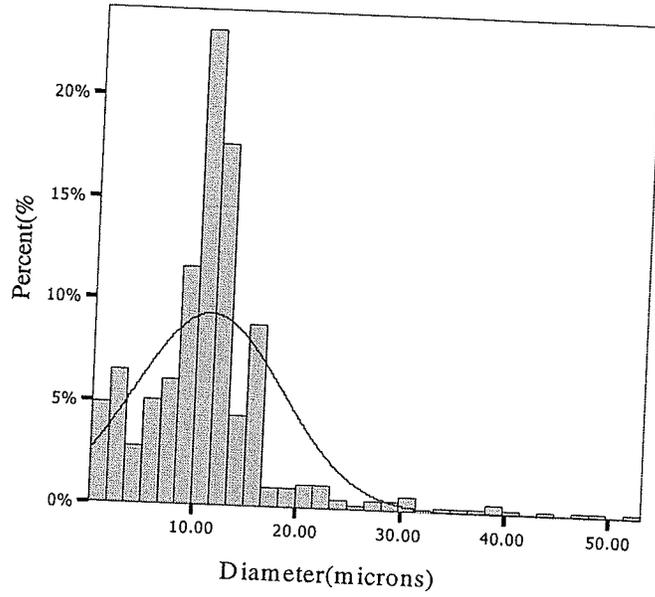
Figure-7 particle size distribution in the raw water from Oxford Lake when measured with Image Pro Plus

Table-6 Particle size distribution for the raw water from Oxford Lake
when measured with Image Pro-Plus

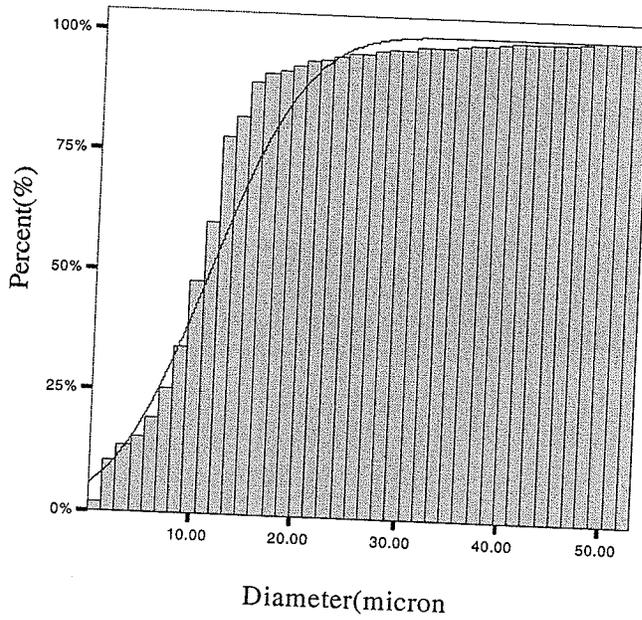
Mean (μm)	11.52
Maximum (μm)	68.66
Minimum (μm)	1.35
Log mean (μm)	9.12
Median (μm)	10.45
Mode (μm)	12.23
Std Deviation	8.64
Percentile 05 (μm)	2.12
Percentile 25 (μm)	7.06
Percentile 75 (μm)	13.21
Percentile 95 (μm)	29.25
Percentile 99 (μm)	51.79

It was found from the PSD results that the distribution curve of the particles fitted well to normal distribution. (Without the aggregated particles, the normality would be improved).

The results of analysis measured with image analysis software of Bioquant95 Classic were showed in Figure-8 and statistics summary was listed in Table-7.



(a) Differential PSD



(b) Cumulative PSD

Figure-8 Particle size distribution for the raw water from Oxford Lake when measured with Bioquant95 Classic

Table-7 Particle size distribution for the raw water from Oxford Lake
when measured with Bioquant95 Classic

Mean (μm)	11.26
Maximum (μm)	53.09
Minimum (μm)	1.27
Log mean (μm)	9.15
Median (μm)	11.17
Mode (μm)	11.17
Std Deviation	7.07
Percentile 05 (μm)	1.58
Percentile 25 (μm)	7.06
Percentile 75 (μm)	13.21
Percentile 95 (μm)	22.88
Percentile 99 (μm)	42.72

Compared with the PSD charts from Image Pro Plus, it was found that the PSD charts were quite similar. Further statistical testing (as explained in Appendix-1) indicated that the two sets of data obtained from Image Pro Plus and from Bioquant 95 Classic respectively were not significantly different at 95 % confidence level.

However, the Image Pro Plus software involved more functions than Bioquant95 Classic, and was easier to operate; Hence Image Pro-Plus was recommended for all the PSD tests in this study and for all the later relevant studies in the lab.

5.2 Particle size distribution in the tap water in Winnipeg

Turbidity, color, temperature, pH, and alkalinity of the tap water in the three particle analysis studies performed were listed in Table-8.

Table-8 Tap water quality in Winnipeg during this study

Run	Turbidity (NTU)	Color (TCU)	Temperature (°C)	pH	Alkalinity (CaCO ₃ mg/L)
1 (12/07/2003)	0.48	4.1	10	6.8	65
2 (12/10/2003)	0.52	4.0	9.8	7.2	68
3 (02/13/2004)	0.40	4.0	9.2	6.9	63
Average	0.47	4.0	9.6	7.0	65.3

Test results indicated that the average turbidity of the tap water was 0.47 NTU and average true color was 4.0 TCU, both of which were under the Guideline for Drinking Water. Other items, such as pH, alkalinity could also be accepted. However, lower turbidity and color didn't provide information on the particles in the water as to their type, size, shape, and so on. Hence further microscopic analysis, using image analysis system was conducted to get more information.

Microscope slides were prepared from the tap water in Winnipeg according to the procedures explained in 4.2.1. The slides were analyzed under microscope using the Image Pro-Plus system.

The microscopic images for the particles in the city water were shown in Figure-9.

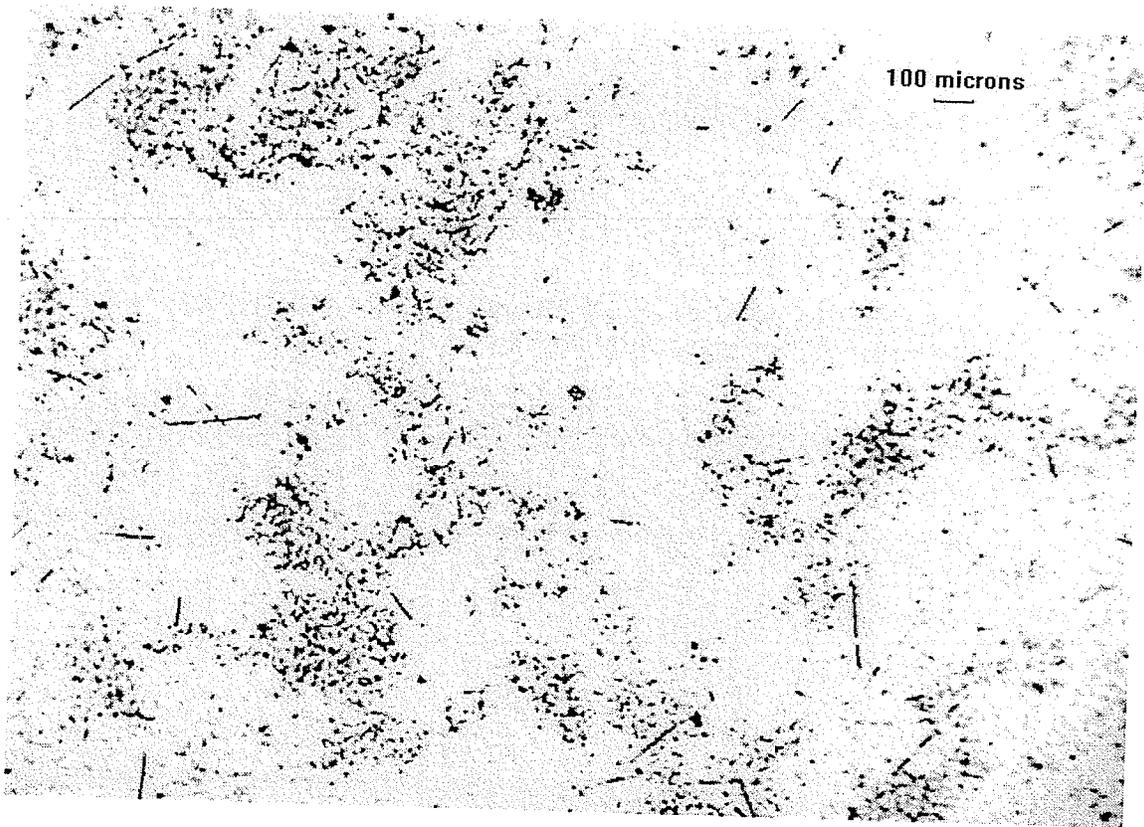
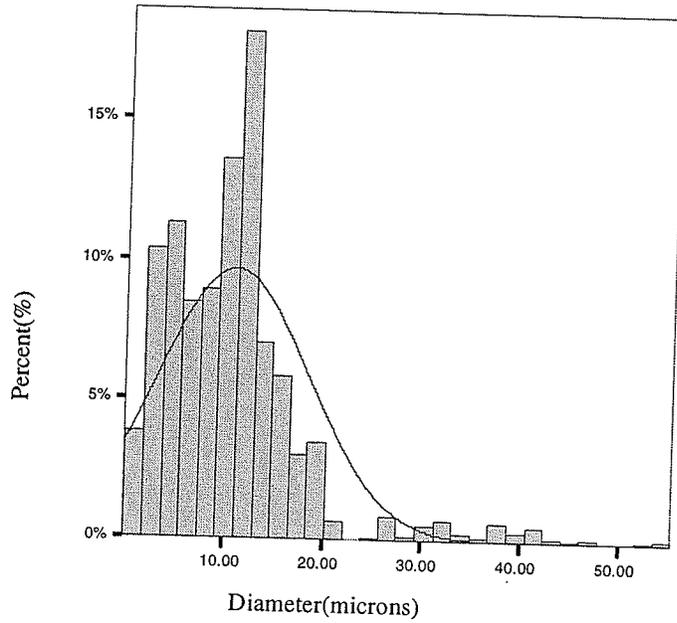


