TO MY PARENTS

ΣΤΟΥΣ ΓΟΝΕΙΣ ΜΟΥ

A STUDY
OF BUBBLE GENERATION AND HYDRODYNAMICS
IN DISSOLVED AIR FLOTATION

BY

KONSTANTINOS REPANAS

THESIS SUBMITTED FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY
IN
DEPARTMENT OF CHEMICAL AND PROCESS ENGINEERING
FACULTY OF ENGINEERING
UNIVERSITY OF NEWCASTLE UPON TYNE
U.K.

MAY 1992

ABSTRACT

In Dissolved Air Flotation the performance of the saturator and subsequent release of the air from the solution is important. In particular the bubble size, the degree of saturation and the hydrodynamic bubble movement are important physical parameters. In this study all these have been investigated.

The factors affecting the bubble size when gas is released from a supersaturated solution and the performance of two types of absorbers a conventional packed column and a Higee Absorber were examined. The size of the bubbles generated from a nozzle have been measured in tap water at different operation conditions of liquid flowrate, gas flowrate and pressure.

The bubble size was measured using a photographic technique and found to decrease with increasing the gas pressure in the conventional saturator, but it was not possible to observe the small bubbles generated using the Higee Technique. For the conventional device, the liquid flowrate had a significant role whereby the bubble diameter fell with flowrate. Bubble uniformity increased as both pressure and liquid throughput increased.

The saturation performance of the two kinds of absorbers were examined. In all the cases, the Higee technique operate better as far the saturation level was concerned. The degree of saturation in the Higee systems was found to be a strong function

of both gas and liquid flowrates as well as the rotational speed (which governs the gas pressure).

Finally, as it may be possible to distribute the saturated solutions and (any bubbles formed) more uniformly throughout flotation tanks if Higee saturators are used, a computer package was adopted to provide enough data for the simulation of the flow patterns in flotation tanks.

ACKNOWLEDGEMENTS

CONTENTS

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

8.0 REFERENCES

CHAPTER 9

APPENDICES

CHAPTER 1

1.0 INTRODUCTION

1.1 DISSOLVED AIR FLOTATION

The earliest attempt recorded using flotation as a separation method involved a British patent in 1860 (RAMIREZ E.R., 1976). This process involves the addition of oil to wastewater where the lighter density of the oil surfaced impurities in the water itself. Since then, significant efforts were carried out to improve the efficiency and the productivity of the "adsorptive bubble separation techniques".

More recently, Dissolved-Air Flotation has become accepted, in particular in the Scandinavian countries and the United Kingdom with more than 50 plants in operation or under construction. The largest dissolved-air flotation plant currently being constructed in the UK is the $315m^3$/day Frankley water treatment works (ZABEL T.F., 1980). Dissolved-air flotation has been specifically developed for the treatment of algal laden and waters. The flocs produced by the treatment of these waters have a low settling velocity, particularly when the water temperature is low, even when polyelectrolytes are added. Treating these waters by flotation requires smaller tanks and produces better

1

treated water quality compared to sedimentation. (BURFITT M. 1975)

There is also an increasing demand for the development and the improvement of techniques in the metallurgical industries which aim to recover metal at relatively high efficiencies and combines the lowest possible demands for energy consumption. The use of rising bubbles as a separation technique is continuously being explored because of the simplicity of the installation and the relatively low running cost. Flotation can play a very important role as: a) you can achieve quantitatively almost total removal of the metals and b) because of its ability to concentrate minerals.

Over the last few years with the increasing awareness of the need to protect the environment, recycling is now a necessary process in which flotation can make a significant contribution and simultaneously decrease the running costs. In wastewater treatment, the problem of recovery or recycling of sub-products continuously challenges us to discover more efficient environmentally friendly methods.

In all the above techniques, the dominant variables are bubble size and rise velocities. These are inextricable connected by the hydrodynamics of the system and it is this area which demands an in-depth study.

1.2 PURPOSE OF THE PRESENT WORK

The broad objective is to look at techniques of producing finely divided gas bubbles by dissolved air flotation.

With the "conventional" dissolved air flotation devices the saturated stream of water is introduced through a restricted nozzle at a high velocity. This will substantially affect the hydrodynamics of the system which interferes with the structure of the fragile flocs if they are present in the solution.

However, Higee Devices are used lately in the field of process intensification, particular for gas/liquid contacting. The basic idea is the application of very big accelerations to the countercurrent flow of gases and liquids in a reticulated torus. In this way fine bubbles are generated and also gases with a very low solubility can absorbed easily into a liquid. (BALASUNDARAM V. & PORTER J.E., 1990).

As Higee techniques can handle more throughput it should be possible to hydrodynamically design the system to produce considerably less turbulence in the flotation tank. For this reason part of the study, is to investigate the hydrodynamic regimes in a tank.

1.3 SCOPE OF THE PRESENT WORK

The scope of this work was to compare the performance of these two techniques. In order to do this, comparison must be made between the bubble sizes which are produced, secondly between the number density of bubbles in the solution and finally between the amount of O_2/N_2 evolved.

Suitable experimental equipment was designed and constructed. As the bubbles size plays an important role in the efficiency of the flotation, a photographic technique, was developed which helped to measure the diameter of the generated bubbles. A device was constructed to measure the quantity of the precipitate air and this was connected in parallel to the main flotation circuit of both the system used.

Finally the hydrodynamics in the laboratory tank was simulated using a computing package "FLUENT". This defined the movement of the bubbles in the tank, thus providing the design criteria necessary for the construction of a system using Higee technology.

1.4 STRUCTURE OF THE THESIS

The ultimate object of this work is to improve the flotation process, thus it is essential to provide a general background on the present technology and this is done in Chapter 2

which surveys the types of the processes and the theoretical mechanisms by which bubbles-particles interact.

The experimental work recorded in this report concentrates on bubble formation and mass transfer thus chapter 3 reflects this by surveying the literature and techniques of characterising bubble processing. Chapter 4 describes the apparatus and measurement techniques on two kinds of saturators. The first one was the conventional packing saturator and a single nozzle was used as a gas distributor, while the second one was a Higee rotating packing absorber. The scope of this investigation was to compare in Chapter 5 the efficiencies of the two arrangements. Also in the same chapter briefly, a model is described for the hydrodynamics of the conventional system.

CHAPTER 2

2.0 LITERATURE SURVEY OF FLOTATION PROCESSES

2.1. TYPES OF FLOTATION TECHNIQUES

Flotation can be described as a gravity separation process in which gas bubbles attach to solid particles to cause the apparent density of the bubble-solid agglomerates to be less than that of the water allowing the agglomerates to float to the surface.

This work is primarily concerned with dissolved air flotation, thus this technique is described in detail. However in order to provide a comparison, other techniques are briefly referred to.

The different methods of producing the gas bubbles give rise to different types of flotation processes which are *electrolytic flotation, dispersed-air flotation, and dissolved-air flotation* (ZABEL F.T., 1980).

2.1.1 Electrolytic flotation

The basis of electrolytic or electro-flotation is the generation of bubbles of hydrogen and oxygen in a dilute aqueous

6

solution by passing a direct current between two electrodes (K.L. SUTHERLAND, 1955).

The process has the disadvantage that the electrodes need periodic replacement and fouling of the electrodes is also a frequent problem. One advantage however is that the bubble formation does not create turbulence, therefore this system is attractive for the removal of fragile flocs.

The bubble size generated in electro-flotation is very small, (45-180μm) and the surface loading is therefore restricted to less than $4m^3/h$ compared with up to $12m^3/h$ for dissolved air flotation.(E. RAMIREZ, 1976)

The application of electro-flotation has been restricted mainly to sludge thickening and small effluent treatment plants, ($4-5m^3/h$). The process has been reported to be suitable for very small water treatment installations (KLASSEN,V.I., 1963)

2.1.2 Dispersed-air   flotation

For this technique the stream of the air is introduced into the solution through a dispersion system which usually is a porous diaphragm made of either sintered glass, ceramic or other appropriate material. The air pressure depends on the hydrostatic head of the liquid above the distributor. This category is used in techniques for the enrichment of ores, where the air is introduced

7

with the help of a stirrer which both disperses and breaks up the bubbles. (K. MATIS 1977)

As described in 2.2.2, a large number of separation techniques using aDsorbed bubbles are not suitable for water treatment applications because either the bubble size tends to be large (>1mm, compared to 30-110μm for dissolved-air flotation and 45-180μm for electro-flotation) or the high turbulence (ore flotation) breaks up the fragile flocs formed during the chemical pretreatment, or undesirable chemicals (molecular flotation, ion flotation) are required to produce the air bubbles.

2.1.3 Dissolved-air flotation

In dissolved-air flotation the bubbles are produced by the reduction in pressure of a water stream pre-saturated with air at a higher pressure. The three main types of dissolved-air flotation are vacuum-flotation, micro-flotation and pressure flotation. (K.MATIS,1979)

Vacuum flotation

In vacuum flotation the water to be treated is saturated with air at atmospheric pressure. A vacuum is then applied to the flotation tank releasing the air as small bubbles (30-90μm). The amount of air available for the flotation is limited by the achievable vacuum. This process is being applied only in the paper

industry for the recovery of fibres. Vacuum-flotation has three main disadvantages: a)it is a batch process, b)it requires sophisticated equipment to maintain the vacuum, c)the amount of air available is limited by the vacuum. The main advantage of this technique is that fine bubbles are formed without the addition of any chemicals which might affect the composition of the solution. (ZABEL T.F.,1980)

Microflotation

The so-called microflotation is an efficient process for removing colloidal pollutants from water. It uses the same principles as vacuum flotation but is generally carried out in laboratory size units. The technique was first introduced in 1965 by Rubin and Cassel. The main difference from other flotation techniques is that microflotation requires very low gas flow rates, extremely small bubbles (40μm) and heterocoagulation of the colloidal dispersions with a hydrous metal oxide. Due to small bubbles and a low flow rates, a relatively large gas/liquid interfacial area per unit of gas flow rate is produced with no severe agitation.

Pressure flotation

Pressure flotation is currently the most widely used dissolved-air flotation process. In pressure flotation air is dissolved in water under pressure and released at the hydrostatic pressure of the tank.

Three basic pressure dissolved-air flotation processes can be used: full-flow pressure flotation, split-flow pressure flotation and recycle-flow pressure flotation (See Fig.1). Each operate under the same basic principle whereby saturated pressurized water is introduced to the flotation tank through a pressure release device and mixed with the flocculated water. In the pressure release device the pressure is reduced to the hydrostatic pressure so releasing the air in the form of fine bubbles (20-100µm). The air bubbles attach themselves to the flocs and the agglomerates float to the surface. The float can be removed from the surface and the clarified water is taken from the bottom of the flotation tank.

In full-flow pressure flotation, the entire influent is pressurized and aerated. In split-flow pressure flotation, a fraction of the influent is subjected to pressurization, while the remainder flows directly to flocculation-flotation tank. This flow scheme offers a cost saving over full-flow pressure flotation, since the saturator and the feed pump only handle a portion of the total flow and therefore smaller units are required. However, as less air is provided in the split-flow system, this process has to operate at higher pressure in order to provide the same amount of air.

For water treatment applications, requiring the removal of fragile flocs, both the above systems are not suitable because any floc formed prior to the air release device would be destroyed by the high shear experienced during the pressure

release. For this application recycle-flow pressure flotation is the most appropriate system.

In recycle-flow pressure flotation, the whole influent flows directly to the flocculation tank or to the flotation tank if separate flocculation is not required. Part of the clarified effluent is recycled, pressurized and saturated with air. Because of the additional flow through the flotation tank due to recycle, the flotation tank has to be designed larger than for the full-flow system especially if the recycle flow required is large, as for sewage sludge thickening.(K. MATIS, 1981)
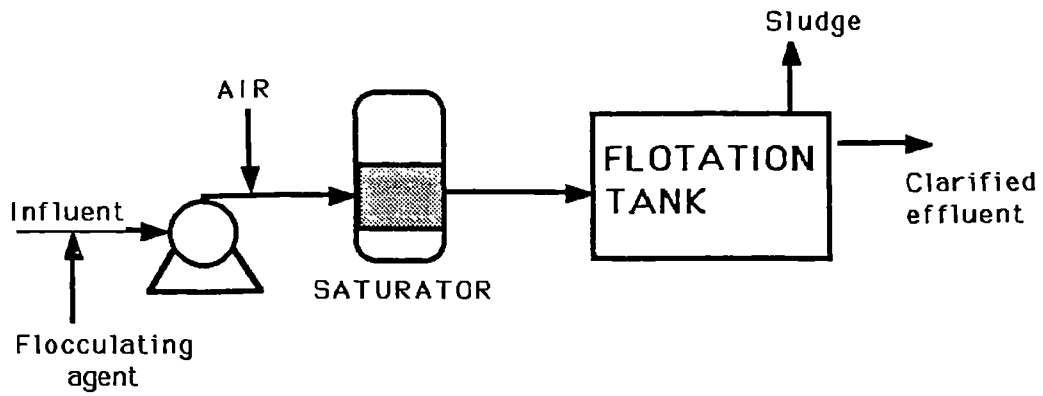
a) FULL-FLOW PRESSURE FLOTATION
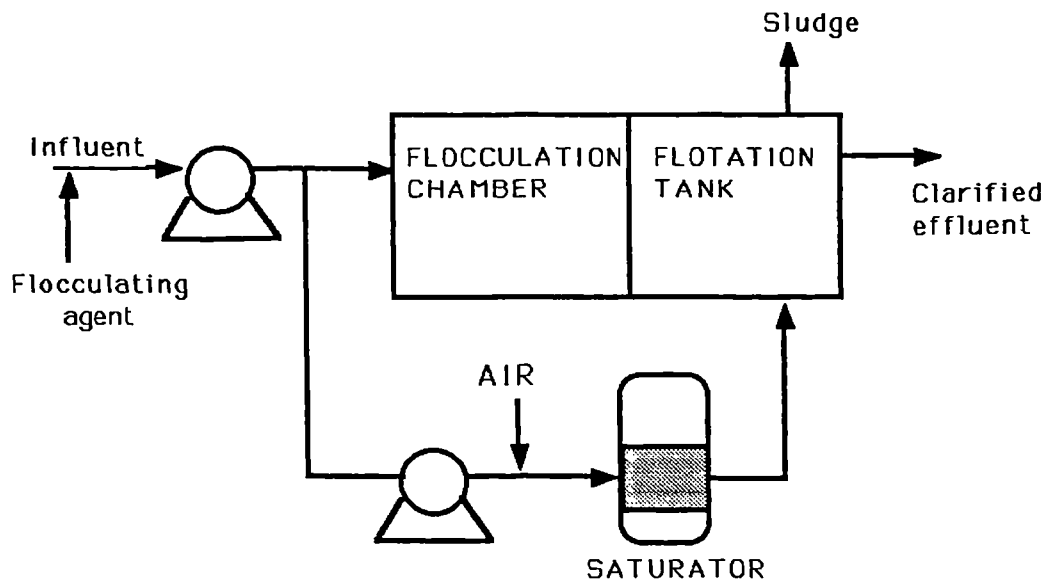
b) SPLIT-FLOW PRESSURE FLOTATION
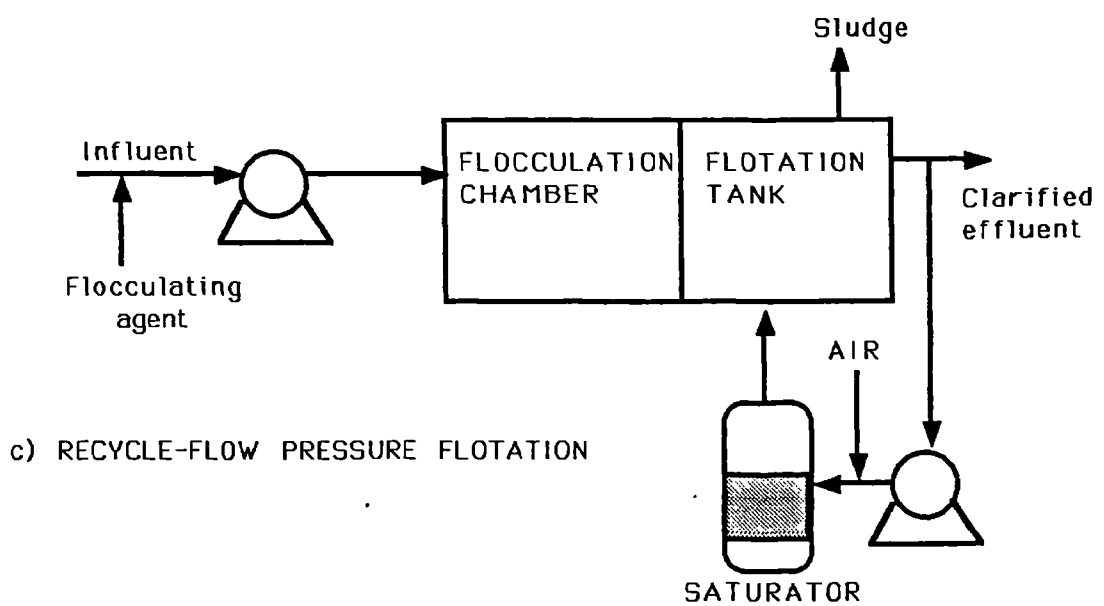
c) RECYCLE-FLOW PRESSURE FLOTATION

FIG.1.Types of pressure dissolved-air flotation

12

2.2 FLOTATION AS A SEPARATION METHOD

2.2.1 General aspects

All separation methods, either physical or chemical, are based on differences in properties on the substances to be separated e.g. the adsorptive bubble separation technique where flotation is included, is based on the differences in surface activities. The substance which is going to be separated might be the size of a molecule or a colloid or larger. These substances are adsorbed or adhered selectively onto the bubbles surfaces which are rising through an aqueous medium. In this way they are separated or gathered in the surface of the solution.

In cases where the substance is not surface active by itself, it can be made active by either the formation of a complex or the adhesion onto another substance which is called collector. In that procedure the substance (in liquid or solid form) are removed from the solution. This does not occur in percolation which is the opposite. Both of these methods are proper and particularly effective in the removal or recovery of small amounts of substances from large quantities of liquid where they are contained.

In particularly flotation has been used for more than a century when it was first used for the enrichment of ores. Today

13

it supplies 90% of the annual production of copper and zinc. In recent years this field has been extended to the treatment of wastewater and potable water.(BUREAU OF MINES, 1975)

Flotation is quite a complicated procedure, because its efficiency depends in many variables. However these can be categorized basically as chemical effects and hydrodynamics.

From the chemical view point the most basic governing factors effect both the particles or ion to be removed and the aqueous medium which they are being removed. These factors are:

i) the crystal lattice of the particles ii) the size of the ions iii) the hydration of the polar groups of the solids iv) the solubility of the surface-active substances and their complexes v) the superficial charge. When considering hydrodynamics, factors such as the degree of stirring, the aeration, bubble coalescence and the probability of the collision between a bubble and a particle are important. The selectivities which are achieved with flotation is generally a result of a balance which must exist between all the factors. Each factor might have an important role in a set of conditions, but its interaction between other factor affect the wide system. For this reason the term "probability of flotation" has been introduced. (KLASSEN V.I, 1963)

This is when a statistical analysis of the process is introduced in order to facilitate the correct evaluation of flotation as a technological process. The probability of flotation of a given particle is determined by the probabilities of individual

states. These consist of the interaction of particles with reagents, collision with bubbles, attachment to bubbles, action of separating forces, conditions of formation and disruption of aeroflocs and processes occurring in the froth layer. (KLASSEN V.I., 1963)

2.2.2. Classification of separation techniques using absorbed bubbles

Fig.2 illustrates these techniques which can be classified into two basic groups: (KARGER B.L, 1967)

The smaller one is called 'Non-Foaming Absorptive Bubble Separation' and in this case the forming of the froth is not necessary. The larger group is called "Foam separation" and it demands the formation of froth or foam for the removal of the component which is going to separated.