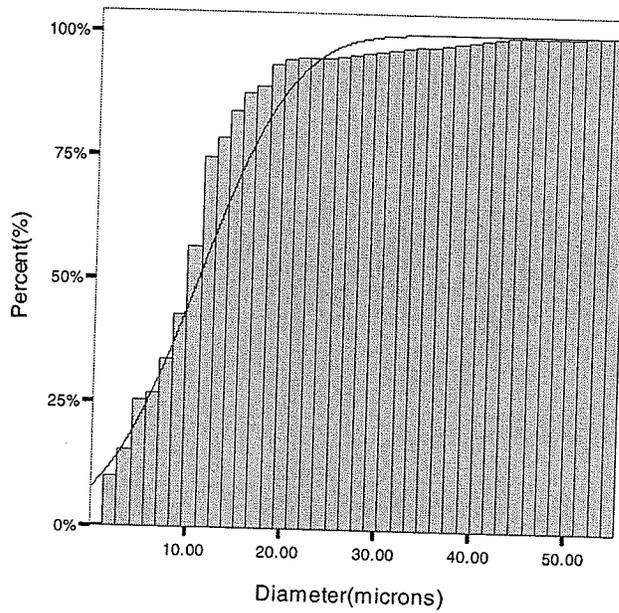
Figure-9 Microscopic images of the particulate in the tap water in Winnipeg

Similar to that in the water from the Oxford Lake, most of the particles in the city water were very small. The PSD results indicated that 94.4 percent of the particles fall on the range of 0 to 20 μm , with the peak occurring at 10.99 μm and the minimum of 1.32 μm for their equivalent diameters, which was the size range for a lot of algae particles. The larger particles, the maximum of 55.37 μm , most likely resulted from natural agglomeration after static settling and concentration.

Figure-10 showed the PSD in the tap water after the test data were processed using SPSS, and the statistics summary was listed in Table-9.



(a) Differential PSD



(b) Cumulative PSD

Figure-10 Particle size distribution in the tap water in Winnipeg

Table-9 Particle size distribution for the tap water in Winnipeg

Mean (μm)	10.99
Maximum (μm)	55.37
Minimum (μm)	1.32
Log mean (μm)	8.80
Median (μm)	9.99
Mode (μm)	11.16
Std Deviation	7.68
Percentile 05 (μm)	1.94
Percentile 25 (μm)	7.06
Percentile 75 (μm)	13.21
Percentile 95 (μm)	27.35
Percentile 99 (μm)	41.70

When compared to the raw water from the Oxford Lake, it was found that both the water samples had low turbidity, the color for the Oxford Lake water was a little higher than that for the tap water in Winnipeg. Further statistical comparison indicated that, with regard to their mean equivalent diameter of particles, the tap water in Winnipeg did not statistically show significant difference to the raw water from the Oxford Lake (to see Appendix-2 for details)

5.3 Effect of coagulation on variation of PSD before and after DAF process

During the jar test, it was found that after addition of the alum, flocs formed in less than five minutes. However, most of the flocs formed were suspended in the water even one

hour after coagulation. Hence the optimum coagulant couldn't be selected with the traditional coagulation jar test method.

Because coagulation and flocculation processes were directly related to DAF process, they were run and tested together in this bench-scale experimental system.

Following the pilot study results by the City of Winnipeg, the alum dosage of 41.7 mg/L was first chosen for coagulation in the first run experiment. The time and loading rate were selected with reference to similar bench-scale experiments and with consideration of the experiment appliance itself. The coagulation time was 2 minutes; flocculation time was 16 minutes with 8.0 minutes at each stage. The hydraulic loading rate was 2.2 m/h. Test results indicated that with the addition of alum, the particles in raw water coagulated in several minutes. The flocs obtained as a result of flocculation had arbitrary shapes. They had water-like color and blended well with background agar, as was shown in Figure-11.

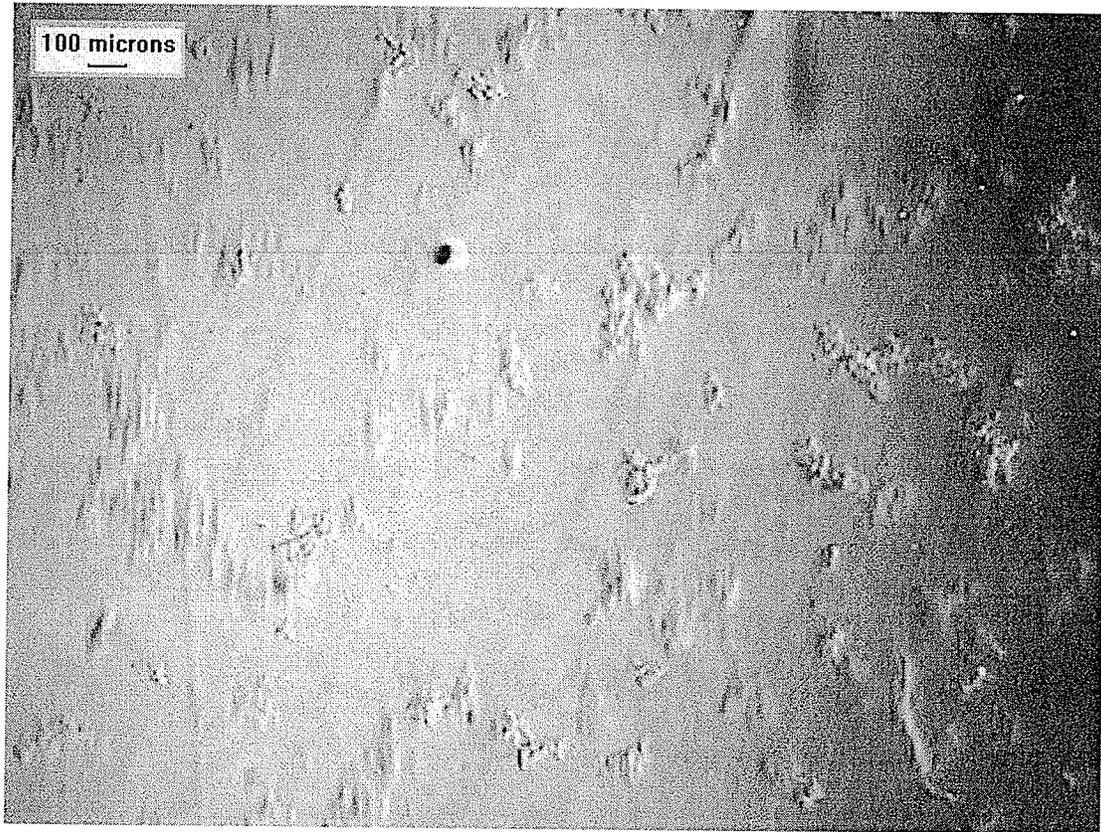


Figure-11 Alum coagulation flocs in the water

(Alum dosage of 41.7 mg/L)

After coagulation, the number of small discrete particles significantly decreased. The particles with equivalent diameter less than $20\ \mu\text{m}$ decreased from about 95.2 % in the tap water to about 14.2 % in the flocculated water, with minimum of $7.03\ \mu\text{m}$. It also indicated that not all the particles, especially those smaller particles, could be agglomerated by coagulation. These small particles remained discrete in the water. They could only be partly removed by DAF, and probably caused the turbidity in the final effluent (Table-10)

Table-10 DAF effluent quality when alum dosage was at 41.7 mg/L

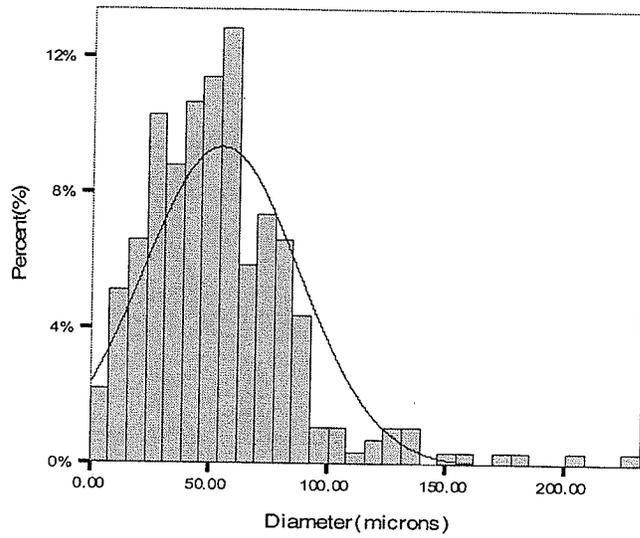
Items	Wpg tap water	DAF Effluent (0.5 hr)	DAF Effluent (1.0 hr)	DAF Effluent (1.5 hr)	DAF Effluent (2.0 hr)	DAF Effluent (2.5 hr)	Average
Turbidity (NTU)	0.47	0.23	0.26	0.29	0.24	0.25	0.25
Color(TCU)	4.0	3.8	3.7	3.9	3.8	3.5	3.7
pH	7.0	6.3	6.5	6.6	6.5	6.2	6.36

The mean equivalent diameter for all the particles was increased from 11.5 μm before coagulation to 54.63 μm after coagulation, and the maximum is 232.00 μm as shown in Table-11. Figure-12 showed the PSD chart for coagulation flocs when alum dosage was at 41.7 mg/L.

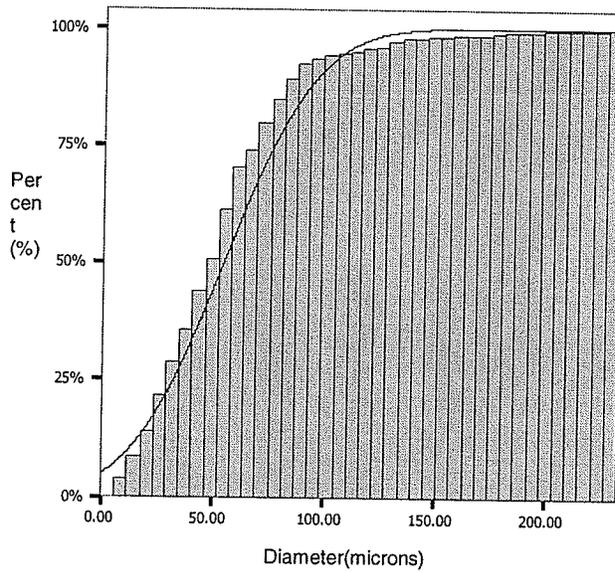
Table-11 Alum coagulation flocs' and floated flocs' size distributions

when alum dosage was at 41.7 mg/L

Items	Raw water	Coagulation flocs	Floated flocs
Mean (μm)	10.99	54.63	61.79
Maximum (μm)	55.37	232.00	238.23
Minimum (μm)	1.32	7.03	7.07
Log mean (μm)	8.80	45.44	46.90
Median (μm)	9.99	51.53	50.27
Mode (μm)	11.16	20.15	41.12
Std Deviation	7.68	33.01	45.87
Percentile 05 (μm)	1.94	12.34	9.64
Percentile 25 (μm)	7.06	31.47	28.44
Percentile 75 (μm)	13.21	70.85	78.78
Percentile 95 (μm)	27.35	120.02	165.45
Percentile 99 (μm)	41.70	186.22	219.28



(a) Differential PSD



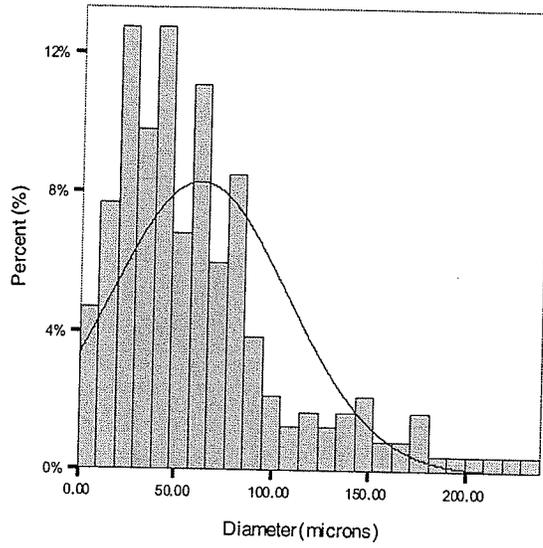
(b) Cumulative PSD

Figure-12 Alum coagulation flocs' size distribution when alum dosage was at 41.7 mg/L

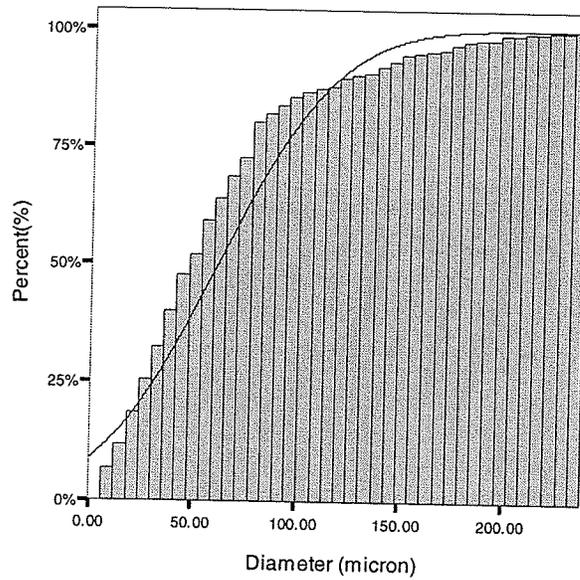
The test results also indicated that more than 75% of the flocs were larger than 30 μm . As was discussed in section 3.1.3, calculation of the rise velocity with Stoke's equation and equations (6) and (7) showed that for a large floc size, high rise velocity could be achieved if a sufficient number of bubbles could attach to the flocs to decrease the aggregate density to less than that of the water. However, because highly pressurized air required much high power costs, it was not economical to have very large flocs in DAFs. As was discussed in the introduction, the optimum particle or flocs size range for DAF was between 20 to 30 μm . And when the size of particles or flocs was close to the bubbles' size it might result in most efficient bubble-particle aggregation and DAF treatment efficiency.

In this experiment, the bubble size was estimated to be about 30 μm (Equation 10). In the first test run when the alum dosage was 41.7 mg/L, about 75 % of the flocs' size (diameter) was larger than the estimated bubble size (Table-11). Much more air would be needed to lift these flocs, yielding the process uneconomical at such a dosage. Hence in the second test run, the alum dosage was lowered to 25.5 mg/L to change the coagulation flocs' size to improve the bubble particle collision efficiency while other conditions, such as coagulation and flocculation time, hydraulic loading rate and saturator operation were kept unchanged.

Figure-13 showed the size distribution of the floated flocs immediately after DAF process. The PSD data were also listed in Table-11.



(a) Differential PSD

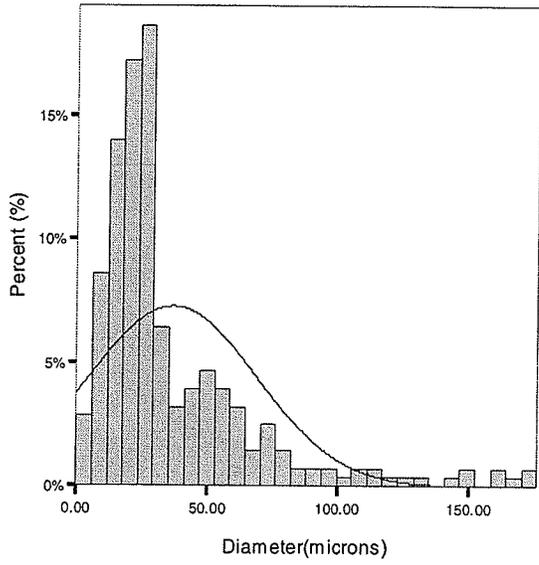


(b) Cumulative PSD

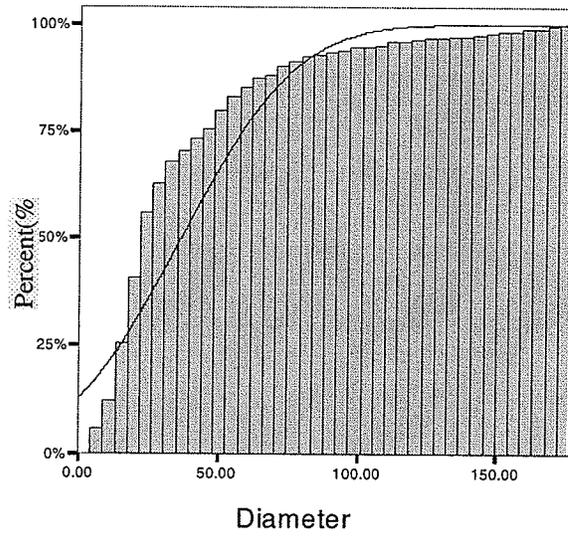
Figure-13 Floated flocs' size distribution
when alum dosage was at 41.7 mg/L

Compared with coagulation flocs, the floated flocs were larger than those before DAF, with mean diameter of 61.78 μm , the minimum of 7.07 μm , and the maximum of 238.23 μm , as was shown in Table-11. Statistical comparison also proved that the difference was significant (Appendix-3). This was probably caused by the additional attachment and aggregation due to the difference in flocs' size and the rise velocity during flotation. As was discussed in the section of Introduction, the rise velocity of the particle-bubble aggregates was mainly dependent on the floc particle sizes when the saturator pressure and recycle ratio were kept unchanged in DAF process. The variety of the floc particle sizes resulted in the difference in both the size of particle-bubble aggregates and their rise velocity. During flotation, these bubble-particle aggregates with different velocities would collide. Such collisions might cause some of the bubble-particle aggregates to attach again and created new larger aggregates. This "secondary flocculation" occurred especially when the difference of the size and rise velocity between the bubble-particle aggregates were significant. When the difference above was not significant, these aggregates would not be formed. This is why the size of the floated flocs (immediately after DAF) was larger than that before DAF, but difference was not very large.

In the second test run, the alum dosage was lowered to 25 mg/L. The size distributions for the floc particles before and after DAF at this dosage were shown in Figure-14 and Figure-15. The statistics summary of the test data was listed in Table-12.