"Non Foaming separation" can be separated into two smaller categories: a) bubble fractionation in which there is a transfer of the components through the liquid surface of a bubble due to absorption or the adhesion of the particles on the bubble

b) solvent sublation is where the component is transferred in the liquid phase but is not blended with the solvent and is found on the top of the system. (SEBBA F, 1962)

'Foam Separation" can be separated into two sub-categories:

a) foam fractionation: which means the removal of the solute is achieved after its absorption on the surface of the bubbles. (LEMLICH R, 1972)

b) foam flotation: which is simply the removal of particles by foaming.

16

The foam flotation can be subdivided into the following categories:
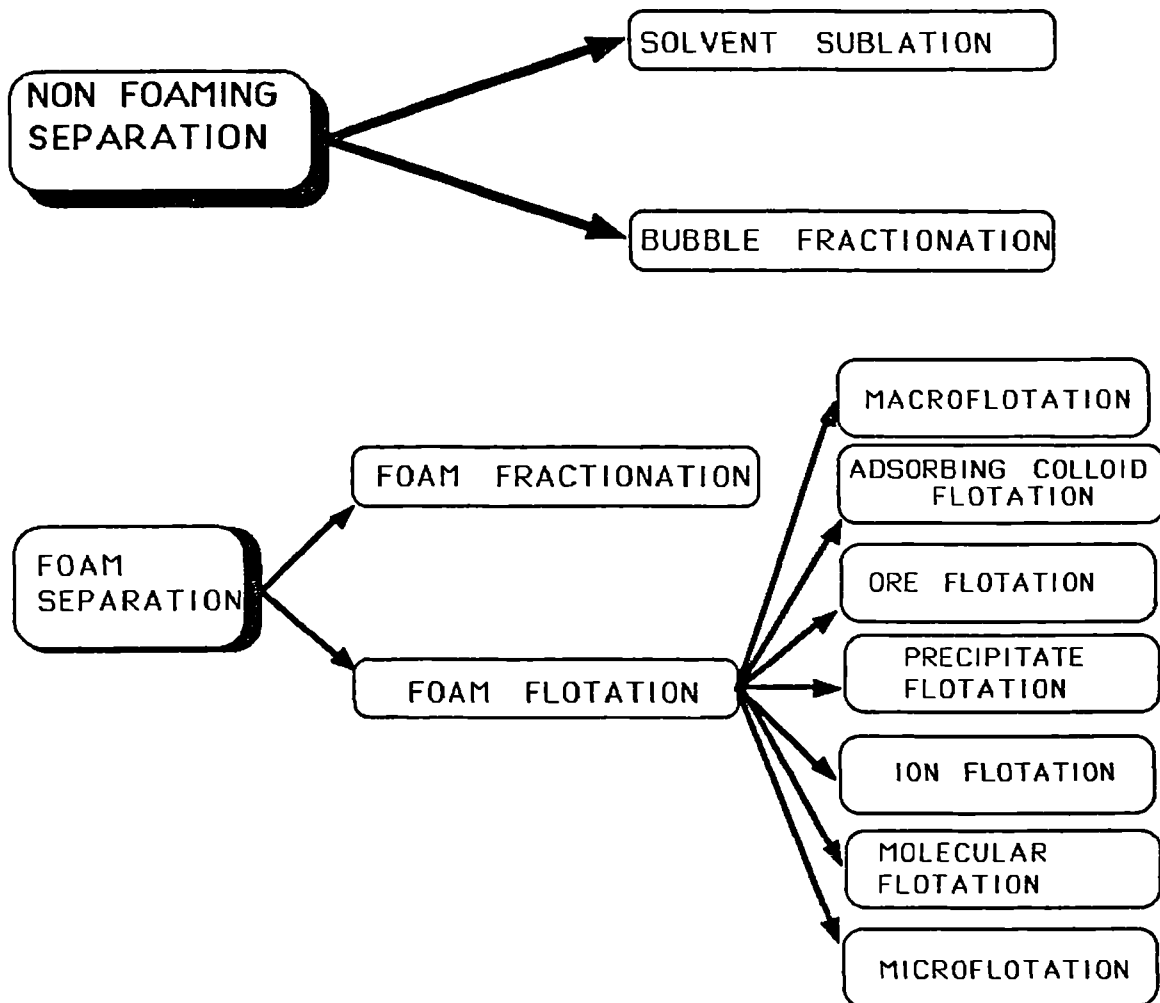
FIG 2. CLASSIFICATION OF SEPARATION TECHNIQUES USING ADSORBING BUBBLES

1)Macroflotation: this is the separation of large particles

2)Adsorbing colloid flotation: where the separation takes place after the adsorption of the solutes on the solutes particles, which have been formed in-situ, and they are removed by flotation.

3)Ore flotation: which is the enrichment of ores. Typical conditions are: the ratio of solids in the pulp, 25-40%, the size of particles <300µm, the bubbles size 0.1-5.0mm. (KLASSEN V.I., 1963)

4)Precipitate flotation: where a sediment is formed first and then is removed by means of foaming.

5)Ion flotation: is the separation by foaming of a non surface-active ion with the help of a collector which forms an insoluble material. This is what eventually appears on the surface as a sediment.

6)Molecular flotation: is the separation by foaming of a non surface-active molecule with a collector which forms an insoluble product.

7)Microflotation: is the separation of microscopic particles and especially colloids or micro-organisms.

2.3 THEORETICAL CONSIDERATIONS

As indicated in 2.2.2 the interaction of particles with bubbles is a very big factor in efficient removal therefore it is necessary to discuss the theoretical aspects.

The equilibrium adsorption of dissolved materials at a gas-liquid interface is given theoretically by the Gibbs equation:(APLAN F.F, 1966)

$$d\gamma = -RT \sum \left\{ \Gamma_i d(\ln a_i) \right\} \qquad [1]$$

where: $\gamma =$ surface tension

$\Gamma_i =$ the surface concentration of the adsorbed

          component i

$T =$ absolute temperature

$R =$ universal constant

$a_i =$ activity of component i

The minus sign shows that materials which concentrates at the surface generally lowers the surface tension.

In the case of ionic surface active substances and under certain circumstances the equation (1) can simplify to the following:

$$\Gamma_s = -d\gamma\{T \ln E_s \, 1/R\} \qquad [2]$$

where E_s is the concentration of the surface active substances. From the above equation Γ_s can be calculated, if the change of the surface tension is known as a function of the concentration of the surface active substance, when a Langmuir type of isotherm may be applicable. On the other hand trace materials follow the linear adsorption isotherm:

$$\Gamma_i = K_i C_i \qquad [3]$$

if their concentrations are low enough.

where K_i is the equilibrium constant between the concentration of the bulk and the surface and C_i is the concentration of the component i.

The free surface energy is decreased with the absorption of heteropolar surface-active reagents and the hydrophobic layer, which is formed around the bubble, acts as a "bridge" so the adhesion between the bubble and the particle can be achieved. The absorption of the surface-active reagent on an interfacial surface depends on the initial concentration of both the pH of the solution and on time. Equilibrium can be achieved within 0.1 sec in the case of alcohols with short chains, several seconds in the case of aromatic amines and some hours in case of sulphuric salts. Generally speaking different mechanisms take place for the adsorption of the surface-active reagent on to the particle under different circumstances, e.g. different values of pH or the presence or absence of other ions.

Surface-active substances act as combinations of two or more mechanisms on the surface of the particles. These mechanisms result in the formation of bonds:

1) between the polar groups and the "sites" on the mineral surface

2) between these sites of the mineral and the rest of the particle

3)between the chains of the hydrocarbon and the surface-active substances

4) between the polar group of this substance.

Because of the bonds which define the hydrophobic character (i.e. the ability to float) of the particles in a particular system, we can achieve a high degree of selectivity in

the field of separation with the appropriate choice of surface active reagents.

Quantatively this can be expressed with the angle of the contact, 9, between the bubble and the particle. This angle is related to the surface tensions of these three phases and is given by the Youngs' equation:

$$\gamma_{SA} = \gamma_{SL} + \gamma_{LA} \sin(9)$$ [4]

where $\gamma SA, \gamma SL, \gamma LA,$ are the coefficients of the interfacial tension between solid-air, solid-liquid, and liquid-air respectively. Another important equation is the Durpe's formula which determines the Work of the adhesion in the interfacial surface in solid-air, W_{SA}.

$$W_{SA} = \gamma_{SL} + \gamma_{LA} - \gamma_{SA} (1 - \cos9)$$ [5]

It is easily understood that to replace the liquid which is on the surface of a particle by the gas (air), a minimum contact angle is required to be formed with the bubble. The Energy of the adhesion between the liquid and the solid must be smaller than the Energy of coherence of the liquid, which for water is 149mJ/m^2 (APLAN F.F, 1966).

22

When the contact angle is decreased (the particles are more hydrophilic) smaller bubbles are required for the stability of the solid-bubble couple. This has been observed (ADVANCED STUDY INSTITUTE, CAMBRIDGE, 1986) in the case where flotation is used for the treatment of wastewaters, where the typical conditions for the contact angle is $(40^{o}-50^{o})$ demand very tiny bubbles (diameter smaller than 0.1mm). (ADVANCED STUDY INSTITUTE, 1982) Flotation is generally promoted by small γ_{SA} and large values of γ_{LA} and γ_{SL} (hydrophobic particles). On the other hand, the absorption of the surface active substances is capable of changing the hydrophilic character of a particle to a hydrophobic one with the change of the interfacial tensions of the Youngs' equation [4] in accordance with the following:

$$-d\gamma/d\alpha=\Gamma_i \qquad\qquad [6]$$

which is another form of Gibbs' equation [1],

where μ=the chemical potential of the surface

active substance

Γ_i=the surface concentration of adsorbed

component i

23

2.4   THE EFFECT OF ADDITIVE REAGENTS

These are substances which are added to the pulp prior or during flotation in order to facilitate the process. They can effect both the properties of the material to be separated and the properties of the liquid, thus are classified as follows: (FUERSTENAU D.W, 1962)

Frothers. The main purpose of frothing agents is to produce quality froth, by changing the surface tension of the water. Also, the introduction of the frothers is responsible for the production of an appropriate size of bubble. This happens by the absorption of the frother at the bubble surface between the air and the liquid.

Most frothers are organic having structural formulas characterized by the presence of two opposing constituents, one part of the molecule being nonpolar and the other polar. They are therefore heteropolar, and consist of one or more hydrocarbon groups attached to one polar group with the hydrocarbon radical having up to five or six carbon atoms. Examples of frothers are pine-oil, soaps and mixtures of aliphatic alcohols.

Another very important property of frothers is that they can drastically improve the collision between the particle and the bubble, thus keeping this aggregate stable, so the undesired

particles which are mechanically trapped in the foam can be removed for recovery from the tailing water. It is noted that frothers must to a certain extent be soluble in water otherwise they will not be able to perform effectively.

Modifying reagents: They have been used to select between different ions or particles that might co-exist in a dispersion system. Among the most important of these are: (APLAN F.F, 1979

Activating agents which are used to improve the attachment of the bubble collector to the particle e.g. sodium sulphide, copper sulphate.

Depressing agents which are used to inhibit flotation of unwanted minerals by coating the particles so that they will not attach themselves to rising air bubbles. At the same time they should not coat minerals which are required to float. Examples of depressing agents are queluacho for calcite, coating sodium silicate for silica and potassium bichromate for galena.

pH regulators: As well as modifying the pH, these sometimes alter the surface of the ores and also regulate the ionization potential of the collectors. Generally lime or soda ash, sulphuric acid, hydrochloric acid, sodium bicarbonate are used.

Dispersion agents: They are mainly used to facilitate or to inhibit the flocculation.

2.5 FACTORS INFLUENCING FLOTATION PROBABILITY

Generally flotation can be considered as a phenomenon where the probability of a particle to reach the foam i.e. the possibility of the flotation, is the product of the three following terms: (KITCHENER J.A, 1983)

1) The probability of collision between the particle and a bubble.

2) The probability of adhesion.

3) The probability of maintaining the adhesion.

The first probability depends on the hydrodynamic characteristics that govern the flotation chamber. The second depends on the superficial forces and the third on the collision with other particles and the turbulence in the system. The adhesion between the particle and the bubble is the basic mechanism of flotation and this stage is the one which defines the kinetic characteristics of the flotation. If we consider the mechanism of flotation, the adhesion is as result of either the collision of the rising bubbles with the particles or as a result of the formation of new bubble on the surface of the particles, a phenomenon which is relevant to the nucleation.

The multiple interrelation of all these phenomena is illustrated in details in FIG 3
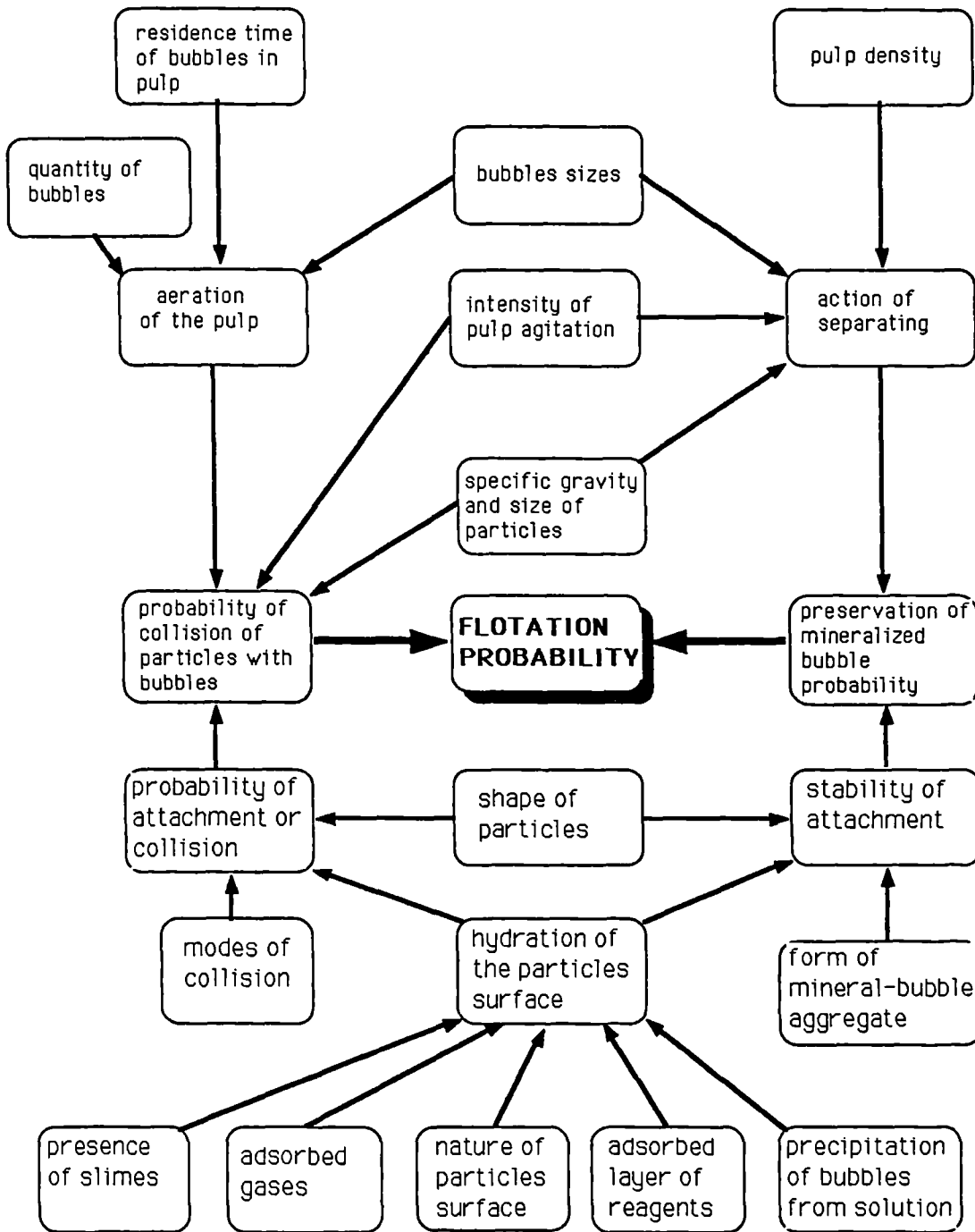
FIG.3. PRINCIPAL FACTORS DETERMINING FLOTATION PROBABILITY

27

Other ways include the trapping of the rising bubbles in the lattice which is due to the flocculation and finally the confinement of the bubble in an aggregate as it forms. This last way does not appear in the flotation with dispersed air because the bubbles, rise to the surface with quite large velocities due to their large size. In that case only the mechanism of collision is important. In the case of dissolved-air flotation, it is possible that all the three aforementioned mechanisms take place. To increase the possibility, therefore to achieve adhesion between the particle and the bubble after the collision it is necessary to add surface active substances. In the following Table (A) the influence of the flotation variables can been seen on the speed of the adhesion.

TABLE A

INFLUENCE OF DIFFERENT VARIABLES OF THE FLOTATION ON THE SPEED OF ADHESION BETWEEN PARTICLES AND BUBBLES

Size of particle:	The bigger the size of the particle the slower the adhesion takes place
Size of the bubble:	The bigger the size of the bubble the quicker the adhesion takes place
Collectors:	Dramatically improve the adhesion
Foaming reagents:	If a collector is present, these only marginally increase the rate of adhesion
Depressing reagents	Dramatically decrease or hinder the adhesion
Bubble-particle contact time:	This must be in the range of 5 msec

The rate of flotation is related to the numbers of the bubbles and independent of the diameter of the bubbles if smaller than 0.1mm. This means that for a given flow rate, the bubbles must be as small as possible, (below the 0.1mm size), thus this increases the number density. (REAY D. 1975)

In the present work efforts were made to determine the bubble size and its influence on flotation efficiency. In order to do this, measurements on the fraction of dissolved air which is released from the saturation solution was used to calculate the bubble number density in turn which has an important influence on the flotation efficiency.

2.5.1 Bubble stability

2.5.1.1.Physical effects

Regarding the physicochemical aspect of the flotation two models are considered today as acceptable. (CLARK A.N, 1983)

In accordance with the first, *electrostatic,* the energy for the coupling of the particle with the bubble is due to electrostatic attraction between one particle and an interfacial surface with opposite charge. In accordance with the second, the particles become hydrophobic with the absorption of the collector and this allows their adhesion with the bubbles.

30

After the bubbles are formed they tend to coalesce. This decreases their surface areas/unit volume and consequently the free energy of the system, and subsequently they tend to rise faster as the result of increased buoyancy. Both of these phenomena can be inhibited with the addition of surfactants which a) stabilize the surface of the bubbles by forming a wet hymenio thus reducing the coalescence potential and b) allow better adhesion of the bubbles to the particles, thus the suspended material is transferred to the surface of the solution.