(a) Differential PSD



(b) Cumulative PSD

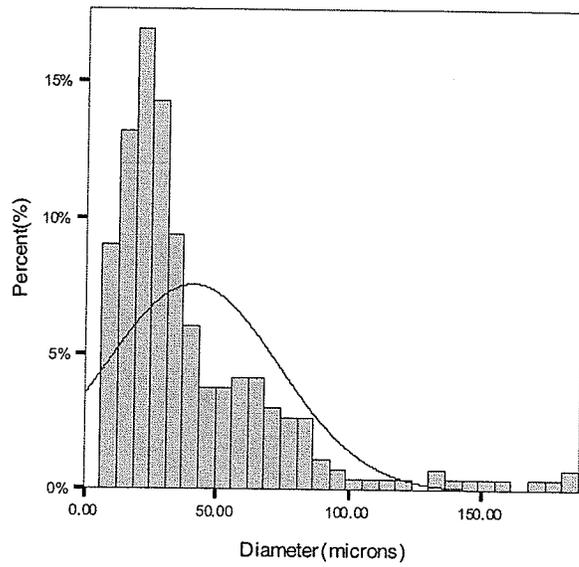
Figure-14 Alum coagulation flocs' size distribution

When alum dosage was at 25.5 mg/L

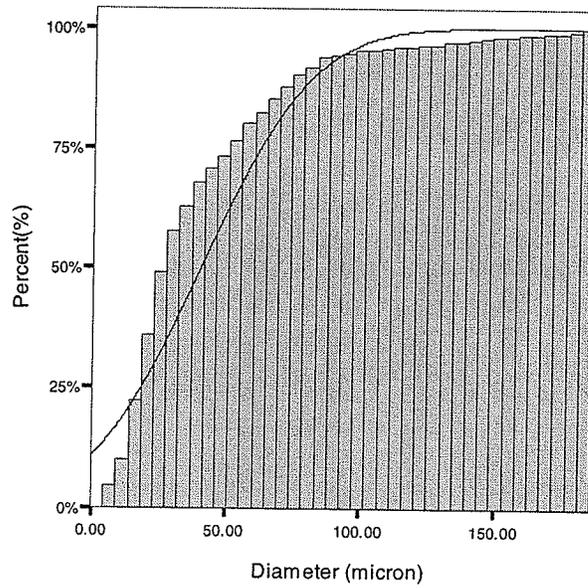
Table-12 Coagulation flocs' and floated flocs' size distribution

when alum dosage was at 25.5 mg/L

Items	Raw water	Coagulation Flocs	Floated Flocs
Mean (μm)	10.99	36.63	40.62
Maximum (μm)	55.37	175.98	185.66
Minimum (μm)	1.32	5.64	6.76
Log mean (μm)	8.80	27.35	31.46
Median (μm)	9.99	24.68	28.65
Mode (μm)	11.16	18.85	21.58
Std Deviation	7.68	32.18	32.75
Percentile 05 (μm)	1.94	7.13	9.90
Percentile 25 (μm)	7.06	17.45	19.80
Percentile 75 (μm)	13.21	47.98	53.32
Percentile 95 (μm)	27.35	111.42	104.48
Percentile 99 (μm)	41.70	169.44	179.73



(a) Differential PSD



(b) Cumulative PSD

Figure-15 Floated flocs' size distribution
when alum dosage was at 25.5 mg/L

Test results indicated that when the alum dosage was lowered to 25.5 mg/L, the turbidity, color, and pH for DAF effluent were almost the same as that when alum dosage of 41.7 mg/L was applied, as was seen from Table-13.

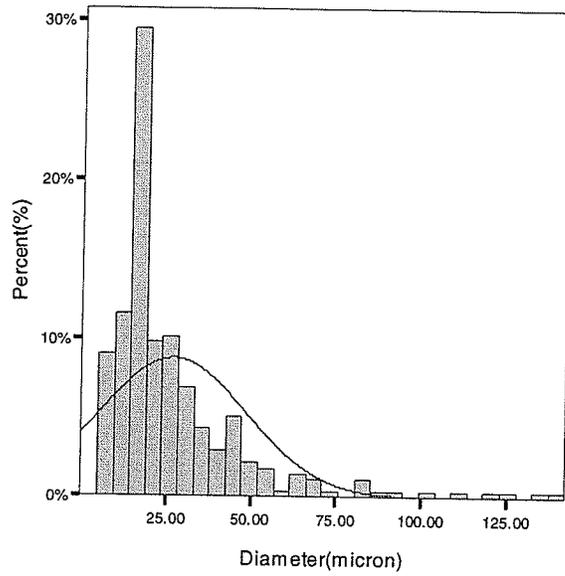
Table-13 DAF effluent quality when alum dosage was at 25.5 mg/L

Items	Tap Water	DAF Effluent 0.5 hr	DAF Effluent 1.0 hr	DAF Effluent 1.5 hr	DAF Effluent 2.0 hr	DAF Effluent 2.5 hr	Effluent Average
Turbidity (NTU)	0.47	0.28	0.27	0.24	0.24	0.25	0.25
Color(TCU)	4.0	3.9	3.8	3.9	3.8	3.8	3.84
pH	7.0	6.7	6.8	6.6	6.5	6.6	6.64

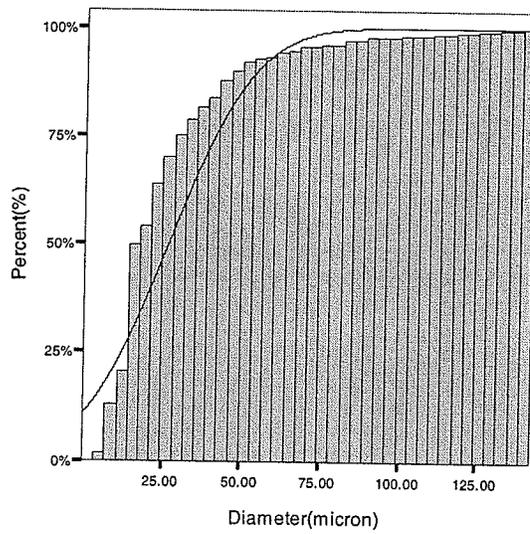
However, the alum flocs' size distribution was quite different. In the alum coagulation flocs, the average equivalent diameter was 36.62 μm , with the maximum of 175.96 μm and the minimum of 5.65 μm , all of which were smaller than those for flocculated particles when alum dosage was 41.7 mg/L. The particles with diameter less than 20 μm accounted for 30.5 %, more than that when alum dosage of 41.7 mg/L was applied. For the floated floc particles, the average equivalent diameter of the flocs was 40.6 μm with maximum of 185.65 μm and minimum of 6.76 μm , and about 26 % of the particles had the diameter less than 20 μm , which meant about 4.5 % of these small particles still remained in the DAF effluent. The actual part would probably be smaller, for some of them might collide and attach to the larger floc-bubble aggregates and were thus removed.

Figure-16 and Figure-17 showed the particle size distribution before and after DAF tank when alum dosage of 15.5 mg/L was applied. The statistical summary of the test data were listed in Table-14.

Test results indicated that when alum dosage of 15.5 mg/L was applied, although the mean size of the coagulation floc particles was 26.82 μm , which fell on the recommended floc size range of 20~30 μm for DAF process, the turbidity of the DAF effluent was at 0.52 NTU, higher than that when alum dosage was 41.7 mg/L and 25.5 mg/L (Table-15). Through analysis of PSD results, it was found that after flocculation, there were about 40.5 % of the particles with diameter less than 20 μm . Such a percentage was much higher than that when alum dosage of 41.7 and 25.5 mg/L were applied. These small particles didn't agglomerate into flocs after coagulation and flocculation. After DAF process, there were about 8.5 percent remain in the water, which resulted in the turbidity increase in the effluent.



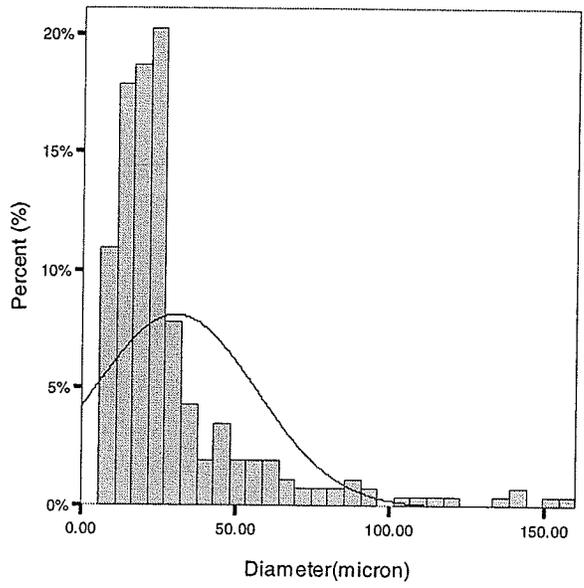
(a) Differential PSD



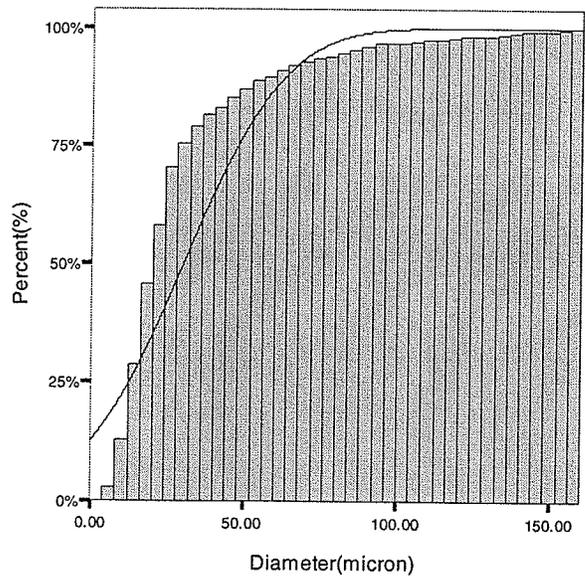
(b) Cumulative PSD

Figure-16 Alum coagulation flocs' size distribution

When alum dosage was at 15.5 mg/L



(a) Differential PSD



(b) Cumulative PSD

Figure-17 Floated flocs' size distribution when alum dosage was at 15.5 mg/L

Table- 14 Coagulation flocs' and floated flocs' size distribution

When alum dosage was at 15.5 mg/L

Items	Raw water	Coagulation flocs	Floated flocs
Mean (μm)	10.99	26.82	30.00
Maximum (μm)	55.37	142.16	160.08
Minimum (μm)	1.32	5.039	7.13
Log mean (μm)	8.80	21.35	23.50
Median (μm)	9.99	19.28	21.96
Mode (μm)	11.16	14.25	15.12
Std Deviation	7.68	21.62	26.29
Percentile 05 (μm)	1.94	7.13	8.73
Percentile 25 (μm)	7.06	14.25	15.12
Percentile 75 (μm)	13.21	32.25	31.47
Percentile 95 (μm)	27.35	70.62	87.60
Percentile 99 (μm)	41.70	128.83	147.72

Table-15 DAF effluent quality when alum dosage at 15.5 mg/L

Items	Tap Water	DAF Effluent 0.5 hr	DAF Effluent 1.0 hr	DAF Effluent 1.5 hr	DAF Effluent 2.0 hr	DAF Effluent 2.5 hr	Average
Turbidity (NTU)	0.47	0.56	0.51	0.49	0.53	0.51	0.52
Color (TCU)	4.0	4.0	3.8	4.1	4.0	4.0	4.0
pH	7.0	6.9	6.8	6.8	6.7	6.7	6.78

5.4 Further discussions

It was demonstrated that coagulation and flocculation controlled the efficiency of DAF process. However, not all the particles in the raw water could be agglomerated by coagulation to reach the sizes fit for DAF treatment. There were always some particles smaller than 20 μm that remained discrete and suspended in water.

Theoretically collisions among the particles and bubbles in the filtration zone in a DAF unit may occur for particles having diameter of at a minimum of 1 μm when the flocculation tank was designed completely on a plug flow basis. In practice, it was very hard to thoroughly remove all these small discrete particles by DAF. A portion of these particles remained in the DAF effluent and directly resulted in the increase of turbidity and color in the effluent.

The PSD results in this study indicated that with increased coagulant dosage, the percentage of the small particles in the coagulated water decreased. However, at the same time, the portion of larger particles increased significantly. The larger particles needed

more air bubbles to be floated and remove them from water, and the bubbles-particle collision efficiency couldn't be optimized.

Test results indicated that when the alum dosage of 25.5 mg/L was applied, although the average size of the floc particles was 36.62 μm , which fell outside the recommended pin-floc size range of 20~30 μm for DAF process, the turbidity and color of the DAF effluent reached 0.25 NTU and less than 3.8 TCU respectively, both of which were significantly lower compared to the raw water. This could be attributed to the reduced amount of particles smaller than 20 μm in the DAF. Further increase in alum dosage showed limited benefit. While at the dosage of 15 mg/L, the mean size of the coagulation flocs was 26.82 μm . Although it fell within the optimum particle size range for DAF process, the number of the small flocs reached 40.5 %, which resulted in higher effluent turbidity and color (Table-16). Hence 25.5 mg/L was regarded as the optimum dosage in this study.

Table-16 Comparison of DAF effluent quality under different coagulant dosages

Alum Dosage [mg/L]	DAF Effluent Turbidity [NTU] (Average)	DAF Effluent Colour [TCU]	% particles smaller than 20 μm in flocculated water	Average particle size in flocculated water (μm)
41.7	0.25	3.8	14.2	54.63
25.5	0.25	3.8	30.5	36.6
15.5	0.52	4.0	40.5	26.82
Raw	0.47	4.0	94	10.99

It is important to note that the velocity gradient (As defined by Cornwell and Boshop, 1983) for the coagulation and flocculation chamber in this study were equal to 240 s^{-1}

and 39.57 s^{-1} respectively, which were lower than that in the pilot study by the City of Winnipeg. The velocity gradient for coagulation and flocculation chamber in the pilot study were reported to be as high as 400 s^{-1} and $60\text{-}80 \text{ s}^{-1}$ respectively. The alum dosage at the pilot study was as high as 60 mg/L under similar temperature conditions. In this study it was shown that higher alum dosage produced larger flocs, which were unnecessary for DAF. The larger flocs needed to be broken into pin-flocs ($20\text{-}30 \mu\text{m}$) under high velocity gradient to achieve better treatment efficiency, which was the case for the pilot study. This would result in higher chemicals and increased power cost thus necessary for effective treatment of the raw water.

Due to lower flocculation intensity, it was possible to apply lower coagulant dosage of 25.5 mg/L successfully for the experiment. Lowering the flocculation mixing intensity allowed for the reduction of the coagulant dosage in DAF process. This may be especially important for cold water DAF process operations where significantly more coagulant had to be used, according to the pilot study by the City of Winnipeg.

The experimental result in this study showed that the flocs floated to the surface of the water were larger than those in the flocculated water entering the DAF unit. The difference between them was significant but not large (to see appendix-3). This was probably due to the difference in size and rise velocity of the flocs in the flocculated water entering the DAF unit, further attachments and aggregation are possible. Such a "secondary flocculation" occurs especially when the difference of the size and rising velocity are significant. Because of this, more compact solids (sludge) with increased size could be expected from the DAF process.

6. Summary and Conclusions

Winnipeg tap water was tested in the bench-scale dissolved air flotation (DAF) unit in spring 2004. The following are the most important conclusions:

1. Effectiveness of DAF process depended not only on the average size of the flocs, but also on their size distribution, especially percentage of particles smaller than 20 μm ;
2. In the bench-scale DAF treatment process of Winnipeg tap water, 25.5 mg/L of alum was the optimum dosage. At this dosage, about 30.5 % of the coagulation flocs were smaller than 20 μm . These small particles couldn't be completely removed by DAF, the residual of which resulted in the effluent turbidity and color.
3. Lower dosage of alum produced too many small particles. While higher dosage resulted in much less of smaller particles, it didn't show improved effluent quality, and needed more air for the process.
4. Due to the difference in the size and rise velocity of the flocs in the water entering the DAF unit, further collision and agglomeration occurred during the flotation, which made the floated flocs more compact with increased size.
5. Comparison of the laboratory study with the pilot study by the City of Winnipeg indicated that the velocity gradient in the flocculation tank was lower in our study (40 s^{-1}). This allowed for lowering optimum coagulation dosage by about 35 mg/L as compared to the city's studies under cool water

conditions. This result suggested that lowering mixing intensity in winter time might allow for reduction in coagulant.

7. Recommendations for Future Work

The PSD test is a valuable analytical tool for evaluating the efficiency of treatment processes. However, the PSD results can be affected by many factors. In the coagulation/flocculation units, the size of flocs may vary with the types and dosage of the coagulants, coagulation /flocculation time, as well as the mixing speed and intensity, the velocity gradient G and temperature in flocculation tank. In DAF unit, the flocs may probably vary with different hydraulic loading rates, recycling ratios, and saturator pressures. This study was mainly focused on the PSD variation through coagulation/ flocculation, and DAF process under different alum dosages while keeping all the parameters unchanged. More work needs to be done to investigate the PSD variation in the processes under different operating conditions. If possible, the tests combined with further filtration units should be done to get more complete data.

8. References

- Adamson, A. W. 1990. *Physical Chemistry of Surfaces*. 5th edition. New York: Wiley-Interscience Inc.
- Camp, T. R. 1968. Floc volume conception. *Journal AWWA*, 60: 656-673
- Cornwell, D. A. and M. B. Boshop. 1983. Determining velocity gradients in laboratory and full-scale systems. *Journal AWWA* 75(9): 470-475
- Edzwald, J. K and J. P. Walsh. 1991. Particulate removal by dissolved air flotation: Laboratory and pilot- plant investigations. *A Report prepared for AWWARF*, Denver, Colorado, U.S.A.
- Edzwald, J. K. 1992. Algae, bubbles, coagulation and air flotation. *Symposium: Separation of Particles from Water*. University College, London, England
- Edzwald, J. K., J. P. Walsh, G. S. Kaminski, and H. J. Dunn. 1992. Flocculation and air requirements for dissolved air flotation. *Journal AWWA* 84(2): 93-100
- Edzwald, J. K. 1995. Principles and applications of dissolved air flotation. *Water Science & Technology* 31 (3):1-23
- Fernandes, B. 2003. Jar test report for Oxford House. Winnipeg, MB. BCA Ltd.
- Gochin, R J. and J. Solari. 1983. The role of hydrophobicity in dissolved air flotation. *Water Resources*. 17: 651-657
- Gorczyca, B. and D. London. 2003. Characterization of particles in slow sand filtration at North Caribou water treatment plant. *Environmental Technology* 24: 831-845
- Gorczyca, B. and J. Ganczarczyk. 1996. Image analysis of alum coagulated mineral suspensions. *Environmental Technology* 17:1361-1369
- Haarboff, J. and L. V. Vuuren. 1995. Design parameters for dissolved air flotation in South Africa. *Water Science and Technology* 31: 3-4
- Hall, T., J. Pressdce, R. Gregory and K. Murray. 1995. Cryptosporidium removal during water treatment using dissolved air flotation. *Water Science and Technology* 31(4): 125-129
- Han, M. Y., W. T. Kim, and S. Dockko. 2000. Collision efficiency factor of bubble and particle in DAF: theory and experimental verification. *Proceedings of the 4th International Conference Flotation in Water and Wastewater Treatment*. Helsinki, Finland