As the bubbles move towards the surface of the solution they collide with each other so it is quite possible for coalescence to occur. The rising velocity depends on the size of the bubbles and also on the presence or not of surface active substances in the solution. Smaller bubbles move with smaller velocities than the bigger ones due to the buoyancy forces. The surface active substances not only decelerate the rising bubbles, but also reduce the adhesion between them due to selective absorption on the surface of the bubbles. The latter property is only valid in the case when all the bubbles have similar sizes, otherwise the bigger bubble will absorb the smaller one. Bubbles with size 0.2mm in pure water behave as solid spheres and we can apply the well-known Stokes-law for Reynold numbers <1. (BUSEV A.I, 1981)

2.5.1.2. Chemical effects

The surface active substances which are adsorbed on the bubbles surfaces, have their polar groups orientated towards the

31

liquid. The surfactants are hydrated and eventually the bubbles are surrounded with an hydrated layer. This layer protects the bubbles from rupturing and also prevents adhesion and coalescence. It has been reported that an increase in concentration of the foaming reagents reduces the size of the bubbles to a certain extent. As the concentration increases there is the continuous removal and assembly of surface active substances on the surface of the liquid and the size reaches steady state.

In the case of dissolved air flotation where the bubbles' radius is too small the pressure in the bubble is increased to a certain point, and subsequently the air contained in the bubble is re-dissolved. So for a stable bubble to exist the pressure of air in the bubble must be equal to or preferably smaller than the external pressure where the liquid is supersaturated with air.

It has been found also that the bubble has a negative charge so all the anions are gathered basically in the air-side of the interfacial surface while all the cations are in the liquid side. Ascending to the surface through the solution, the bubbles increase in size because of the decrease of hydrostatic pressure, so the rising velocity is increased. Because of the positive superficial potential which exists in every interfacial surface, they tend to take a spherical shape eventually if they have sizes <1.5mm, regardless of of the flotation technique. (NEMEROW N.L, 1971)

2.5.2. Foam stability

Finally as the bubbles reach the surface of the solution they form a foam and the stability of this is important. On reaching the surface they "push" the liquid upwards and become surrounded with a liquid hymenion. They assemble side by side and in this way they form froth. The froth, because it has a n increased free surface energy, as a result of the big interfacial surface liquid-air appears thermodynamically unstable. The foaming is a dynamic balance, as new bubbles are added continually from the solution others disappear from the top of it. In steady state conditions, the volume of added air and subtracted air are equal. The number of bubbles which are added is bigger because of their adhesion on the way up. For this reason the bubbles in the top layer of the froth are bigger. The average thickness of the liquid hymenion between the bubbles is 1μm. The liquid which is trapped between them goes back into solution because of gravity effects and as a result, the thickness of the hymenion decreases, so they start to adhere each other. They also adhere because of the bigger pressure which exists inside t h e smaller bubbles. Generally speaking the quality of the foam is affected by a large number of variables but it mainly depend on the chemical composition of the hymenion. When in solution there are more than one surface substances, due to fractionation in bubbles which in turn is due to the different rates of adsorption. (FUERSTAU D.W,1962)

33

CHAPTER 3

3.0 BUBBLE CHARACTERISTICS

3.1 BUBBLE-PARTICLE INTERACTION

3.1.1 General considerations

In mineral flotation the particles are generally large typically $50\mu m$ in diameter or larger, therefore bubbles have to be large, of the order of 1mm, and the solid content in the pulp is normally high, of the order of 25% by weight.

In effluent treatment by contrast, the particles are typically small less than $20\mu m$ in diameter and close to neutral buoyancy, and they are also present in very dilute concentration, often as low as 50ppm. It has been found advantageous to use very small bubbles, often less than $100\mu m$ in diameter. These are generated by dissolved air flotation or electroflotation. In characterising removal efficiency two parameters can be used: Collection Efficiency, E_c, and a Thickening Parameter, TP. The

34

former depends on the bubble size and the latter on the degree of air saturation. (MATIS K., 1977)

3.1.1.1 Collection Efficiency of Flotation

Experience has shown that, at a given gas supply rate, more efficient removal is possible if the bubbles are small, and it is of interest to try to predict, or, measure the effect of bubble size and particle size on the collection efficiency, E_c, defined as the fraction of particles in the bubbles' path which actually collides with bubble.

SUTHERLAND has found that: (COLLINS G.L., 1976)

$$E_c = 3d_p/d_b \qquad [7]$$

where: d_p= diameter of the particle

d_b= diameter of the bubble

At a given gas rate, the volume swept out by the bubbles is inversely proportional to the bubble diameter. Flotation rates equals the product of collection efficiency and swept volume. Hence, the rate of flotation predicted by the above equation should vary as (d_p/d_b).

The hydrodynamics of the collection of particles by bubbles was studied by FLINT and HOWARTH (1971). They found

that particle behaviour was characterized by two dimensionless groups:

$$K=(\rho_p * d_p^2 * u_t)/(9 * \mu * d_b) \qquad [8]$$

$$G=(\rho_p - \rho_l) * d_p^2 * g / 18 * \mu * u_t \qquad [9]$$

where: ρ= the density

d= the diameter

μ= the viscosity of liquid

g= the gravitational acceleration

u_t= the bubble terminal velocity

Subscripts p,l,b refer to particle,

liquid and bubble.

In case of fine particles ($K<0.1$, $d_b<20\mu m$) the collection efficiency was independent of K but strongly dependent on G, i.e. that for fine particles the inertia effects were very small in comparison with the viscous effects. In this regime the collection efficiency was:

$$E_c = \frac{G}{1+G} \qquad [10]$$

REAY & RATCLIFF (1973) investigated the case of bubbles less than 100μm in diameter and particles less than 20μm. They derived an equation of motion of the particle and the bubble and also calculated the collection efficiency (Ec) and obtained an equation similar to this derived by SUTHERLAND (1955) (Eq.7)

$$E_c = \alpha (d_p/d_b)^\beta \qquad [11]$$

where the constants α and β were functions of the particle-to-fluid density ratio.

3.1.1.2 Thickening Criteria

Thickening can be related to air saturation and the quantity of air, C, released when the pressure of the liquid is reduced to 1 atmosphere is: (VESILIND P.A 1983)

$$C = fS_a P \qquad . \qquad [12]$$

where f is the fraction of saturation

achieved. (Typical values 0.50-0.85)

Sa = saturation concentration of air at

Atmospheric pressure

P = pressure in retention tank (Atm)

The total amount of air in a flotation tank is (DICK R.I., 1972)

$$A_{in} = (fS_aP)LQ = S_aQ \qquad [13]$$

L=recycled rate as fraction of Q

Q=feed rate of influent

The last term (S_aQ) is the amount of air dissolved in the feed, assuming full saturation. If the feed is aerobic sludge, the fraction contributed to the sludge by oxygen may have to be subtracted. After the pressure is released, the air at equilibrium is:

$$A_{eq} = S_a(L + 1)Q \qquad [14]$$

The amount of air available for flotation is either the difference, or

$$A = A_{in} - A_{eq} = S_a(fP-1)LQ \qquad [15]$$

In most of these cases it is more convenient to measure the Dissolved Oxygen (DO) rather than the quantity of released air. In these cases the modifying formula of Dicks, which has been suggested by (BRATBY and MARAIS, 1975) is used.

$$C_a = [(O_p + fPN_9) - (O_9 + N_9)]V_r \qquad [16]$$

O_p =measured DO at operating P and T, mg/l

O_9 =dissolved oxygen concentration at 1 Atm and θ $^{\circ}$C, mg/l

N_9 = dissolved nitrogen concentration at 1 Atm and θ $^{\circ}$C, mg/l (estimated) ·

Vr=recycle volume, 1

9 =operating temperature, ^{0}C

The principle parameter in the design of a dissolved air-flotation system is the air/solid ratio, A/S.

Assuming that all the wastewater flow is pressurized, the air to solid ratio is given by Eckenfeder and Ford (REYNOLDS T.D 1970)

$$A/S = 1.3 * S_a(fP - 1)/S_s \qquad [17]$$

where A=air available for flotation (mg)

S_a=influent solids concentration (mg/1)

S_s=suspended solid concentration (mg/1)

For a system where pressurized recycle is used the above equation is modified to

$$A/S =(Q * S_s)/1.3 * S_a(fP - 1)L \qquad [18]$$

In order to characterize flotation plants GEHR and HENRY (1976) suggested the following thickening parameter, TP. If we assume that A is the air available for flotation in mg, S the influent solid concentration in mg/l, S_f the float solids concentration in mg/l, Vs the sludge volume in l and V the volume of liquid in the flotation tank, then the effective influent solid concentration, C_{ef}, will be :

$$C_{ef} = \text{TOTAL SOLIDS IN FLOTATION TANK}/V \qquad [19]$$

where V=recycle volume V_r + sludge volume V_s

and the Effective Thickening Time T_f will be :

$$T_f = S_f/C_{ef} \qquad [20]$$

Therefore,

$$TP = T_f / (A/S) \qquad [21]$$

The terms in this formula can be modified for use with continuous flow unit by evaluating the C_{ef} over a unit time period.

By rewriting the terms of the thickening parameter in terms of their basic components, the TP can simplified to:

$$TP = \frac{S_s * V}{A} \qquad [22]$$

The TP should be constant for a particular sludge and flotation unit, varying only with chemical dosage. The TP can be used to compare the amenability of sludges of different types, or at various flotation plants. The higher the TP the more easily the sludge can be floated. The TP can also be used to assess the effects of different polymers on flotation of a particular sludge, the higher the TP the better the performance. (MARTIN M.J., 1974)

3.1.1.3 Mechanisms for attachment of bubbles onto particles in Dissolved Air Flotation

The use of Stoke's equation for a dissolved-air flotation process is valid assuming unhindered movements on an air-solid agglomerate (VRABLIK E.R., 1959)

$$u_t = g(\rho_1 - \rho_g)d_s^2 / 18\mu \qquad [23]$$

where :

u_t = terminal rise velocity of the gas-
solid agglomerate

ρ_l = density of the liquid

ρ_g = density of the gas-solid
agglomerate

d_a = diameter of agglomerate

μ = viscosity of liquid

g = acceleration due to gravity

There are three different mechanisms by which bubbles can assist the suspended solids in rising to the surface illustrated in FIG. 4 and are:

1) Adhesion of a gas bubble to a suspended or solid phase.

2) Trapping of a gas bubble in a floc-structure as the gas bubble rises.

3) The absorption and adsorption of gas bubbles in a floc-structure as the floc structure is formed. (BIESINGER M.G., 1974).

The maximum possible contact in the first method may be established by dissolving the gas into the stream that contains the

43

suspended phase due to surface tension acts as a plane for bubble nuclei formation when the gas precipitates out of the solution.

The second mechanism depends upon the floc structure being sufficiently irregular in structure formation in order that a rising bubble may be trapped in the surface irregularities. The larger the floc diameter the greater the probability that a rising gas bubble shall trap itself and either not miss the floc-structure or "flow around" the floc structure because of flow lines established around the rising gas bubbles.

The third method of dissolved-air flotation includes the formation of a floc around not only the suspended phase but also around the gas-bubbles. This permits the formation of nuclei on the surface of the suspended phase as well as allows the trapping of the rising bubbles in the surface irregularities of the floc in addition to absorbing gas bubbles in the floc formation.

By all the three aforementioned mechanisms a three phase system (g-l-s) is created in which the following three interfacial tensions exert governing effects:

a)the gas-solid tension (g/s)

b)the solid-liquid tension (s/l)

c)the gas-liquid tension (g/l)

Together they determine the contact angle at the point of conjunction of the three phases. The larger the angle the greater is the tendency of the bubbles to adhere to the particles.
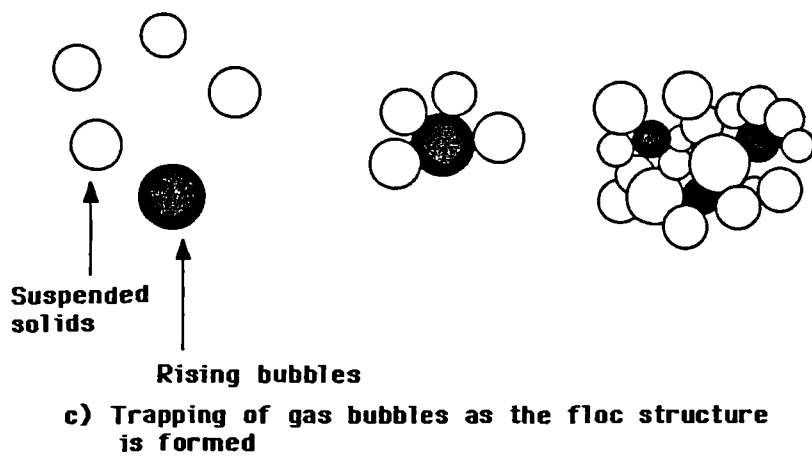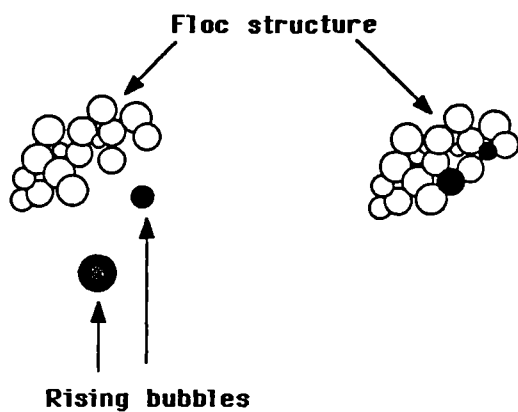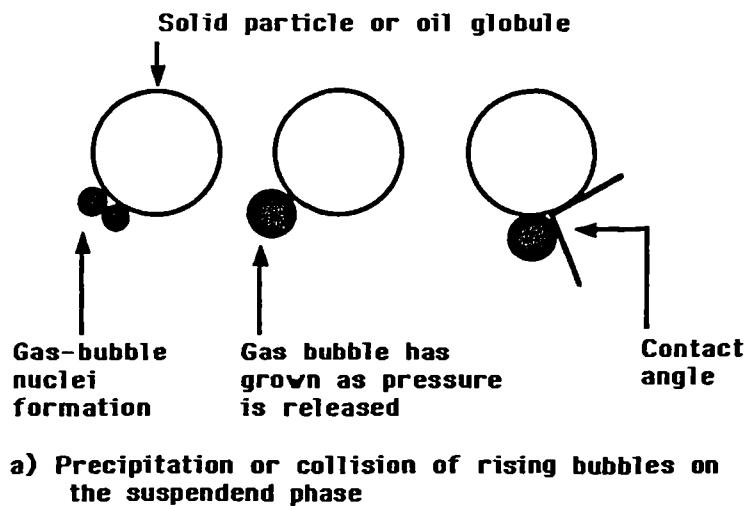
Solid particle or oil globule

Gas-bubble nuclei formation

Gas bubble has grown as pressure is released

Contact angle

a) Precipitation or collision of rising bubbles on the suspendend phase

Floc structure

Rising bubbles

b) Trapping of gas bubbles in a floc structure

Suspended solids

Rising bubbles

c) Trapping of gas bubbles as the floc structure is formed

FIG.4 MECHANISMS FOR BUBBLES-PARTICLES ATTACHMENT

45

3.2 MECHANISMS OF BUBBLE FORMATION

It is clear from 3.1 that the bubble size is critical for good flotation performance, thus, part of this work was to assess the size of bubbles formed at a particular nozzle. A review of the theories of bubble formation and size measurements data is necessary.

3.2.1 BUBBLE FORMATION FROM A SINGLE ORIFICE

This review is in two parts: firstly, dealing with a gas flowing through a nozzle, and secondly with nucleation as a result of saturated liquid flow through the nozzle. It is necessary to consider the first because this defines the upper limit of size if there is gas desorption within the body of the nozzle.

3.2.1.1 FORMATION REGIMES

There have been numerous studies on bubble formation where an orifice has been used as a distributor. A comprehensive survey and discussion of these studies have been made by (KUMAR R. 1972). In all the studies it can be concluded that bubble formation under gravity conditions could take place in different regimes depending on the physical properties of the liquid, orifice size, the volume of the gas·chamber underneath the orifice and the

gas flow rate (McCANN D.J., 1971). These regimes can be classified mainly into the following.

Static Regime

This occurs at very low gas flowrate and with a reasonably small gas chamber volume below the orifice where individual bubbles of more or less regular shapes are formed. (DAVINSON L. 1956). In this regime the frequency of bubble formation is directly proportional to the gas flowrate while bubble size is independent of the viscosity of the liquid and gas flowrate but depends on the orifice diameter and surface tension of the liquid (JACKSON R 1964). Thus, in this regime the balance between the buoyancy and surface tension forces, which leads to the following equation (assuming complete wetting of the orifice), from which bubble size at detachment from the orifice can be roughly estimated, since bubble formation is a dynamic process.

$$V(\rho_l - \rho_g)g = \pi d_h \sigma \qquad [24]$$

where: V= is the volume of the bubble

g=Acceleration due to gravity

ρ_l=Density of the liquid .

ρ_g=Density of the gas

d_h=Diameter of the orifice

σ=Surface tension

Neglecting the density of the dispersed phase ρ_g compared to that of liquid phase ρ_l, at detachment the above equation can be written as in a dimensionless form:

$$\frac{d_b}{d_h} = c \left[\frac{4\sigma}{g(\rho_l - \rho_g)d_h^2} \right]^{1/3} \qquad [25]$$

where the constant $c = (1.5)^{1/3} = 1.15$

In practice the bubble is acted upon by forces in addition to buoyancy and surface tension, so that c will not have the value shown above. Experimental work has shown that equation is fairly good at determining the size of bubbles but that a better value of c in the equation would be approximately unity. It can be seen from the above equation that for a given gas liquid system at a given temperature the bubble diameter varies with the orifice diameter raised to the power of one third.

Constant frequency regime

The regime occurs at a moderate gas flowrate, where the inertia of the liquid becomes more important than the surface tension (LEIBSON I. 1959). In this regime bubble frequency is independent of gas flowrate but depends on the orifice diameter as observed by some investigators (DAVIDSON L. 1956) but not by others (EVERSOL W.G., 1941) while bubble size increased with increasing flowrate and the volume of the gas chamber. But the effect of increasing the orifice diameter was found by some workers (DAVIDSON 1956) to increase bubble size while others (VAN KREVELEN 1950) found bubble size to be independent of the orifice but depends on the gas flowrate.

Turbulent regime

This regime takes place at high gas flowrate where bubbles are no longer formed individually, instead there is a considerable spread of bubble size with the production of numerous small bubbles (JACKSON R 1964), owing to the momentum of the gas issuing from the orifice being sufficient to maintain it as a jet before it breaks up into separate bubbles. Thus, in this regime bubble size decreases with increasing gas flowrate, as observed by LEIBSON et al, who studied the behaviour of bubbles as a function of orifice Reynolds number.

49

3.2.1.2 THEORETICAL MODELS FOR SINGLE ORIFICE BUBBLE FORMATION

Several models have been proposed to predict the size of the bubble at the orifice. All these models are based on the same form of balance to describe the growth of the bubble, which takes place in discrete phases (one, two or three stage models). Bubble growth takes place either at constant flow conditions, constant pressure conditions or in the intermediate conditions.

Bubble formation at constant flow conditions means that, the gas flowrate passing into the bubbles remains constant during bubble formation, this can be obtained by using a small gas chamber underneath the orifice, and a large pressure drop across the orifice. Growth at constant pressure conditions arises from the presence of large gas chamber volume, such that the pressure drop across the orifice is small, hence the chamber pressure remains constant, while gas flowrate and the pressure drop are time dependent the growth is said to be in the intermediate conditions.

Theoretical models on bubble formation at constant pressure were discussed by some investigators (DAVIDSON J.F., 1960), who considered the force balance and bubble formation to take place in one stage, two stage growth was considered by others (LANAUZE R.D., 1974). In the intermediate conditions a number of investigators (MARMUR A., 1976) proposed a one stage model,while others (KHURANA A.K, 1969) proposed two and three stages models. All these models are discussed below.

One stage model

DAVIDSON AND SCHULERS (1960), proposed a model for growth of a bubble in a viscous and in inviscid liquid. The model assumes that the bubble is formed at a point source within the liquid, where the gas is supplied and its motion is governed by the balance of the buoyancy force and the drag forces due to viscosity and the inertia. Bubble detachment is assumed to take place, when the bubble centre has covered a distance equal to its own radius. On the assumptions that the bubble is spherical throughout its formation, and the momentum of the gas is negligible, the authors have shown that, for the case of inviscous liquids, and small gas flowrates bubble volume is given by the following equation, which was obtained by considering the balance between the buoyancy force and the inertia force only:

$$V = C \frac{Q^{6/5}}{g^{3/5}}$$

[26]

where C= is a constant has a value of 1.378

Q= is the volumetric flowrate

By assuming that the bubble moves at all instants with the Stokes velocity appropriate to its size, the authors have derived a simple equation, valid for viscous liquids and small gas flowrates. This equation gives bubble volume in terms of the

51

physical properties of the system, gas flowrate an deceleration due to gravity. More complicated equations were also developed for the case of large gas flowrates for both viscous and inviscous liquids. However the equation did not give bubble size directly and a graphical method is needed to evaluate bubble size from these equations. Fig.5 shows the forces acting onto bubble in one stage model.
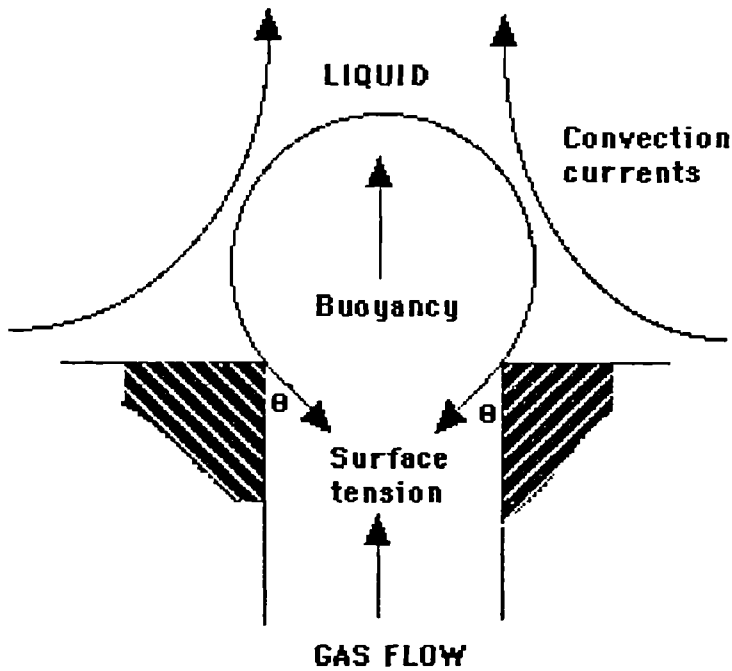

FIG. 5 Forces acting on bubble at orifice

Two stage model

GADDIS et al (1986) have made an extensive investigation for bubble formation valid over a wide range of viscosities and gas flowrates. According to their model the bubble growths in two stages.

In the first stage *expansion*, the bubble remains attached to the nozzle up to the point when the resultant of the lifting forces just exceeds the resultant of the restraining.

Further increase in bubble volume causes imbalance o f forces, *detachment*, and the bubble lifts while still being connected to the nozzle through a neck. (see FIG.6) The neck contracts and the bubble finally detaches itself from the nozzle.

Prediction of the bubble volume at the end of the expansion stage can be obtained from the balance in forces. Difficulties arise in determining the detachment volume. Two assumptions are used to overcome these difficulties. (RAMAKRISHAN S. 1969)

1) The equation of motion is also applied in the detachment stage for a prescribed bubble geometry.

2) The bubble detachment volume, V, is calculated from the equation: (RUFF K., 1972)

$$V = V_e + \Delta V \qquad\qquad [27]$$

where V_c = The volume of the bubble at the end of the expansion stage.

ΔV = The excess volume corresponding to the gas flow in the bubble through the neck during the detachment period period.

The volume of the bubble at the end of the expansion is calculated from the force balance illustrated in FIG.6 and the individual forces are defined as follows:
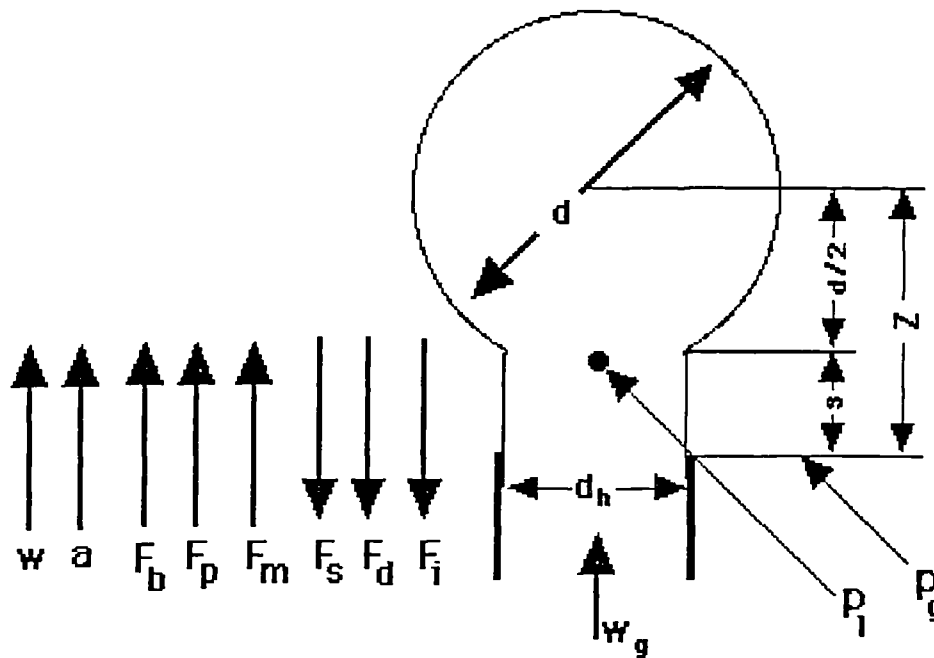
.   .

W = Bubble velocity

a = Bubble acceleration

F_b = Buoyancy force

F_p = Pressure force

F_m = Force due to gas momentum

d_h = Nozzle diameter

s = Neck length

W_g = Gas velocity through the nozzle

F_s = Surface tension force

F_d = Drag force

F_i = Inertia force

d = Bubble diameter

P_l = Liquid pressure at the plane of the bubble base

P_g = Gas pressure in the nozzle at the plane of the bubble base

FIG. 6 Model of bubble attached to the nozzle through cylindrical neck.

The bubble expands because of gas flow through the nozzle and the lifting forces acting on the bubble are:

Buoyancy force F_b

$$F_b = \frac{\Pi}{6} d^3 (\rho_l - \rho_g) g \qquad [28]$$

where: d = the diameter of the bubble

g = the acceleration due to gravity

ρ_l = density of the continuous phase

ρ_g = density of the dispersed phase

Pressure force F_p

$$F_p = \Pi / 4 \, d_h (p_g - p_l) \qquad [29]$$

where: d_h = nozzle diameter

p_l = liquid pressure at the plane of the bubble base

p_g = gas pressure in the nozzle at the plane of the bubble base

Force due to gas momentum $\dot{F}_m$

$$F_m = \frac{\pi}{4} d_h^2 \rho_g W_g \qquad\qquad [30]$$

where: ρg = density of the dispersed phase

$W g$ = gas velocity through the nozzle

Surface tension force F_d

$$F_s = \eta \, d_h \, \sigma \qquad\qquad [31]$$

where: σ= the surface tension

η=Dynamic viscosity of the continuous phase

Drag force F_d

$$F_d = \frac{27\eta V}{2d} + \frac{81\rho_l V^2}{32\pi d^2} \qquad\qquad [32]$$

Where: V=Bubble volume at the end of the detachment stage

Inertia force F_i

$$F_i = (\frac{99}{32\eta} + \frac{9\rho_g}{2\eta\rho}) \frac{\rho_l V^2}{d^2}$$ [33]

Finally a balance of forces exists at the moment of bubble detachment is:

$$F_p + F_b + F_m = F_s + F_d + F_i$$ [34]

Substitution gives:

$$d^3 = S + \frac{L}{d} + \frac{T}{d^2}$$ [35]

S,L, and T are constants given by:

$$S = \frac{6d_h\sigma}{(\rho_l-\rho_g)\,g} (1-\frac{We}{4})$$ [36]

$$L = \frac{81\eta V}{\Pi(\rho_l - \rho_g) g} \qquad [37]$$

$$T = (\frac{135}{4\Pi^2} + \frac{27}{\Pi^2 \rho_l}) \frac{\rho_l V^2}{(\rho_l - \rho_g) g} \qquad [38]$$

$$We = \frac{d_h \rho_g w_q^2}{\sigma} = \frac{16\rho_g V^2}{\Pi^2 d_h^3 \sigma} \qquad [39]$$

Where We is the gas Weber number. The first term on equation (35) takes into consideration the surface tension force reduced by the force due to gas momentum. The second term is due to viscous drag. The third term combines the form drag and the force due to bubble acceleration. Since the form drag is basically due to liquid inertia, the last term is the resultant of all inertia forces. Equation (35) can be solved iteratively.

For low moderate gas pressure the following approximations can be made:

$$S = \frac{6 d_h \sigma}{\rho_l g} \qquad [40]$$

$$L = \frac{81\eta V}{\Pi g} \qquad [41]$$

59

$$T = \frac{135 \ V^2}{4\Pi^2 g} \qquad\qquad [42]$$

The model has been criticized by LANAUZE and HARRIS (1974) and they pointed out the weakness and the limitation of this model. They claimed that RAMAKRISHNAN (1969) et al used a static force to describe the lift off point and by doing so they ignored the fact that the centre of the bubble (about which the force balance applied) was moving upwards before and after the lift point which indicated a continual resultant upward forces on the bubble.

WRAITH A.E. (1971) proposed a two stage model for bubble formation in a inviscous liquid. This model is based on potential flow analysis for a stationary expanding sphere and assumes that in the first stage the bubble is hemispherical and transfer into the fine sphere detaches from the orifice, occurs in the second stage where the buoyancy force is dominant after the bubble has risen a distance equal to its radius.

3.2.2 THEORY OF BUBBLE NUCLEATION IN DISSOLVED AIR FLOTATION

The size of bubbles has been shown to greatly affect the performance of flotation processes (CASSELL et al 1975). Although the bubbles produced in DAF are small, of the order of 100μm (VRABLIK, 1959), even smaller bubbles are generally considered advantageous (KITCHENER 1981, WOOD 1973). Studies of the nucleation and growth of microbubbles by WARD (1970) and TAKAHASI (1979) have shown that energy must be imparted to a liquid supersaturated with air before bubbles will form.

The production of very fine bubbles required for DAF can be accomplished by dissolving air in water under pressure and subsequent flashing to the normal pressure. The bubbles produced in this way adhere to solid or liquid particles in liquid and reduce the specific gravity. The hydrodynamic performance of generated bubbles has scarcely been studied, and in the following topic we will try to consider the major factors affect the size and the hydrodynamics of generated bubbles.

3.2.2.1 Diameter of generated bubbles

Consider the formation of a bubble nucleus V_2 from the supersaturated liquid. It is assumed that the volume of the liquid is very large, pressure and temperature are constant, the change

61

in free Energy of the bubble surface is negligible and the concentration in the liquid is small. Thus the change in free energy as the result of the formation of the bubble nucleus has been given by WARD C. (1970) as:

$$\Delta F = \sum_i n_{ni}(a_{ni}-a_{li}) - (P_n-P_l)V_2 + \sigma A \qquad [43]$$

Consider a spherical bubble formed at the radius r from the supersaturated liquid of the molar fraction of air x_a. Within the bubble, let air be one component. Thus, eq. (43) can be applied to bubble formation in dissolved air pressure flotation.

$$\Delta F = n_n(a_n-a_l) - (P_n-P_l) (4/3)\pi r^3 + 4\pi r^2\sigma \qquad [44]$$

Putting: $P_n = P_l + 2\sigma/r$ and $\Delta a = a_n - a_l$

$$\Delta F = n_n\Delta a + (4/3)\pi\sigma r^2 \qquad [45]$$

Assuming that air is an ideal gas, we obtain the molecular chemical potential of air inside the bubble:

$$a_n = a_0 + \kappa T \ln(P_l + 2\sigma/r) \qquad\qquad [46]$$

Where a_0 is the molecular chemical potential at the standard state. The molecular chemical potential of the dissolved air is:

$$a_1 = a_0 + \kappa T \ln(\xi x_a) \qquad\qquad [47]$$

where ξ is a coefficient. Therefore,

$$\Delta a = \kappa T \ln\left(\frac{P_l + 2\sigma/r}{\xi x_a}\right) \qquad\qquad [48]$$

Henry's law applies to the dissolved air content and partial pressure of air. Thus, ξ, is equal to Henry's law constant. Hence:

$$\Delta F = \kappa T \ln\left(\frac{P_l + 2\sigma/r}{\xi x_a}\right) + \frac{4}{3}\pi r^2 \sigma \qquad\qquad [49]$$

It has been already assumed that air is an ideal gas. Putting $P_1=P_0$ (atmospheric pressure), we obtain the change in free energy as a result of the formation of the bubble nucleus through reduction of dissolved pressure P_A to atmospheric pressure P_0,

$$\Delta F = (P_0+2\sigma/r) * 4/3\pi r^3 * \ln(\frac{P_0+2\sigma/r}{P_0}) + 4/3\pi\sigma r^3 \quad [50]$$

where $\sigma=$ the surface tension

In FIG.7 a schematic diagram of ΔF versus r is shown.
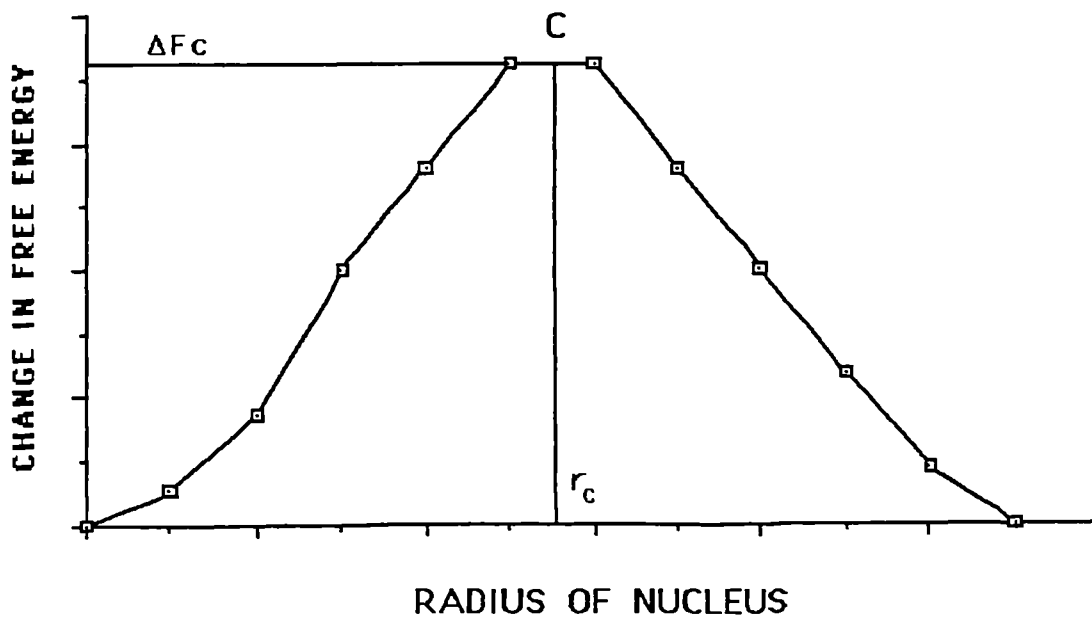
FIG.7 Free energy for bubble nucleation

The point C is determined from the condition:

64

$$\frac{\partial F}{\partial r} = 0 \qquad \text{as follows:}$$

$$\Delta F_c = \frac{16/3\pi\sigma^3}{(P_A-P_o)^2} = 4/3\pi\sigma r_c^2 \qquad [51]$$

$$r_c = \frac{2\sigma}{P_A-P_o} \qquad [52]$$

It is obvious then that the diameter of the generated bubble becomes smaller with dissolve air pressure and the quantity can be used to calculate the first nucleated size of bubble due to a pressure reduction on a saturated liquid.

Once the first small bubbles are formed they can coalesce due to their close proximity and thus the number concentration need to be evaluated as follows.

3.2.2.2 Number of bubbles

The critical number of generated bubbles per unit volume of water is obtained by dividing the generated air flowrate G by the liquid flowrate and by the critical bubble volume V_c. If

Equation (53) is used to obtain the critical volume, then the initial number of bubble is:

$$V_c = \frac{4}{3}\pi \left(\frac{2\sigma}{P_A - P_o}\right)^3 \qquad [53]$$

$$N_{b_c} = \frac{G/Q}{V_c} \qquad [54]$$

Alternatively if the average diameter is calculated from equation (55):

$$d_{av} = \left(\frac{\sum N_j * d_j^3}{\sum N_j}\right)^{1/3} \qquad [55]$$

where N_j = Number of bubbles with diameter d_j

The number of bubbles per unit volume N_b is given by:

$$N_b = \frac{G/Q}{V} \qquad [56]$$

66

It is obvious that the number of the bubble is theoretically strongly influenced by dissolved air pressure and increased with liquid flowrate.

3.2.2.3 Coalescence of bubbles

Coalescence is called the phenomenon where bubbles grow in diameter by feeding on small bubbles (RAMIREZ E.R.,1976). Generally bubbles and microbubbles coalesce when two bubbles collide and form a single bubble. There are three factors which favour coalescence:

1) The presence of non-uniform diameter bubbles where the large bubbles "gobble-up" the small bubbles by collisions. This is true since the rate of the large bubbles is considerably greater than that of small bubble and thereby favour collision.

2) Violent agitation tends also to coalesce bubbles.

3) The presence of a large surface area in contact with the bubble-liquid surface. The large surfaces serve as deposition points for the microbubbles where coalescence can readily take place. Some of these factors are considered as follows:

a) Volume of generated bubble

After discharge of the supersaturated water through the nozzle a numerous tiny bubbles are formed. The bubbles rise in the flotation tank and collapsed at the water surface. Bubble diameter determining by measuring a number of bubbles (100-200) after taking photographs. When a bubble is spherical the volume of air is occupied by a single bubble under atmospheric pressure is given by the following equation:

$$V_b = \frac{P_o + \rho_w gh + 4\sigma/d_{av}}{P_o} * \frac{\pi}{6} * d_{av} \qquad [57]$$

Where h is the depth from the liquid surface to the bubble.

In our experiments the bubble diameter is measured at the top of the vessel and so the effect of liquid depth is negligible.

b) Uniformity of bubble size

Not only does uniformity of size influence coalescence but also the physical properties of the floated material often determine the optimum bubble size needed to carry out the flotation. Hydrophobic materials are easier to float than are hydrophilic. Substances which have densities close to one require finer bubbles than do materials that have densities considerably greater than one. Rise rates of bubbles is an extremely important factor in efficient flotation (RAMIREZ E.R.,1976). It is also preferable in the applications of gas-liquid systems that the size of the bubble is not only small but also as uniform as possible. In order to express the uniformity of bubble size an index $\hat{\pi}$ has been introduced by (UNNO H., 1980) and is equal to:

$$\hat{\pi}= \frac{\varepsilon}{d_{av}} \qquad [58]$$

where ε=the standard deviation of the size spectrum.