- Han, M. Y. and Y. H. Park. 2000. Bubble size measurement in dissolved air flotation. *Proceedings United Conference of KSWW and KSWQ for the year 2000*. Taejeon, Korea
- Hatukai, S., Y. Ben-Tzur, and M. Rebhun. 1997. Particle counts and size distribution in system design for removal of turbidity by granular deep bed filtration. *Water Science and Technology* 36(4): 225-230
- Federal Provincial Subcommittee on drinking water of the federal provincial territorial committee on environmental and occupational health. 2001. *Guidelines for Canadian Drinking Water Quality*
- Jodlowski, A. 2001. Effect of pre-ozonation and coagulation treatment on particle-size distribution of algal agglomeration. *Environmental Protection Engineering* 27(3): 59-71
- Kaminski, G. S., H. J. Dune, and J. K. Edzwald. 1991. Comparison of dissolved air flotation to other high rate clarification methods. *Proceedings of Water Research for the New Decade*. AWWA, 345-365. Philadelphia, Pennsylvania
- Kaminiski, I., N. Vescan, and A. Adin. Particle size distribution and wastewater filter performance. *Water Science and Technology* 36(4): 217-224
- Kerker, M. 1969. The scattering of light and other electromagnetic radiation. *Academic Press* New York, USA
- Kitchener, J. A. and R. J. Gochin. 1981. The mechanism of dissolved air flotation for potable water: basic analysis and a proposal. *Water Resources* 15: 585-590
- Kitchener, J. A. 1984. The froth flotation process: past, present, and the future- in brief. *The Scientific Basis of Flotation*, Ed. K. J. Ives. NATO ASI Series, Martinus Nijhoff, Boston, USA. Pp. 3-51
- Lawler, D. F. 1997. Particles size distribution in treatment processes: theory and practice. *Water Science and Technology* 36(4): 15-23
- Lawler, D. F., E. Izurieta, and C. P. Kao. 1983. Changes in particle size distributions in batch flocculation. *Journal AWWA* 75(12): 604-612
- Lawler, D. F., C. R. O'Melia, and J. E. Tobiason. 1980. *Integral Water Treatment Plant Design: from particle size to plant performance*. New York. McGraw-Hill
- Li, D. H. and J. J. Ganczarczyk. 1986. Application of image analysis system for study of activated sludge flocs. *Water Pollution Resource Journal* 31: 130-140
- Longhurst, S. J. and N. J. D. Graham. 1987. Dissolved air flotation for potable water treatment: a survey of operational units in Great Britain. *Public Health Engineer* 14(6): 71-76

Park, Y., M. Han, D. Kwak, and C. Park. 2002. Effect of particle and bubble size on the removal efficiency in DAF. School of Civil, Urban & Geo-system Engineering, Seoul National University, Korea

Parker, D. S. 1972. Characteristics of biological flocs in turbulent regimes. *Serl Report* No. 70-5. University of California, Berkeley, U.S.A.

Pernitsky, D., K. Kjartanson, D. Drohomerski, P. Wobma, M. Adkins, and S. Quiigley. 1996. The Winnipeg water treatment pilot plant paving the way to the future. *Proceedings of the 48th Annual Conference of the Western Canada Water and Wastewater Association*, Regina, SK.163-172

Plummer, J. D., J. K. Edzwald, and M. B. Kelly. 1996. Removal of Cryptosporidium from drinking water by dissolved air flotation. *Journal AWWA* 87(9): 85-95

Sawyer, C. N. /McCary, P. C. /Parkin, G. F. 1994. *Chemistry for Environmental Engineering*. 4th edition. New York: McGraw-Hill Inc.

Schers, G. J.. 1991. Flootation, theory and practice. *Graduation Thesis*. Department of Civil Engineering, Technical University Delft

Sulman, H. L., H. F. K.Picard, and J. Ballot. 1905. US Patent835439. May 29th, 1905
Takahashi, T., T. Miyhara, and H. Mochizuki.1979. Fundamental study of bubble formation in dissolved air flotation . *Chemical Engineering* , 12: 275-280

USEPA. 1998. National primary drinking water regulations: Interim enhanced surface water treatment; final rule, part V. EPA., 40 CFR Parts 9, 141, 142. *Federal Regulations*. 63:24:69478

USEPA. 1998. National primary drinking water regulations: Disinfectants and disinfection by-products; final rule, part IV. EPA.,40 CFR Parts 9, 141, 142. *Federal Regulations* 63:241:69390

Walker, W. W. 1983. Significance of eutrophication in water supply reservoirs. *Journal AWWA* 75(1): 38-42

Wardlaw, V. E., R. Perry, and N. J. D. Gramham. 1991. The role of algae as trihalomethane precursors- a review. *Water SRT-Aqua*. 40(6): 335-345

Wiesner, M. R. and P. Mazounie. 1989. Raw water characteristics and the selection of treatment configurations for particle removal. *Journal AWWA*, 81(5):80-88

Winnipeg Water Consortium.1998. Final report: City of Winnipeg water treatment plant phase two pilot program. Winnipeg, Manitoba: Water and Wastewater Department

Winnipeg Water Consortium. 2001. drinking water quality enhancement program- executive summary and summary report. Winnipeg, Manitoba: Water and Wastewater Department

Winnipeg Water Consortium. 2002. Phase III conceptual design summary report. Winnipeg, Manitoba: Water and Wastewater Department

Wobma, P., K. Kjartanson, B. Bellamy, and D. Pernitsky. 1995. Dissolved air flotation versus direct filtration for a low turbidity, high algae surface water. *Proceedings 1995 AWWA Water Quality Technology Conference*, New Orleans, LA, 1243-1268

Wobma, P., K. Kjartanson, B. Bellamy, and D. Pernitsky. 1999. Effects of cold water temperature on water treatment unit process. The City of Winnipeg, Manitoba

Wortel, N. C. 1991. Flotation in the Netherlands. *Research Paper, KIWA*, Nieuwegein. McGraw-Hill Inc. New York, U.S.A.

Appendixes

Appendix-1 Significance of the difference in particle size for the raw water from Oxford Lake as measured by Bioquant95 Classic and by image Pro Plus system

The statistical comparison is made according to the following equation:

$$\mu_1 - \mu_2 = \pm t^*s / [(N_1 N_2 / (N_1 + N_2))]^{1/2}$$

Where:

μ_1 and μ_2 are means of different sets of test data;

N_1 and N_2 are number of cases;

s is standard deviation for tests;

t is obtained from t table using $(N_1 + N_2 - 2)$ degrees of freedom, and normally at 95% confidence level.

If the results of computation using the right side of the equation are greater than the left side of the equation, then it can be judged that the differences between the two values are not significant. If larger, then the difference is judged significant.

For the city water in Winnipeg and the raw water from Oxford Lake:

$$\mu_1 = 11.52 \quad s_1 = 8.64 \quad N_1 = 556$$

$$\mu_2 = 11.26 \quad s_2 = 7.07 \quad N_2 = 430 \quad s = (s_1 + s_2) / 2 = (8.64 + 7.07) / 2 = 7.855$$

$$\mu_1 - \mu_2 = 11.52 - 11.26 = 0.26$$

$$t^*s / [(N_1 N_2 / (N_1 + N_2))]^{1/2}$$

$$= t(556 + 430 - 2) * 7.855 / [556 * 430 / (556 + 430)]^{1/2}$$

$$= 1.645 * 7.855 / 15.57$$

$$= 0.83 > 0.26$$

$$\text{or: } \mu_1 - \mu_2 < t^*s / [(N_1 N_2 / (N_1 + N_2))^{1/2}]$$

Hence, it can be concluded that the particle size for the raw water from Oxford Lake as measured with Biquant95 classic and measured with Image Pro Plus are not significantly different at 95% confidence level.

Appendix-2 Significance of the difference in average particle size between the city water in Winnipeg and the raw water from Oxford Lake

$$\mu_1=11.52 \quad s_1=8.64 \quad N_1=556$$

$$\mu_2=10.99 \quad s_2=7.68 \quad N_2=924 \quad s = (s_1+s_2)/2 = (8.64+7.68)/2 = 8.16$$

$$\mu_1 - \mu_2 = 11.52 - 10.99 = 0.53$$

$$t^*s / [(N_1N_2 / (N_1+N_2))^{1/2}$$

$$= t(556+924-2)*8.16 / [556*924/(556+924)]^{1/2}$$

$$= 1.645*8.16/18.63$$

$$= 0.72 > 0.53$$

$$\text{or: } \mu_1 - \mu_2 < t^*s / [(N_1N_2 / (N_1+N_2))^{1/2}$$

Hence, we conclude that, the difference between the two sets of data for the water from the Oxford Lake and the city water in Winnipeg is not significant at 95% confidence level.

Appendix-3 Significance of the difference in average size between alum coagulation flocs and floated flocs

(1) When alum dosage is at 41.7mg/L

$$\mu_1=61.78 \quad s_1=45.67 \quad N_1=235$$

$$\mu_2=54.63 \quad s_2=33.01 \quad N_2=272 \quad s = (s_1+s_2)/2 = (45.67+33.01)/2 = 39.24$$

$$\mu_1 - \mu_2 = 61.78 - 54.63 = 7.15$$

$$t*s/[(N_1N_2)/(N_1+N_2)]^{1/2} = t(235+272-2)*39.24/ [235*272/(235+272)]^{1/2}$$

$$= 1.645*39.24/11.23$$

$$= 5.74$$

$$<9.0$$

Hence, the difference in average size between alum coagulation flocs and the floated flocs when alum dosage is at 41.7 mg/L is significant at 95% confidence level.