The smaller value of index represents the more uniform size. It is difficult to generate both small and uniform bubbles, thus the development of a device which produces very small bubbles hydrodynamically will not only improve the efficiency of gas

69

liquid contacting processes but also stimulate the application of the device to many kind of other processes.

3.3. AIR SATURATION

3.3.1 Dissolved air-Theoretical aspects

As indicated in 3.2.2.2 the bubble density depends on the degree of saturation and hence the theoretical aspects of saturation need consideration.

Dissolved air flotation uses bubbles of air generated under controlled conditions by release from a supersaturated solution of air in the water. The main reason for supersaturation of a pulp by air is a sharp decrease in pressure in many portion of the pulp. Release of gas from solution can occur either as a result of cavitation or effervesence.

Solubility of air in the water is given by Henry's law:

$$X_a = \frac{P_a}{H} \qquad [59]$$

where H is a constant at a given temperature.

70

The mass X_a of a slightly soluble gas that dissolves in a definite mass of liquid at a given temperature is very nearly directly proportional to the partial pressure of that gas P_a.

In FIG. 8 is shown solubility of air in the water at various pressures and temperatures, (BRATBY J., 1975), and confirmed the linear relationship of equation (59).

MASS OF PRECIPITATE AIR/LITRE OF SATURATOR FEED (mg air/litre water)
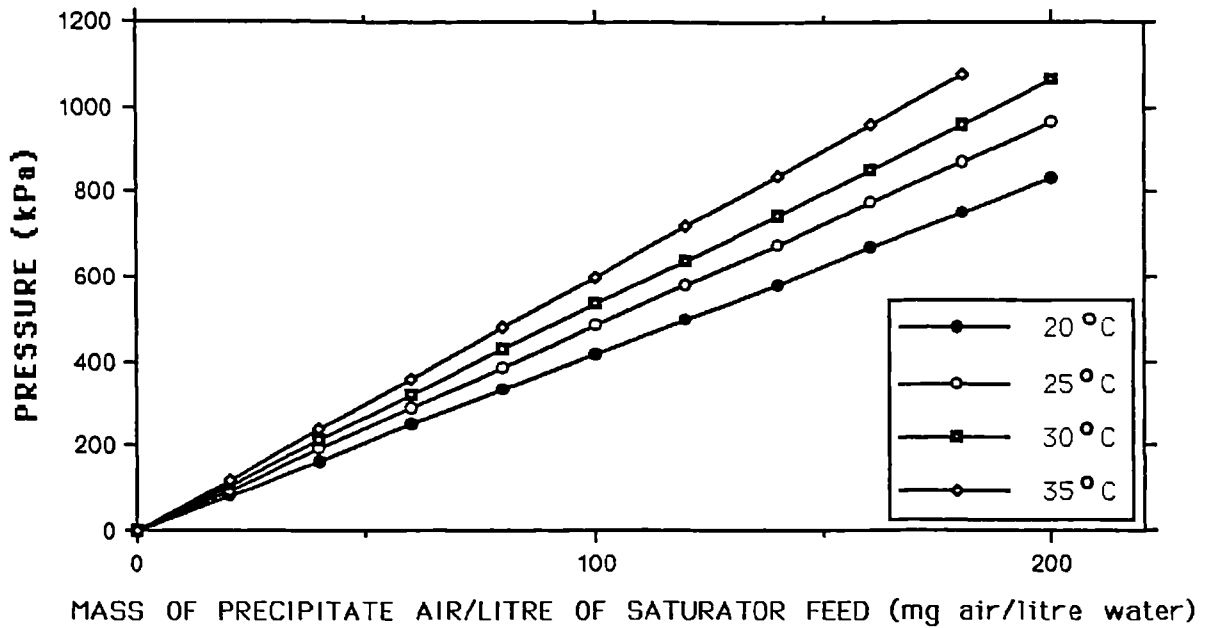
FIG. 8 Theoretical concentrations of air in water
at different temperatures and pressures.

The quantity of air C which can be released from the solution, theoretically, when the pressure is reduced to 1 Atm can be estimated from the equation (GEHR J., 1978).

$$C = S_a P \qquad \qquad [60]$$

Sa = saturation concentration of air at

Atmospheric pressure.

P = pressure in retention tank (Atm)

The actual quantity of air released will depend on the turbulent mixing conditions at the point of pressure reduction and on the degree of saturation obtained in the pressurizing system. Since the solubility in the industrial waste may be less than that in the water, a correction may have to be made to the previous equation. Also, VRABLICK (1959) has shown that a linear relationship exists between pressure and solubility for most industrial waste and that the slope of the curve depends on the nature of the waste.

3.3.2 Dissolved Air Generation rate

As we can see from eq (60) the solubility of air in water increases in direct proportion to the air pressure. The number of moles of dissolved air in $1cm^3$ is expressed as:

$$N_m = \frac{\rho_w}{.M_w} \star \frac{X_a}{1-X_a} \qquad [61]$$

where N_m = moles of air dissolved in the water

ρ_w = density of water

x_a = molar fraction of air at dissolve pressure

M_w = Molecular weight of water

Because $x_a \ll 1$ then by eq. (61) and by Henry's Law we obtain:

$$N_m = \frac{\rho_w}{M_w} * \frac{P_T - P_w}{H_E}$$ [62]

where P_T = Total pressure

$\dot{P}_w$ = Vapour pressure of water

H_E = Henry's law constant

In dissolving air in water under pressure P_a and subsequent flashing to atmospheric pressure P_0, the excess number of moles of dissolved air in $1cm^3$ water is written as:

73

$$N_m = \frac{\rho_w}{M_w} \frac{P_a - P_o}{H_E} \qquad [63]$$

On the assumption that air is an ideal gas, the generated air volume, V_a at the same temperature under atmospheric pressure is written as:

$$V_A = \frac{\rho_w}{M_w} * \frac{P_a - P_o}{P_o} * \frac{RT}{H_E} \qquad [64]$$

where R= Gas constant

T= Absolute temperature

Assuming that all dissolved air in water changes into bubbles the theoretical generated air flowrate can be obtained from the above equation.

3.3.3 TYPES OF SATURATION SYSTEMS

In the process of gas-liquid contact a numerous of devices have been employed to enhance the mass transfer between the two phases. In dissolved air flotation techniques a number of studies were made to examine the design criteria for design saturator vessels. In all these studies the main subject is to maintain the quantity of air (gas) added below the theoretical quantity of air

as this minimizes the amount of excess air which must be removed by a retention tank or contact vessel. If the free air is not removed, flotator efficiency will be greatly impaired due to large bubble formation. There are two main retention tanks (saturators) arrangements:

The Static and the Dynamic.

3.3.3.1 STATIC SATURATORS

The static designs are employed when aeration efficiencies below 50% are acceptable. Investigators of the static designs have indicated aeration efficiencies of 50 percent. These efficiencies are based on the amount of air dissolved in the retention tank effluent and do not include any free air, present as finely dispersed bubbles, which may be dispersed in the retention tank effluent. The free air percent in the static type retention tank discharge represents approximately 33% of the total air present in the discharge.

3.3.3.2 DYNAMIC SATURATORS

These are generally bubble, spray, plate, packed column or mechanical enhance mixer devices, employed for efficiencies greater than 90%. The turbine type retention tank has indicated aeration efficiencies of 92%. However, in the case of packed

75

tower it has shown that large towers will be required to obtain 90% plus aeration efficiencies.

3.3.3.3. HIGEE TECHNIQUES

Lately has been introduced another type of efficient mass transfer device. Higee technique is a rotating mass transfer apparatus in which centrifugal forces is used to intensify mass transfer (ASTARITA G. 1983).

Higee comprises a rotor containing the packing arranged as a toroid and a stationary casing. The packing is a reticulated material, which is characterized by both large surface area per unit volume and a high voidage.

Gas enters via nozzles in the casing at high pressure and then migrates through the rotating annulus of packing. Small bubbles are formed and then come into contact with the scrubbing liquid, which having been distributed at the "eye" of the packing annulus, is forced outward by the centrifugal force. Treated gas leaves through the centre of the machine while the loaded solution is returned to the centre line over a weir and is drained from the casing. Experiments were carried out using different liquid/gas ratios and speeds to observe their effect on contactor performance (BELL C. 1975)

HIGEE FEATURES

Higee has a number of special features which differ significantly from more conventional mass transfer devices. Among the most important are:

Small size

Low weight

Short contact time

Low liquid hold-up

Insensitive to motion or orientation

Rapidly attains steady state

Non foaming

Quick emptied and easily cleaned.

Three of the operating features are among the greatest considerations and they will relate to:

i) Mass transfer

ii) Throughput capacity

iii) Power consumption

i) Mass transfer

The rate of the mass transfer in a bubble column is affected by:

a) The mean bubble size and hence the interfacial area for mass transfer;

b) The relative velocities between the phases, i.e. turbulence and hold-up;

c) The stability or renewal of bubble surface

Considering each of these features in turn

a) Initial bubble size

It is obvious that the smaller the bubble size the greater the interfacial area available for mass transfer. When small bubbles form at an aperture the size of the bubble is determined by aperture size and by the balance of the forces acting upon it. The bubble will continue to grow much larger than the aperture until the buoyancy forces tending to make the bubble break away and rise become greater than the surface of interfacial tension forces. In the single bubble regime this balance of forces results in the Equation (35).

78

While this equation may be an over-simplificaion in real life situations because viscosity and inertial forces are ignored, it is clear that bubble diameter is inversely proportional to the cubic root of the "g" force. In the rotary de-aerator the "g" can be replaced by ωr^2 where ω is the rotational speed in radians/sec. and r refers to the radius. With "g" forces in the range 100-1000 times terrestrial "g" the bubble diameter will be 4.6 to 10 times smaller and the interfacial area correspondingly larger than in a stationary vessel. (SARDAR H. 1984).

b) Relative velocity

In a conventional stationary bubble reactor there is a pressure exerted upon the bubble reactor which results from the static head of liquid above it. As the bubble rises this pressure is decreased and the bubble expands and accelerates. In a rotary de-aerator the pressure on the bubble at any point is the head of the liquid times its density times the "g" force. As a bubble "rises" from periphery to the centre therefore the pressure is initially much higher but reduces rapidly as both the height of the liquid and the "g" force are reduced from periphery to centre. Unhindered this would result in a tremendous buoyancy forces and high bubble velocities with the resulting enhanced mass transfer rates.

c) Surface renewal

It has been shown that when a bubble collides symmetrically with a narrow obstruction its subsequent behaviour will be dictated by the buoyancy and kinetic energy released on impact. If the sum of these are greater than the surface energy created by splitting then breakdown will occur creating two smaller bubbles. If the buoyancy/kinetic energy is less only deformation and bouncing will occur. In the centrifugal field buoyancy and kinetic energy will be much larger than in a static apparatus so bubble breakdown will be greater and the equilibrium bubble size much smaller. This vigorous bubble breakdown produces new interfacial are while maintaining   the small bubble size.

2) Throughput/Capacity

In a stationary bubble reactor/stripper the downward velocity of the liquid, and hence vessel diameter, are constrained by the velocity at which bubbles will rise. If the liquid velocity were to approach or exceed the bubble rise velocity the bubbles would be entrained and carried out by the fluid. The bubble rise velocity is indicated by Stokes Law. From this is clear that "g" will have a large and proportional effect upon the bubble velocity. In the rotary de-aerator the very much enlarged bubble velocity can therefore countered by a high liquid velocity in the opposite direction. This enables very high capacities to be obtained in small

rotational equipment, the overall effect being to reduce the size and weight of the de-aerator considerably. (KATTI S.1986)

3) Power Consumption

In the first generation of Higee units, the liquid and gas contacted in film flow conditions rather than having a continuous liquid phase with bubbles dispersed in it. The principle disadvantage of this was the excessive power consumption resulting from accelerating all the liquid to the rotor tip speed and the energy was lost by impact with the stationary walls. With a continuous liquid phase confined within a totally rotating unit, only the net energy imparted to the fluid needs to be put into the system, since the fluid after treatment is returned to the axis of the machine, its velocity is reduced and much of the kinetic energy "recovered". The net power requirement is orders of magnitude smaller as a result. (DANCKWERTS P. 1966).

3.4 MASS TRANSFER IN BUBBLE PROCESSES

Many of the industrial processes, including DAF involving mass transfer of a diffusing solute from the bulk fluid of one phase into the interface to the bulk of the second phase. The diffusing solute transfers from phase P_1 where the concentration is higher than equilibrium into phase P_2. Thus mass transfer takes place from the bulk fluid of phase P1 to the interface and then

81

from the interface to the bulk fluid of the other phase P2. In the interior of bulk fluids mass flux is accomplished by mixing to turbulent fluctuations and the concentrations of the diffusing solute in the interiors is thus practically constant as is shown in FIG.10.

In the boundary layer near the interface the turbulence diminishes which causes a concentration gradient to develop as the interface is approached, until at the interface the mass flux encounters resistance due only to the mechanism of diffusion.

Several different theoretical models have been developed, each representing a simplified mode of mass transfer, but most of models are based on the following assumptions.

1) The resistance to mass flux is the sum of the resistance of each phase and the resistance of the interface. However, the interface resistance may be taken to be negligible and in this case, taking into account that the mass flux within a single phase is independent of the other phase, the total resistance to mass transfer considered as the sum of phase resistances known as *additivity of resistances*.

2) Near the interface the two phases are in equilibrium, and the equilibrium is established more rapidly than the change of average concentration in either bulk fluid.

Two are the most well-known models in mass transfer processes. The film model where we assume that there is a region in which steady state molecular diffusion is the transfer

mechanism. The penetration theory where the interface is continously being impinged by unsteady molecular diffusion.

3.4.1.FILM MODEL

According to this model steady state mass transfer occurs by molecular diffusion across a stagnant, or laminar flow film at the interface between the phases, in which the fluid is turbulent. All the resistance is assumed to be confined inside the film and therefore mass concentration gradients arise only inside this film in bulk fluids, the concentration being constant and equal to some average values. So, the mass rate m' transferred across a unit area of interface per unit time, is proportional to the concentration gradient between the bulk fluid and the interface so that: (SHERWOOD T.K. 1975)

$$m' = \frac{-D}{\delta_{eff}} (C_o - C_{in}) = -k(C_o - C_{in}) \qquad [65]$$

where C_o=the average concentration in the bulk fluid, kg/m^3

C_{in}=the average concentration in the interface, kg/m^3

D=the diffusivity, m^2/s

k=mass transfer coefficient, ms/kg

δ_{eff}=the effective film thickness, m

The weak point of this theory is the definition of a stagnant film of a definite (but unknown) thickness.

3.4.2 BORDER DIFFUSION LAYER MODEL

A better theory has been established taking into account the actual conditions near the interface. This model in contrast with the film model considers:

1) The effect of liquid motion on mass transfer.

2) Molecular and convective diffusion in both radial and tangential conditions.

3) The absence of a clearly define layer thickness.

According to this model distribution of the diffusing matter in a turbulent stream has a four-layer structure as is shown in FIG. 9 The relation which exists between the thickness of the diffusion sublayer δ and the viscous sublayer δ_0 is: (AZBEL D. 1981)

$$\delta = \left(\frac{D}{\eta}\right)^{1/n} \delta_0 \qquad [66]$$

where η=kinematic viscosity

n=constant determined experimentally

n=2 for gas-liquid system

n=3 for liquid-gas system.
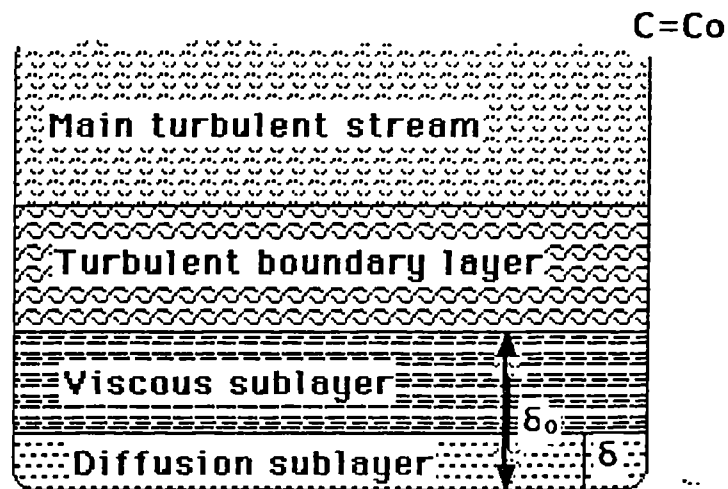
FIG.9   Distribution of the diffusing substances
in a turbulent stream
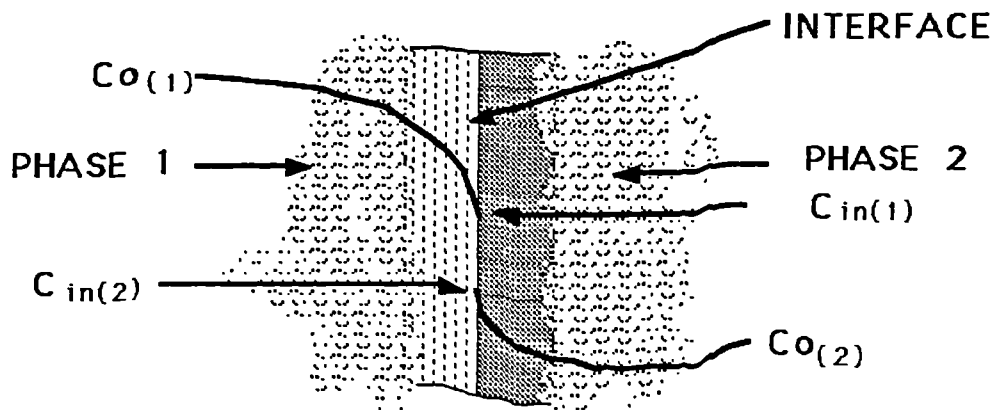
FIG.10 Concentration distribution in phases during
mass transfer

3.4.3 PENETRATION MODEL

In this model mass transfer is observed as an unsteady time dependant process. The exposure time of fluid elements to mass transfer at the interface is so short that steady-state characteristics do not have time to develop and any transfer that does take place is due to molecular diffusion. According to the penetration model, a gas bubble rising in the liquid and liquid elements being in contact with the bubble surface for a time equal to that for a bubble to rise one diameter. Mass transfer is effected during a cycle in which each eddy in the liquid come to the surface where diffusion takes place and the eddy randomly return to the bulk phase (LEVENSPIEL O. 1972). The eddies are assumed to remain at the interface for the same time duration, τ. For this time duration, gas diffuses into the liquid eddy in manner described by the diffusion equation:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \qquad [67]$$

where: c=local gas concentration

x=the distance from the interface

For small diffusion rates and when the time duration is small we can apply the following boundary conditions on the above equation.

C_0 at   t=0   and   x>0

C_0 at   x→ ∞   and   t>0

C_{in} at   x=0   and   t>0

where C_0 is the average gas concentration in the liquid bulk

C_{in} is the concentration at the interface

The mass transfer coefficient is obtained after solving the above equation and it is:

$$k=2(D/\pi\tau)^{1/2}$$ [68]

where   D= the diffusivity

τ= the contact time

88

3.5 BUBBLE SIZE MEASUREMENT TECHNIQUES

These can be classified to be either direct or indirect techniques

3.5.1 DIRECT TECHNIQUES

Photographic techniques:

This is the most widely used method and is applicable for transparent systems or for systems with low turbidity.

Three factors can be estimated by this method. The size of the bubble, the rate of the growth of the bubble with time assuming spherical shape, and the rise velocity of them.

The basic principle of these techniques is that photographs are taken from a certain distance using microscopes or borescopes adapted to a camera. The light source consists of a flash unit or a stroboscope so the fast movement of the bubbles is captured on the surface of a sensitive film. As the size of the bubble is relative to the distance of the bubbles from the lenses, the magnification factor has to be known. This can be found by either placing a scale to be photographed at the same distance as that between the bubbles and the camera or installing a graticule onto the lenses.

More recently Video tape recorders and T.V. cameras are connected to measure not only the size of the bubbles but also the electromobility and the zeta potential of them. (FUKUI Y. 1982)

Electro-conductivity techniques:

A typical bubble detector is shown in FIG.11 As we can see this consists of two stainless steel needles both well insulated. The smallest bubble diameter that can be detected depends on the distance between the needles, which is in the range of 0.1-1.5mm (LEWIS D.A. 1981). In principle the technique is based on the difference in electrical conductivity between the liquid and the gas phase. The conductivity will drop when the bubble comes into contact with the needle and then rise, depending on the liquid, once the bubble had passed the tip of the needle.

output from upper electrode

output from lower electrode

Glass fibre support for electrodes

Stainless steel needles

Exposed tip of needle

Tip separation
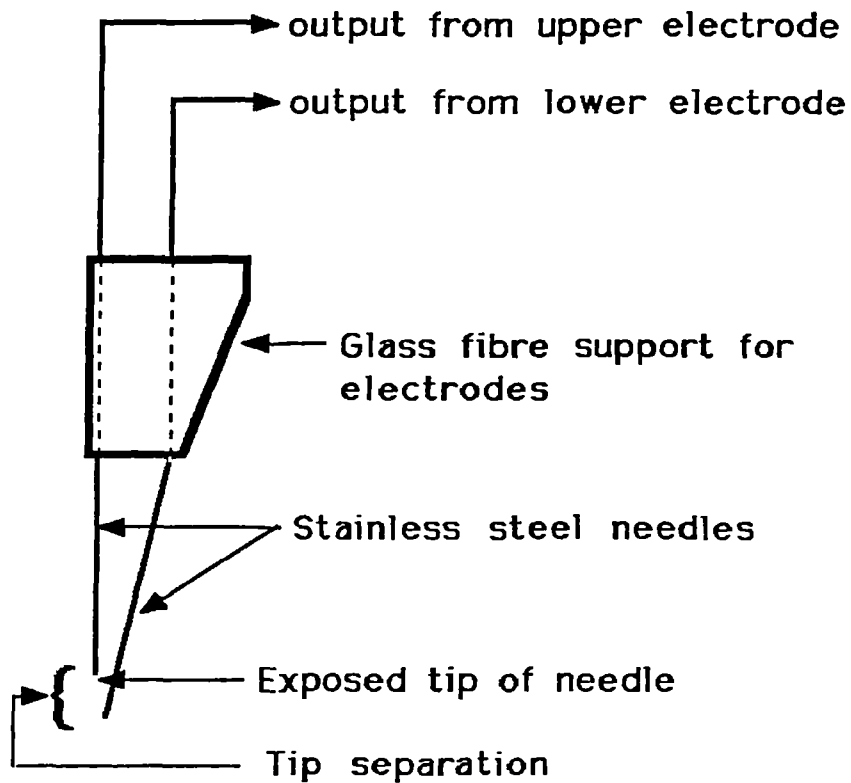
FIG. 11. Typical bubble detector assembly

3.5.2 INDIRECT METHODS

By measuring some other parameters, bubble size can be obtained with the following techniques:

a) Count technique: If we know the total volume of a known number of bubbles and the volume of an individual bubble, it is then easy to determine the diameter of the bubbles.(BENZING R. 1955)

91

b) Vibro-acoustic technique: With this method it is possible to measure the frequency of the formed bubbles, by placing a microphone near to the orifice, and the sound of the detachment bubbles is transferred by means of pulses on an oscilloscope through a pre-amplifier. (HUGHES R. 1955)

c) Light scattering technique: The idea of this method is to allow a beam of light to pass through a dispersion system (i.e. bubbles-water). A photo cell is placed on the other side of the column or the tank and it receives the part of the incident beam that passes through the dispersion without being scatter thus the beam's intensity depends only on the projected area of the dispersed phase. (CALDERBANK P. 1956)

FIG.12 shows the classification of the techniques used to measure bubble diameter and from this survey it was decided to use the basic photographic technique because it was simple to use, inexpensive and easy to calibrate.
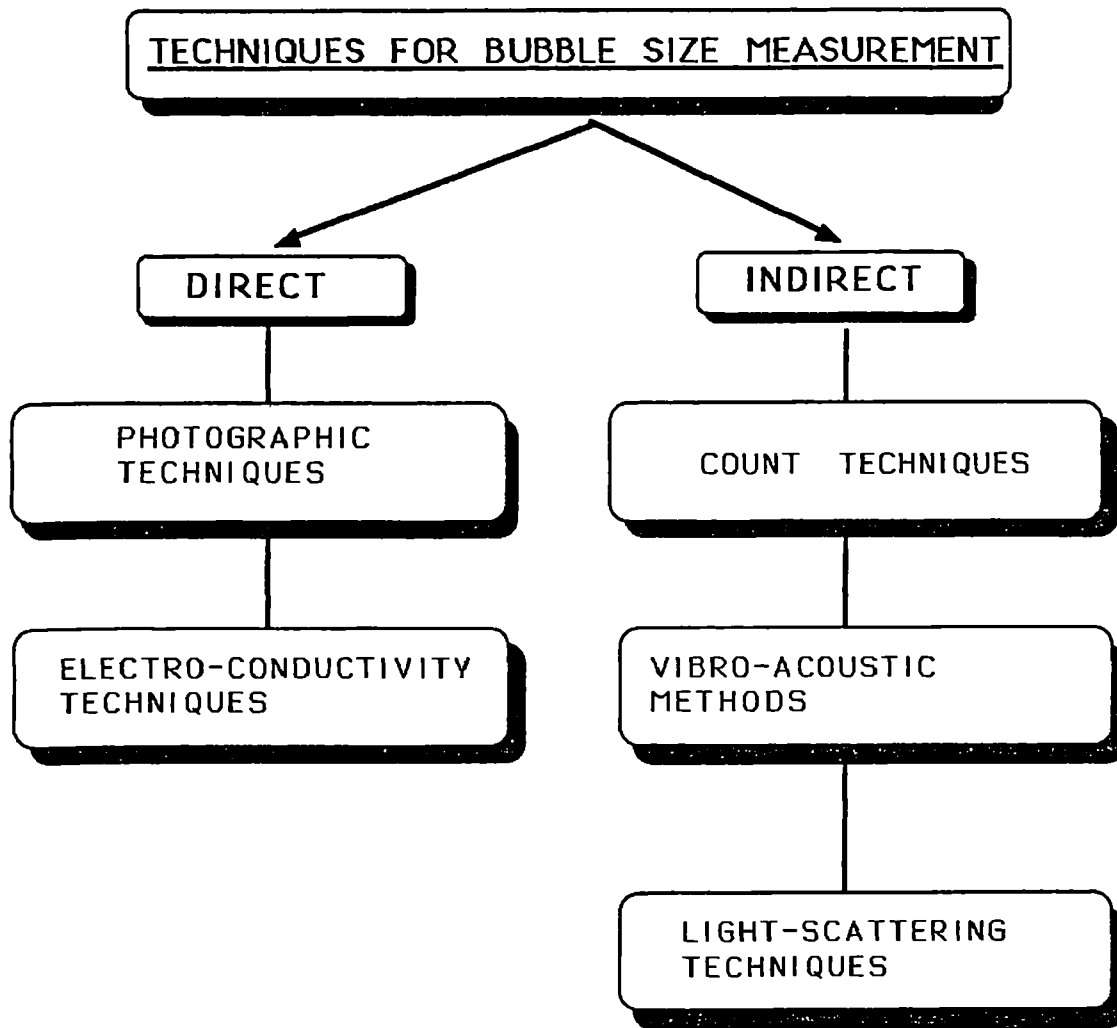
FIG.12   CLASSIFICATION OF BUBBLE MEASUREMENT TECHNIQUES

CHAPTER 4

4.0 EXPERIMENTAL WORK

4.1 DESIGN OF SATURATORS

4.1.1 CONVENTIONAL SYSTEM

A common method for gas transfer is to use packed columns. These consist essentially of a column packed with a proprietary packing, through which the liquid is percolated in an atmosphere of gas. Packings are available in many shapes and sizes. The shape is selected so that for a given superficial volume as much surface is exposed as is practicable to pass a reasonable flow of liquid through the packing. The larger the packing, the greater is the flow that can pass through it per unit cross sectional area, but the lower is the total exposed surface per unit volume. For high gas transfer efficiency, a large surface per unit volume of packing is required as gas transfer takes place at the gas-liquid interface on the packing surface. Hence the "best" packing is one allowing a high rate of liquid transmission while presenting a large interface for gas transfer.

An important practical consideration in packed columns is the distribution of the liquid over the packing. If the liquid is not distributed evenly then "dry" areas of packing result which reduce the effective packing volume. Further, the design should minimize

94

the opportunity for liquid to pass down the walls of the column, presenting a path of least resistance which reduces the effect of a large interfacial area. This is prevented to a certain degree if the ratio of nominal packing size column/diameter is less than 1:8.

The packed column system (saturator) which was used in our experiments is shown in FIG.13. Compressed air and water were mixed first in an eductor, and then through a sparger introduced at the top of the saturator. During the experiments it was important for the pressure in the saturator to be constant. This could be achieved in two ways. Either, by controlling the pressure release safety valve or, by keeping the level of the water in the saturator constant, by controlling the outlet valve. Also it is worth mentioning that no air was bubbled through the water at the bottom nor positively circulated through the packing. The packing consisted of 25mm Raschig rings (HY-PACK, stainless steel, nominal size 25mm) which occupied a volume from the above the distributor to 15 cm from the bottom. The feed from the centrifugal pump passed through the holes of the distributor at the top of the saturator and was sprayed over the whole area of the packing by jet action. This distributor was made from a stainless steel disc 20cm in diameter with 100x1mm holes. The Raschig rings were allowed to cover the distributor in order to retard the tendency of the water to spray directly onto the walls of the saturator which would have introduced by-passing of the packing and reduced the efficiency.

All the pressure readings were made with the help of a pressure gauge which was connected to the saturator. Normally at least 10 minutes were allowed in order to achieve equilibrium in every setting.

LIQUID FEED

PRESSURE RELEASE
SAFETY VALVE

COMPRESSED
AIR

PRESSURE GAUGE

25.00cm

40.00cm

22.10 cm

25 mm
Raschig
Rings
packing

LEVEL CONTROL
GAUGE

15cm

SUPPORT
GAUZE

WATER+AIR

TO FLOTATION TANK
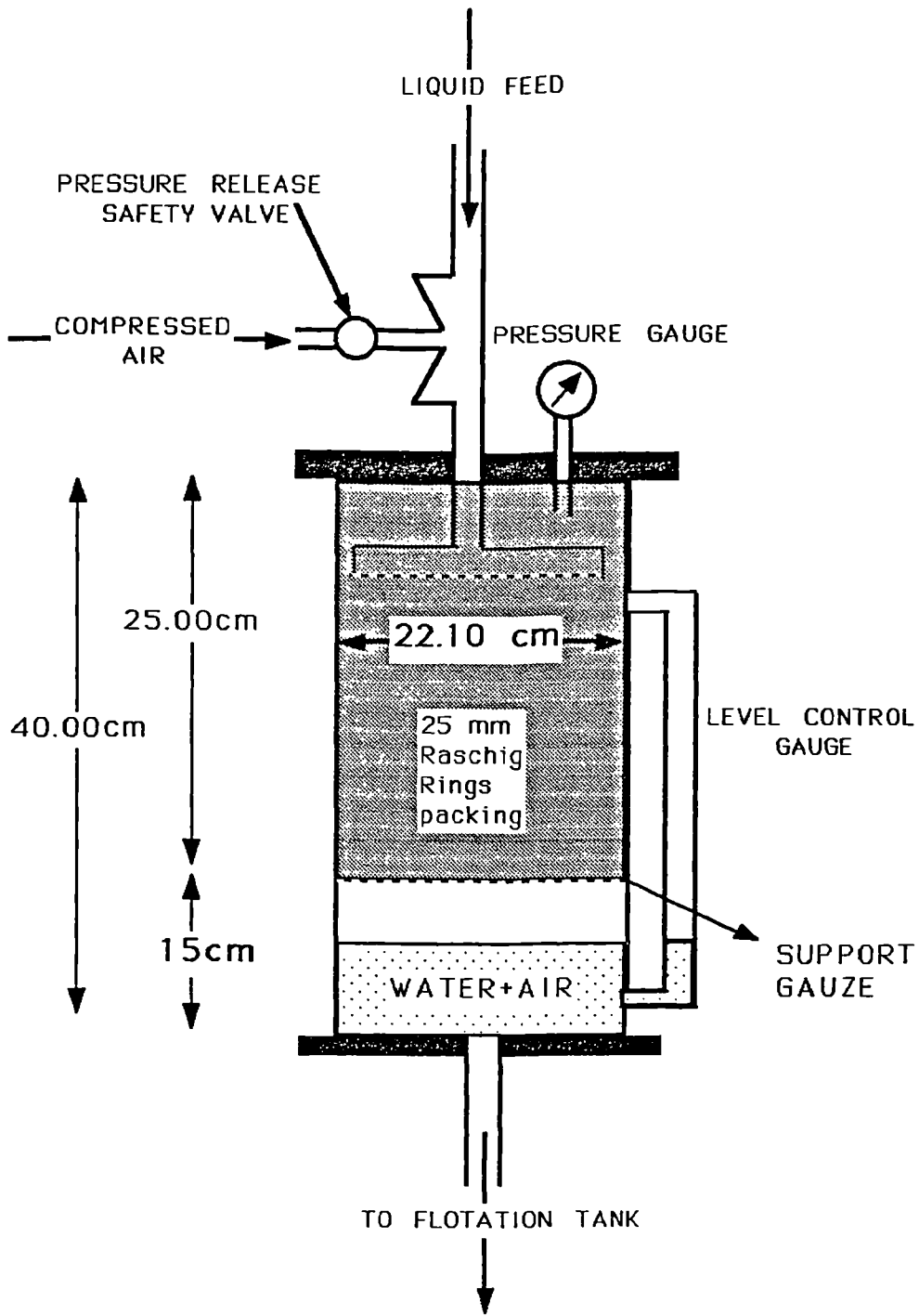
FIG.13 SCHEMATIC REPRESENTATION OF
CONVENTIONAL SATURATOR

4.1.2. HIGEE ROTATING DISK

In FIG.14 is shown schematically the main parts of the Higee absorber which was used in order to obtain results comparable with those of the conventional saturator. The Higee rotating distributor which was tested during the experiments incorporates a torus with a radial depth of 10cm and an axial thickness of 2.5cm rotating up to 1500rpm.

The gas passed through two radial tubes into the peripheral plenum chamber of the rotor. From this chamber it was then fed into the outer periphery of the annular liquid pool, using a membrane. Gas bubbles are generated in this way and discharged at the distributor under intense acceleration fields and travel radially inwards under the influence of very high buoyancy. Then they coalesce rapidly at the inner surface of the liquid annulus.

Liquid is introduced to the rotor from a stationary nozzle distributor close to the inner liquid surface, and is discharged at the outer radius, thereby providing a counter current flow regime. However, having reached the packing outer radius, the liquid is then transferred axially into another chamber where it moves radially inwards to a discharge lip only marginally outboard of the gas-liquid interface in the packed chamber. This was the point where sample of the treated liquid collected and submitted to further analysis, i.e., measurement of precipitate air and bubbles photographs.
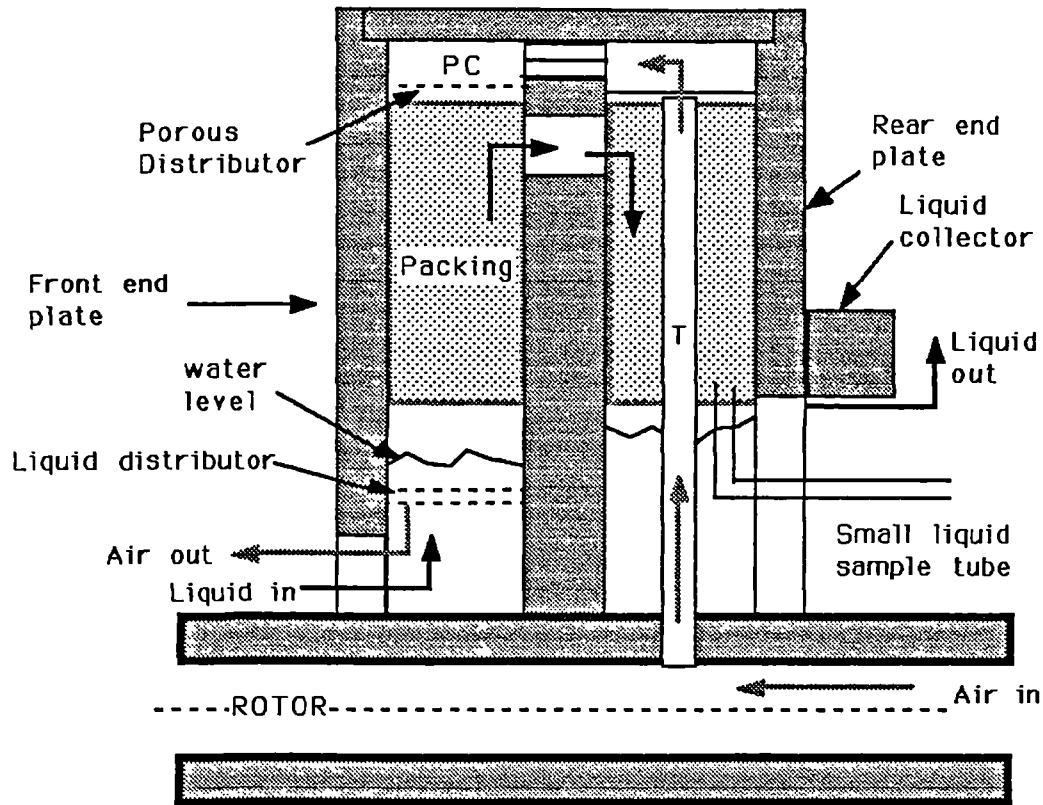
FIG.14   THE HIGEE ABSORBER

4.2   PRECIPITATE AIR MEASUREMENTS

4.2.1 RELEASED AIR TECHNIQUE

This technique is appropriate for use with the conventional saturator when the liquid throughput is relatively low and the saturated liquid is not exposed to atmospheric pressure before reaching a gas bubble nozzle (section 4.3).

To measure the air volume produced from the saturation tank, an apparatus was built according to CONWAY et al (1981). This is shown in FIG.15. Supersaturated water was allowed to flow

through a restriction valve C into the first cylinder, while water was displaced from the second, having valve A open to maintain constant atmospheric pressure in the system. The released air then was driven into an inverted 250ml burette which was immersed in a 2lt graduated cylinder. The volume of the water displaced from the graduated cylinder was equal to the volume of the water and released air added in the first one. So by opening the valve B it was possible to measure subsequently the volume of the water added to the first cylinder. The difference between the two volumes of water represented the volume of air released.