(2) When alum dosage is at 25.5mg/L

$$\mu_1=41.30 \quad s_1=32.75 \quad N_1=266$$

$$\mu_2=36.62 \quad s_2=32.18 \quad N_2=279 \quad s = (s_1+s_2)/2 = (32.75+32.18)/2 = 32.465$$

$$\mu_1 - \mu_2 = 41.30 - 36.62 = 4.68$$

$$t*s/[(N_1N_2)/(N_1+N_2)]^{1/2} = t(266+279-2)*32.465* [266*279/(266+279)]^{1/2}$$

$$= 1.645*32.465/11.67$$

$$= 4.58$$

$$<4.68$$

Hence, the difference in average size between alum coagulation flocs and the floated flocs when alum dosage is at 25.5 mg/L is significant at 95% confidence level.

(3) When alum dosage is at 15.5mg/L

$$\mu_1=30.00 \quad s_1=26.29 \quad N_1=258$$

$$\mu_2=26.62 \quad s_2=21.62 \quad N_2=278 \quad s = (s_1+s_2)/2 = (26.29+21.62)/2 = 23.955$$

$$\mu_1 - \mu_2 = 30.00 - 26.29 = 3.71$$

$$t \cdot s / [(N_1 N_2 / (N_1 + N_2))]^{1/2} = t(258+278) \cdot 23.955 \cdot [258 \cdot 278 / (258+278)]^{1/2}$$

$$= 1.645 \cdot 23.955 / 11.57$$

$$= 3.41$$

$$< 3.71$$

Hence, the difference in average size between alum coagulation flocs and the floated flocs when alum dosage is at 15.5 mg/L is significant at 95% confidence level.

Appendix-4 Specification of the heavy duty diaphragm-type injector metering pump

HEAVY DUTY DIAPHRAGM-TYPE INJECTOR METERING PUMPS

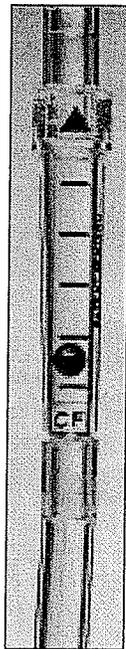
FPUDT1500 Series

\$299

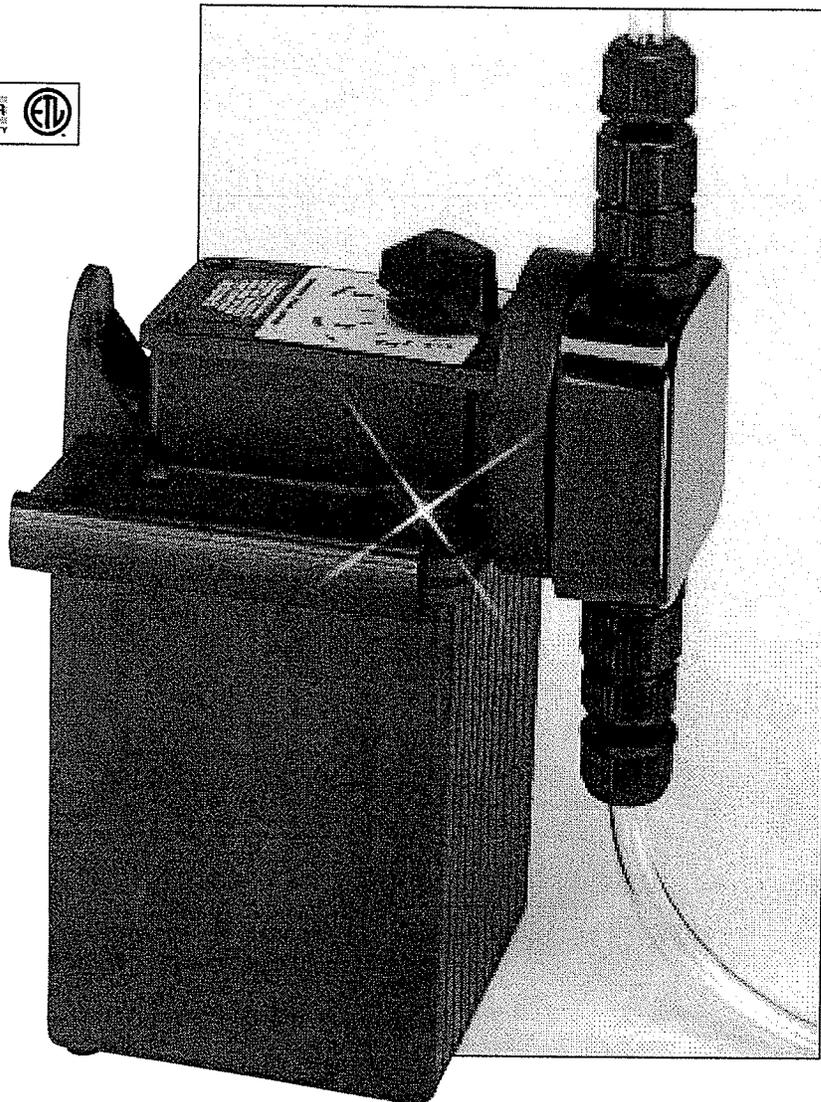
Basic Unit



- ✓ Single Intake and Discharge
- ✓ Check Valve Design
- ✓ Quick Adjusting Feed Mechanism
- ✓ Heavy-Duty Cartridge Pumphead
- ✓ Teflon®/EPDM Diaphragm
- ✓ Optional Timer Available
- ✓ Supplied with Flow Indicator and 7.5 m (25') of Tubing
- ✓ Can be Wall- or Shelf-Mounted
- ✓ 100% Duty Cycle



Comes with handy flow indicator. Additional pump accessories available in this section.



The FPUDT1500 Series injector pumps feature a heavy-duty cartridge valve pumphead made of injection-molded polypropylene. The pump includes double-sealed PVDF cartridge valve fittings, Viton® O-ring seals, ceramic ball checks, Hastelloy C valve springs, and a Teflon®/EPDM diaphragm. Units with the optional built-in electronic percentage timer allow the user to adjust the feed rate with just the timer or to adjust both the stroke of the diaphragm and the timer for precise feed control. The pump can also be purchased as part of a tank system.

MOST POPULAR MODELS HIGHLIGHTED!

To Order (Specify Model No.)					
Model No.	Price	Max. GPD	Max. mL/Min	Strokes/min	Max. psi
FPUDT1501	\$308	8.3	22	14	125
FPUDT1502	308	12.9	34	14	125
FPUDT1503*	299	17.4	46	30	125
FPUDT1504*	299	31.0	82	30	125
FPUDT1505*	299	29.2	77	45	125
FPUDT1506*	299	49.0	129	45	125
FPUDT1507*	299	34.9	92	60	125
FPUDT1508*	299	60.0	158	60	125
FPUDT1509*	299	68.4	180	125	125
FPUDT1510*	299	119.7	315	125	70

Comes with fittings, adaptors, flow indicator, 1.5 m (5') each of polyethylene and vinyl tubing, and complete operator's manual.

*Available with built-in dual control stroke and 5 second cycle timer. To order, add suffix "-D" to model number and \$38 to price.

For 230 V/60 Hz voltage, add suffix "-230V60" to model number and add \$10 to price.

For 220 V/50 Hz voltage, add suffix "-220V50" to model number and add \$10 to price.

For 24 V/60 Hz voltage, add suffix "-24V60" to model number and add \$10 to price.

Ordering Example: FPUDT1506-D, pump with 45 RPM, 49.0 max. GPD, 129 max. mL/min range, and optional timer, \$299 + 38 = \$337.

SPECIFICATIONS

Pumphead Material: Standard polypropylene; acrylic optional

Diaphragm Material: Teflon®/EP standard; Teflon®/Viton®, ethylene propylene, Viton® optional

O-Ring Material: Viton® standard, EP, silicone optional

Cartridge Body Material: PVDF

Motors: 14, 30, 45, 60, 125 RPM

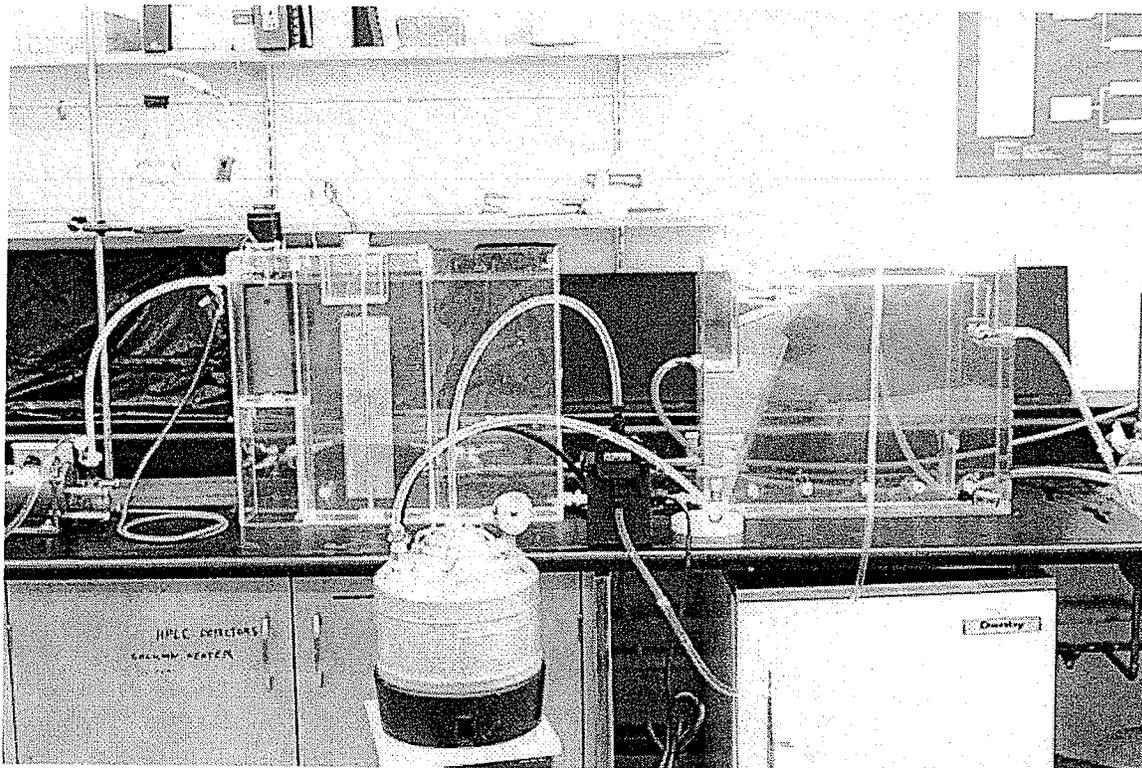
Voltage: 115 V, 60 Hz, optional 230 V/60 Hz, 220 V/50 Hz, 24 V/60 Hz