MANOMETER

INVERTED BURETTE

2 LT GRADUATED
CYLINDER

WATER INLET
FROM
PRESSURIZED
TANK

MEASURE WATER
OVERFLOW
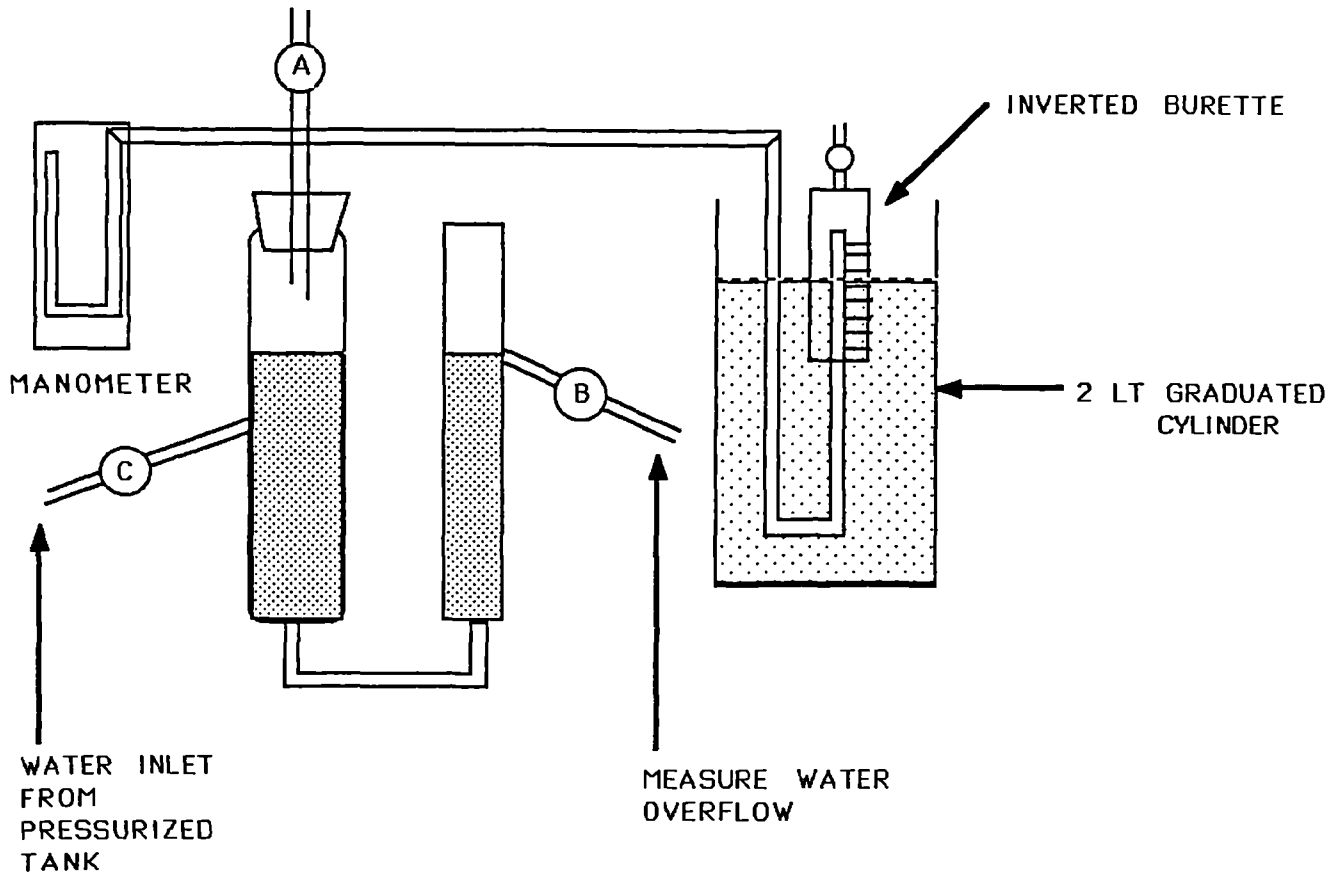
FIG 15 APPARATUS FOR THE DETERMINATION
OF THE AMOUNT OF PRECIPITATE AIR

4.3 DESIGN OF THE GAS BUBBLE NOZZLE

In the field of flotation techniques it has been proposed by (VRABLIK, 1959) to use needle valves for introducing the air saturated water into the flotation tank. However, their use does give rise to certain difficulties. Needle valves have to be carefully adjusted according to the precise conditions (pressure, liquid flowrate) in order to satisfactorily cause the desired

101

formation of gas bubbles. Also, needle valves have a tendency to become blocked and they are relatively costly to replace or repair when they become worn or otherwise faulty.

The nozzle which was used in our experiments was designed and constructed in the laboratory and is shown in FIG.16. The main parts of it are:

1) A transversely divided housing 1,7, constructed from stainless steel having a through passage in the form of a cylindrical bore the diameter of which was 2.5cm (1inch).

2) Two stainless steel discs, 2 and 3, were disposed diametrically within the housing and were spaced 6.35mm(1/4inch) apart by a spacer ring, 6, thereby a chamber, 8, was formed. The two housing parts are releaseably interengaged by screw threads to clamp the two discs with the spacer ring in between them.

3) Disc 2 had an orifice,4, located 4mm from the wall of inlet housing 1; the diameter of orifice was 3.2mm(1/8inch). Disc 3 was provided with an orifice, 5, located 2mm from the wall of outlet housing 7 and diametrically opposed to orifice 4. The diameter of orifice 5 is 6.35mm(1/4inch).

In use, pressurized air saturated water is passed through orifice 4 at high velocity into chamber 8 where it impinges on disc 3. In flowing to outlet orifice 5 the water must change direction and impinge upon the cylindrical surface of chamber 8 and then again change direction before leaving chamber 8 via orifice 5. In passing through the orifice 4 the pressure is greatly

reduced. Impingement of water on the metal surfaces and changes in direction cause violent turbulence which in turn causes air to come out of the solution in the form of tiny bubbles. Finally, the water+air mixture leaves chamber 8 via orifice 5. This has a larger diameter than orifice 4 since it is desirable that the greatest pressure drop occur across orifice 4 (thus causing release of the major proportion of the dissolved gas within chamber 8.
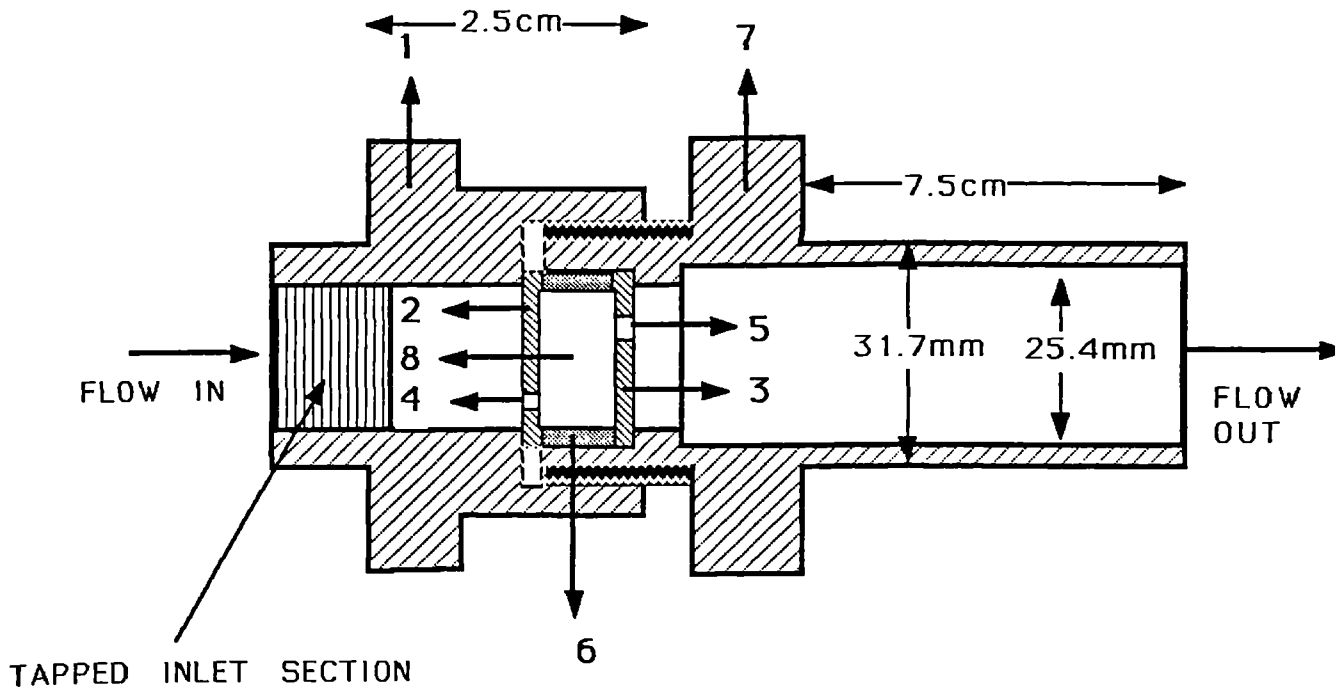
1,7 HOUSING
2,3 DISCS
4   INLET ORIFICE 3.2mm
5   OUTLET ORIFICE 6.35mm
6   SPACER RING
8   CHAMBER
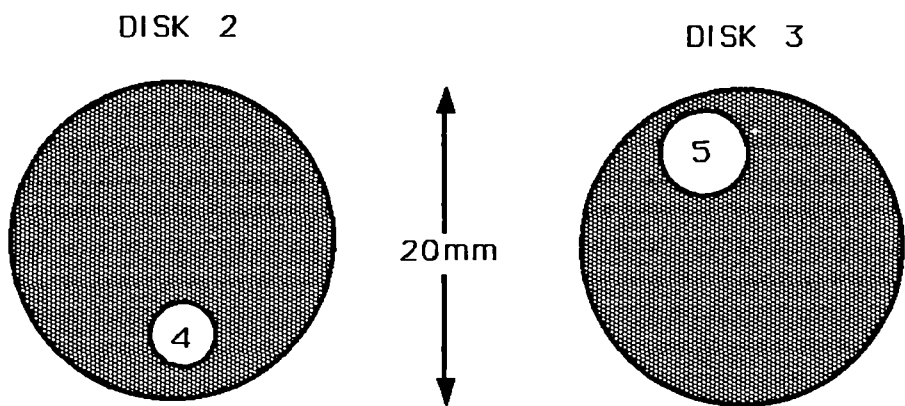
FIG.16   GAS BUBBLE GENERATION NOZZLE

104

4.4 DESIGN OF FLOTATION CIRCUIT

The configuration of the experimental set-up is given in FIG.17. Tap water was mixed with air which was added at the pump suction of the centrifugal pump. The entire flow was then held in the saturator and then was admitted through the nozzle to the flotation tank where the air comes out of the solution in form of tiny bubbles throughout the entire volume of liquid. A portion of the effluent 25% of the entire flow was taken from the top of the flotation tank and was recycled through the saturator.

Experiments were carried out under different pressures 10-60psi and different flowrates 5-20cm^3/sec. To accomplish this a stream of supersaturated water in air was diverted after the saturation tank either to the bubble observation chamber or through a 8mm needle valve to the precipitate air measurement device.

COMPRESSED AIR

EXCESS OF AIR

25%
Recycle

Valve

ROTAMETER

RECYCLE
PUMP

INLET

SATURATOR

EFFLUENT

FLOTATION
TANK

76.0cm

Valve

←——91.5CM——→

1/10 of stream

PIPES DIAMETER 28mm
Mat: Polypropylene

BUBBLES
OBSERVATION
TANK

PRECIPITATE AIR
MEASUREMENTS
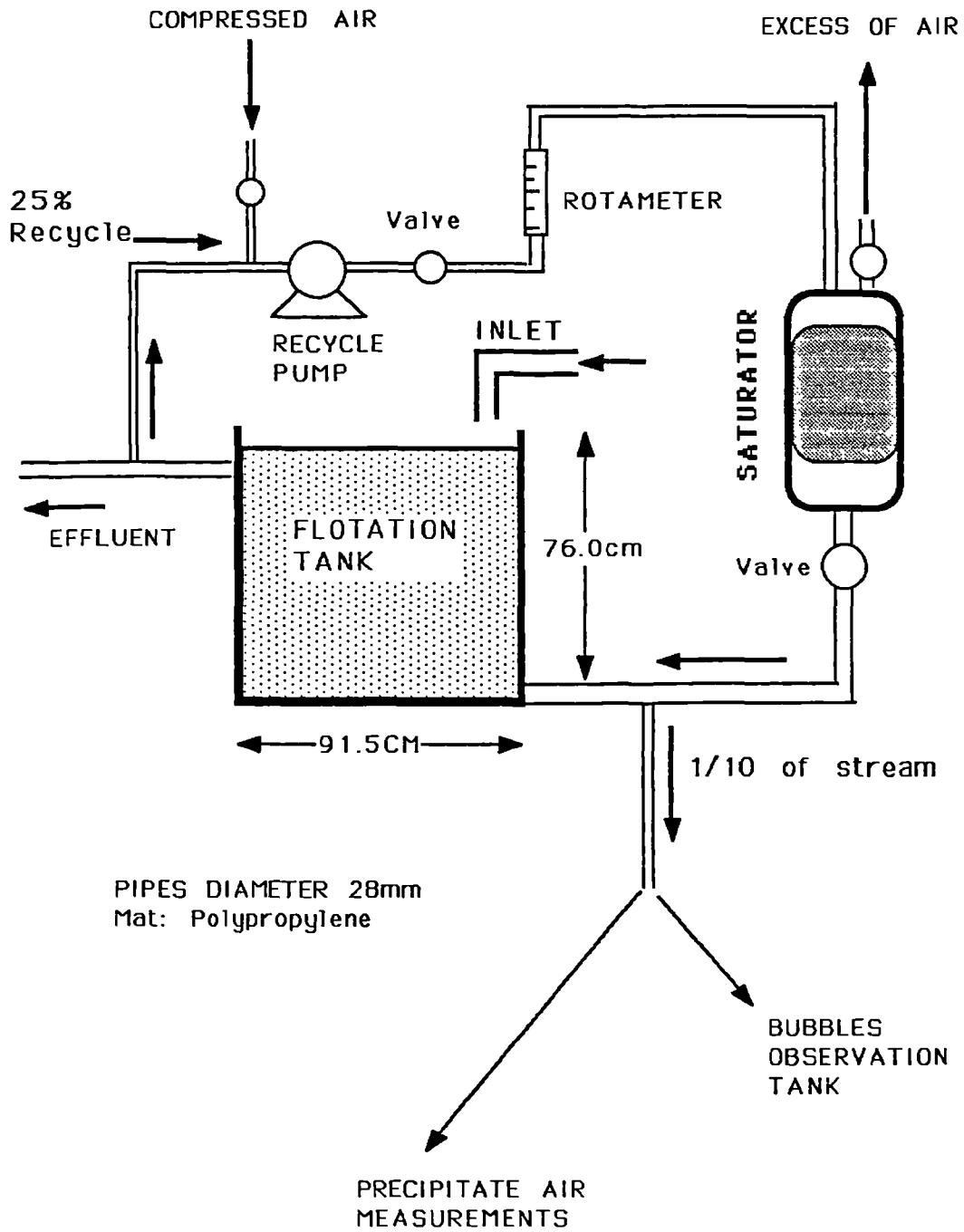
FIG.17 SCHEMATIC FLOW DIAGRAM OF THE EXPERIMENTAL
APPARATUS

4.5 BUBBLE SIZE DETERMINATION

4.5.1 BUBBLE OBSERVATION APPARATUS

The photographic technique which was used for the determination of the bubbles diameter, basically consisted of a borescope, a 35mm camera, a flash unit and an observation tank.

A) *BORESCOPE*

This was a rigid OLYMPUS borescope (F080-044-000-55) with length of 44cm and diameter of 8mm. The direction of view through the lenses was 0° and the field of view 55°. Finally the depth of field could vary from 5mm to infinity.

B) *CAMERA*

The camera which was used to photograph the bubbles was a 35mm OLYMPUS OM-2 and this was coupled with a refconvertor and an appropriate adaptor. By attaching the refconvertor into the eyepiece of the camera, it was possible for the operator to observe the object from a more comfortable position. The camera was mounted to the borescope with the aid of a special OLYMPUS adaptor.

C) *LIGHT SOURCE*

An OLYMPUS flash PE-280 was used to freeze the motion of the bubbles while a KMI light source (KMF-5) using a 100 watt quartz halogen lamp was used to illuminate the dispersion of the bubbles, so the focusing was achieved easier. The light was guided

from the light source to the borescope through a fibre light cable. The flash duration was in the range of 5-20μsec.

D) *OBSERVATION TANK*

The observation tank was made of perspex (40cmx31cmx18cm). A wire 0.22mm in diameter was allowed to immerse into solution close to the front side of the perspex tank making focus easier in this way. The sides of the observation tank were needed cleaning every 15 minutes due to adherence of the bubbles onto them and making in this way difficult the observation of the bubbles.

The arrangement of the apparatus to measure the size distribution of bubbles formed in different conditions is shown in FIG.18.
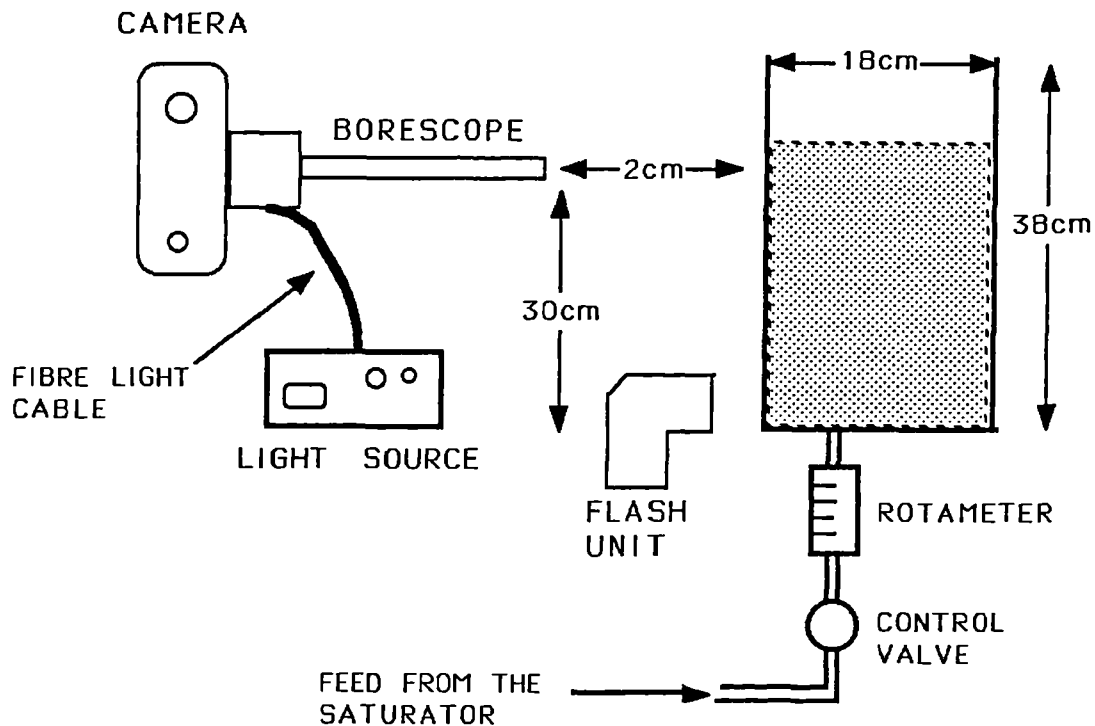
FIG.18   APPARATUS FOR MEASURING BUBBLE SIZE
DISTRIBUTIONS

4.5.2   PHOTOGRAPHIC   TECHNIQUE

The available light energy was directed into dispersion. The flash unit was moved for correct illumination at different conditions, following a trial and error method. Sometimes a diffuser was used.