Dimensions: 127 H x 140 W x 238 mm D (5 x 5.5 x 9.4")

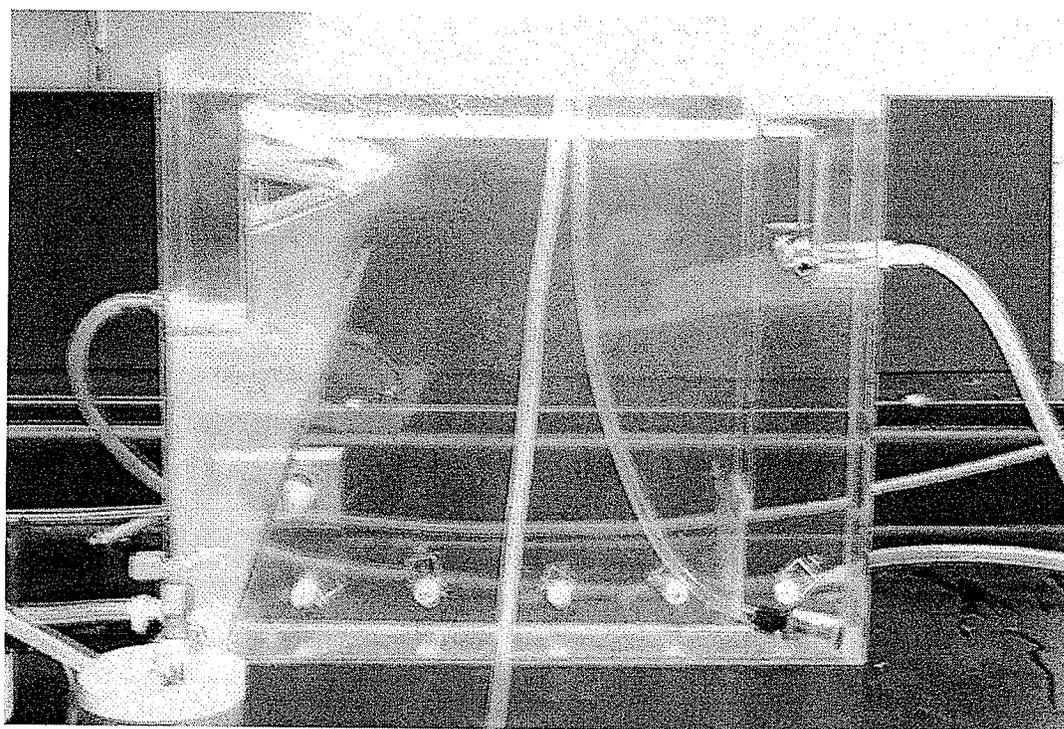
Shipping Wt.: 4.5 kg (10 lb)

Tube Dimensions: 3/8" O.D., 1/4" I.D.

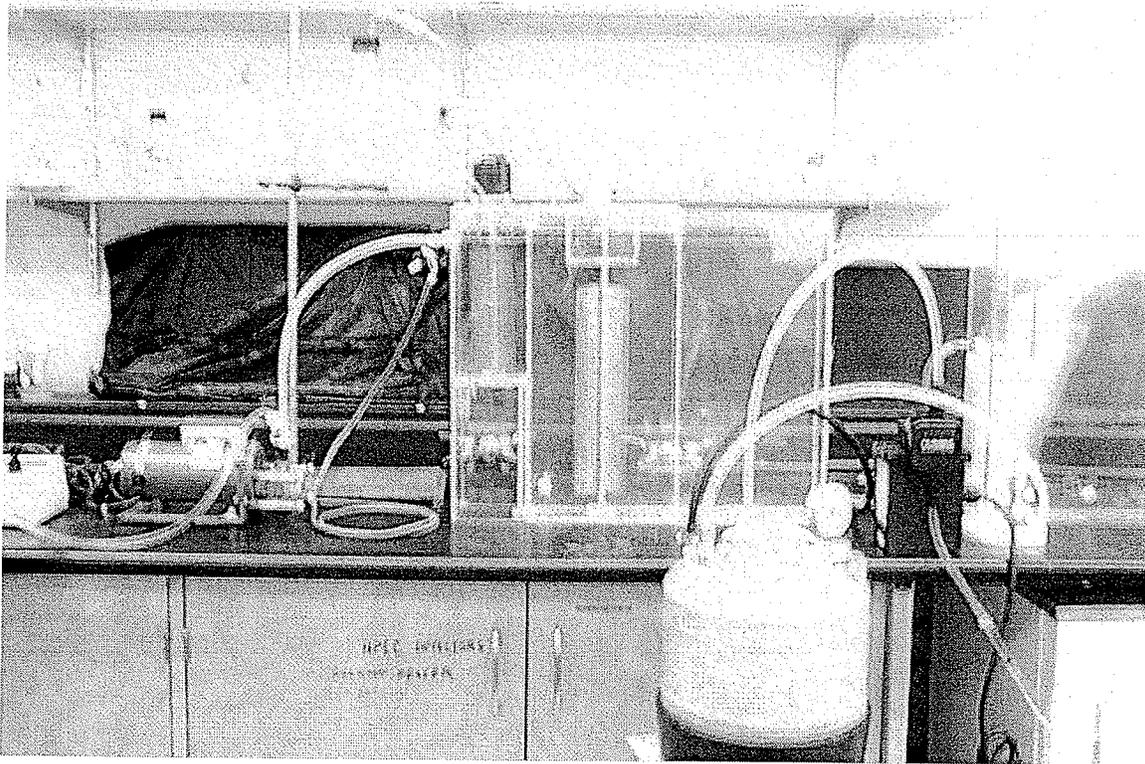
Appendix-5 Experiment appliance photographs



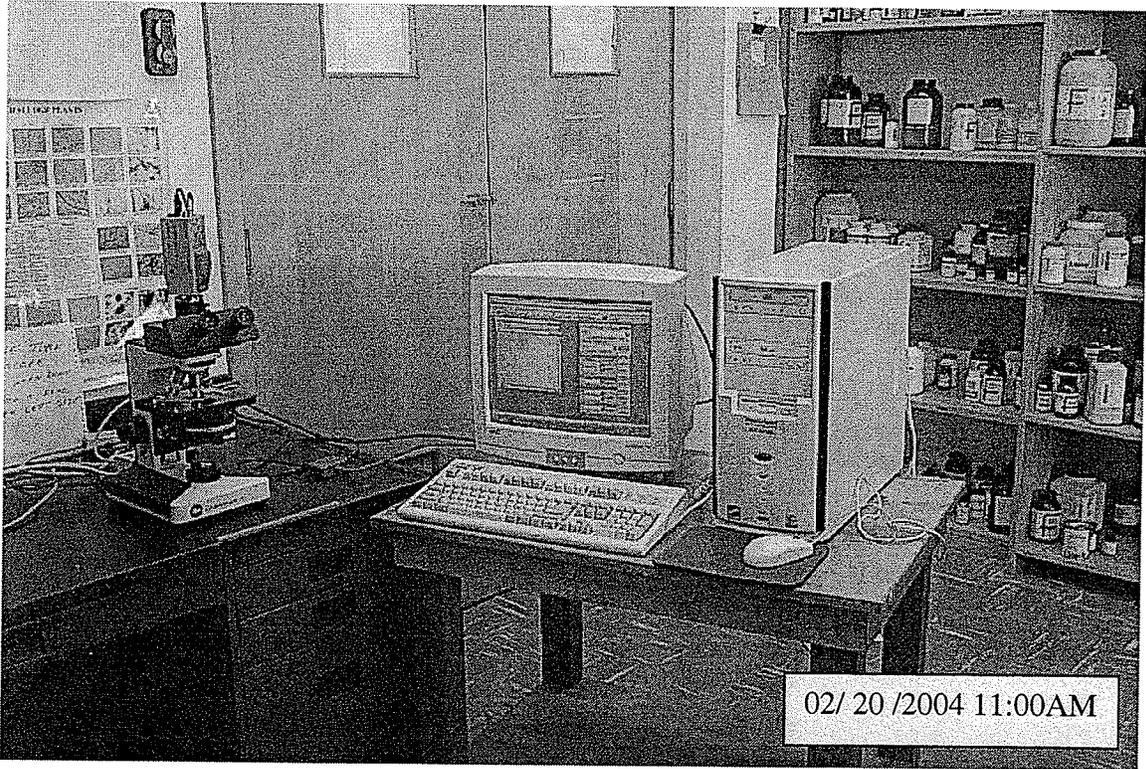
The Whole DAF Test Appliance



DAF Unit (tank)



Saturator and Diagram Pump



Microscope and digital image analysis system