The camera and the borescope were focused by looking through the lenses at a certain object, (wire 0.22mm) held 2-3mm from the front wall of the perspex tank until it produced a sharply defined image. This ensured that the plane of focus was in the actual dispersion. For a good bubble definition a high contrast

film was necessary (ILFORD 400), developed in a high contrast developer.

All the photographs were taken in a perspex tank under the same conditions in order to eliminate any error. The supersaturated solution coming via the main pipe and the branched pipe was inserted in the perspex tank through a nozzle similar to one which has been already described. The flow rate could be accurately controlled with the aid of a control valve and a rotameter. At each pressure a sequence of photographs of bubble was taken. Size distributions were therefore measured from photographs taken at this time. The resulting negatives from the photographs were projected on a large screen, and the size of the wire was used as the scaling factor. The total magnification was x50.

CHAPTER 5

5.0 RESULTS AND DISCUSSIONS

5.1 DEGREE OF SATURATION

5.1.1. CONVENTIONAL SATURATOR

5.1.1.1 MEASUREMENTS

The quantity of air which is precipitated from a supersaturated solution has a great effect on the flotation performance. Experiments were carried out to measure the quantity of released air in a pressure range of 10-60 psi and for a liquid flowrate of 5-20cm^3/sec. The gas flowrate was in the range of 0.5-1 lt/sec providing a constant, high gas/liquid (G/L) ratio.

All the measurements took place in the device which was described in Chapter 4 (sect.2) and was constructed in the laboratory. The apparatus was connected in parallel with the flotation tank. A portion of the water stream supersaturated in air leaving the saturator was directed through an 8mm needle valve in the first cylinder, as is shown in Fig.15. The reading for every setting of pressure and liquid flowrate was taken after 10min after equilibrium was reached. In order to estimate the efficiency of saturation and to provide a comparison with the experimental results, theoretical values of the precipitated air were obtained

from Henrys law and then converted to the actual volume of air by multiplying it with the current liquid flowrate.

5.1.1.2 Results, Discussion and Conclusions

Figures (19a-19f) show the relationship between generated air flowrate and liquid flowrate. The tabulated data are reported in appendix 4. In these Figures the solid lines are the theoretical values obtained by Henry's law (see eq.59) where the squares show the data points. The close correlation shows that Henry's law is obeyed over this pressure range.

FIG.20 and 21 combine these results to show the effect of pressure and liquid flowrate and it is obvious that the degree of saturation is a strong function of pressure.

FIG 19a

FIG 19b

113
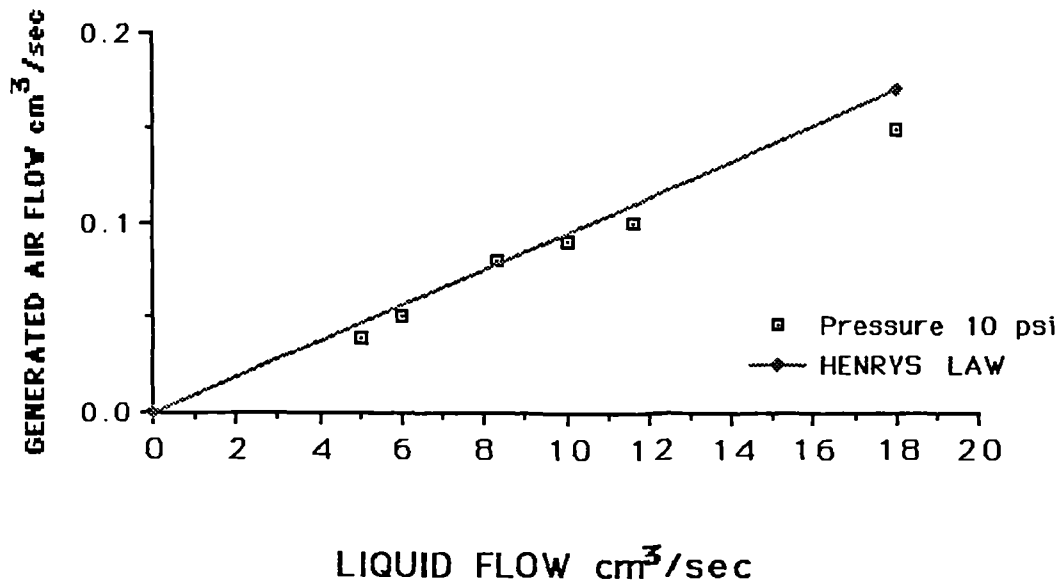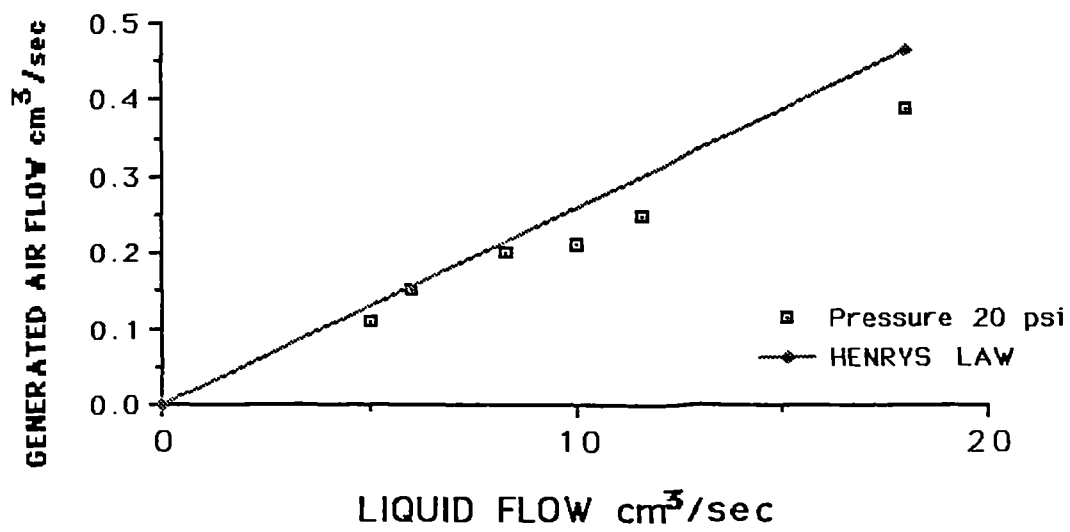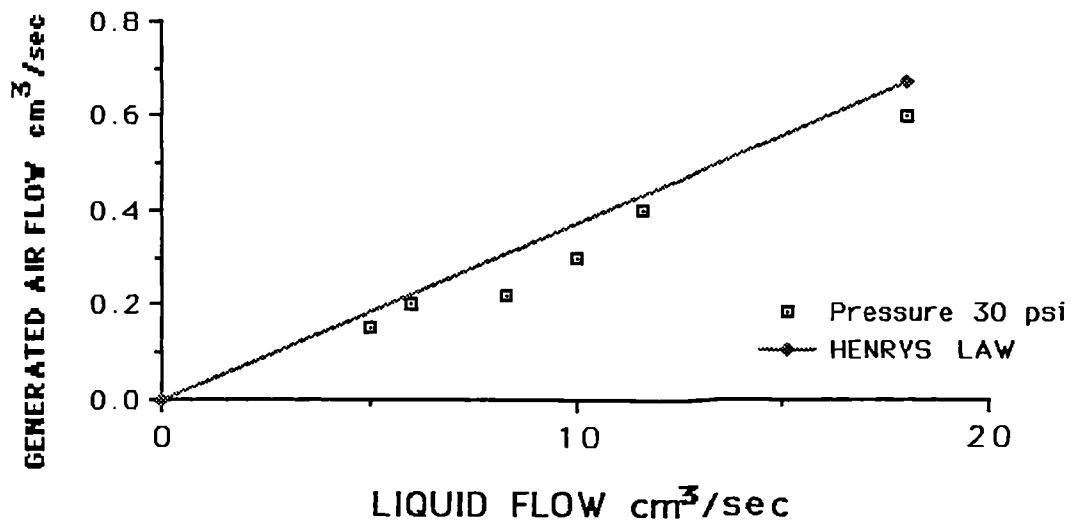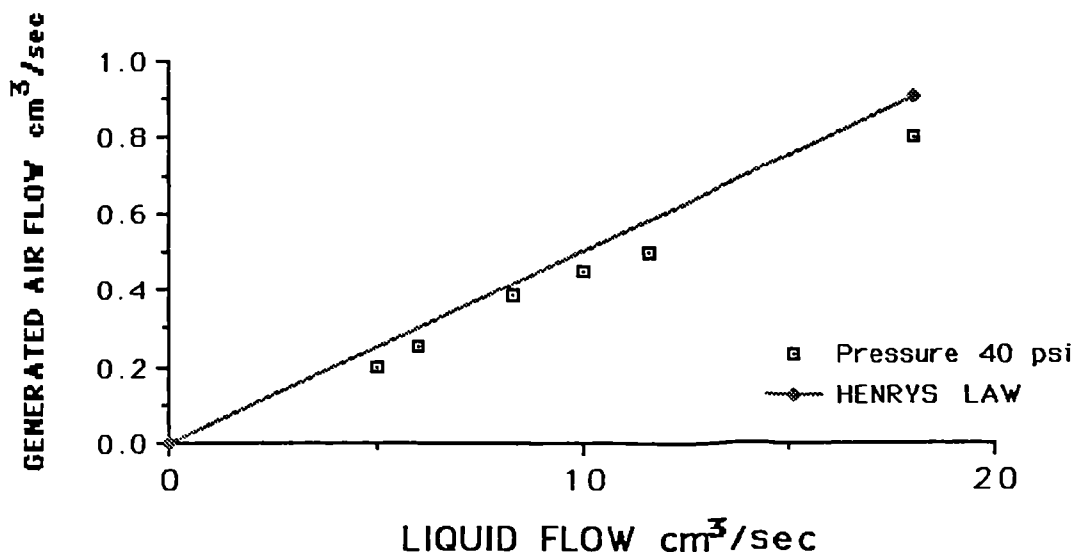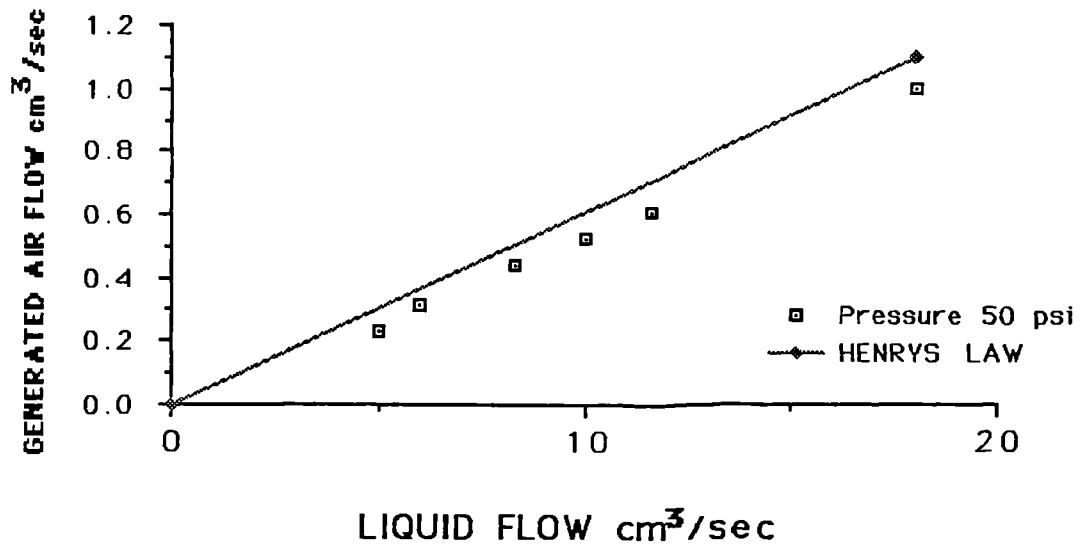
FIG. 19c

FIG. 19d

FIG 19e
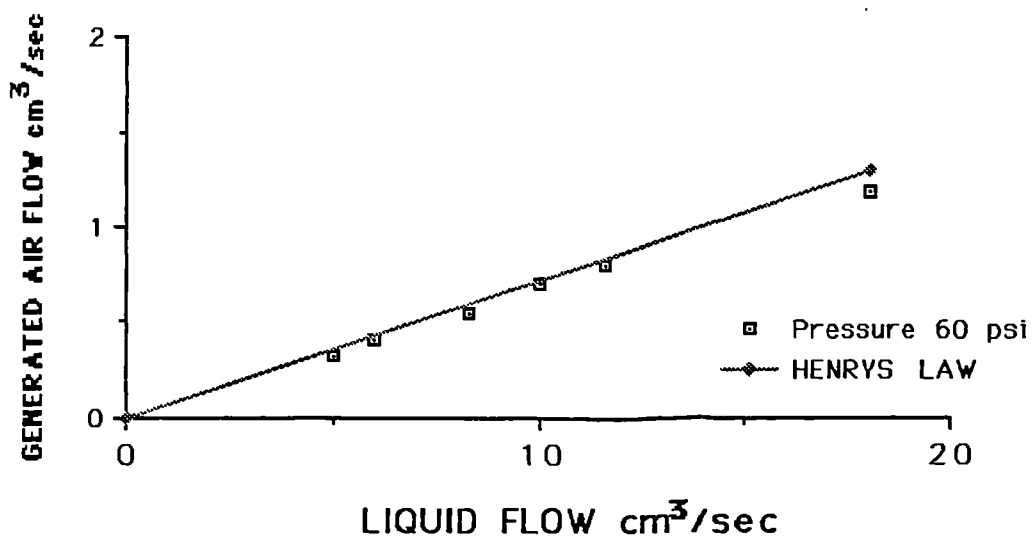
FIG 19f
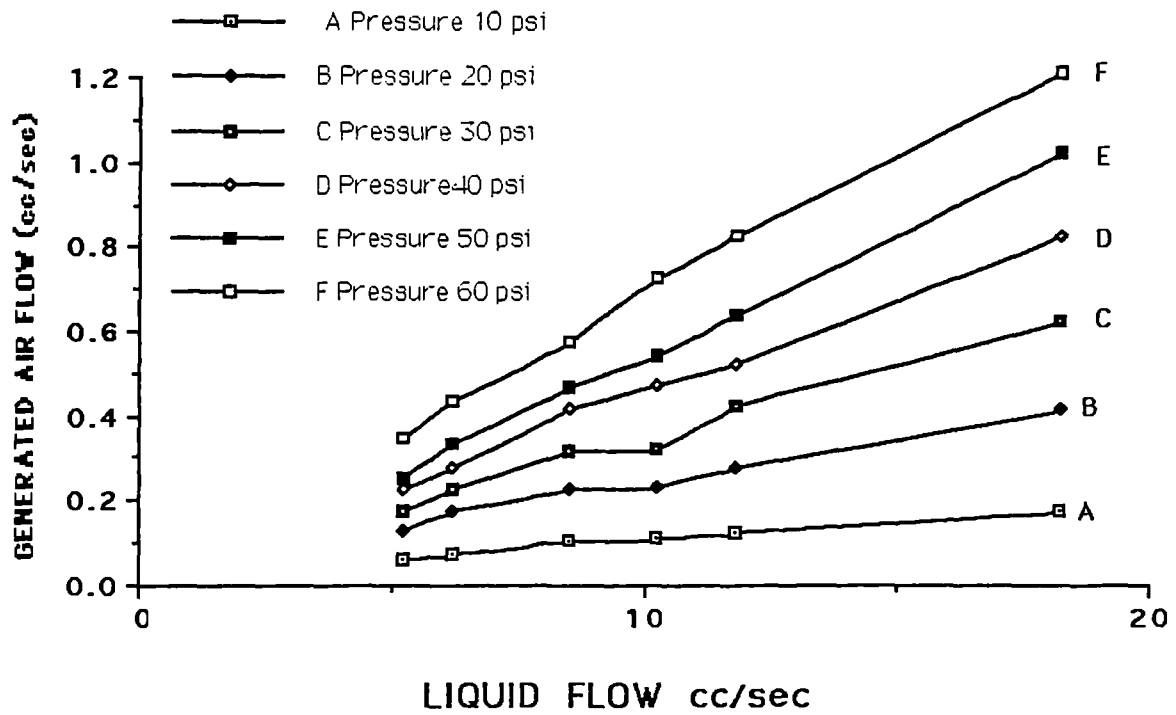
FIG.20   EFFECT OF LIQUID FLOWRATE ON THE
GENERATED AIR FLOW

116
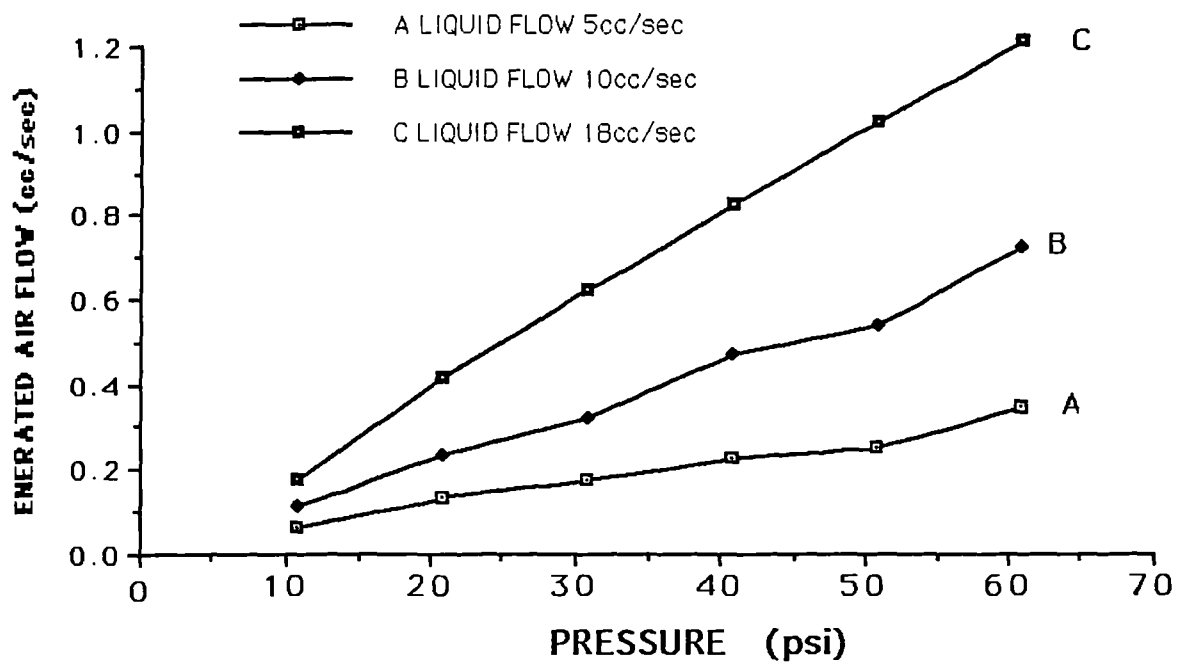
FIG. 21 EFFECT OF PRESSURE ON THE GENERATED
AIR FLOWRATE

The amount of precipitated air also increases linearly with an increase in liquid flowrate. Provided saturation was attained, experimental values corresponded very closely with the theoretical saturation concentrations. This method, therefore provides a convenient measure of the actual amount of air precipitated from saturation feeds. It also provides a means of assessing the efficiency of different saturation procedures and determining the influence of various factors such as needle valve configuration, turbulence and dilution water.

Factors affecting Degree of Saturation

CONWAY A. et al (1981), have carried out experiments using the same device as it was described in Chapter 4, to measure the quantity of the precipitated gas but they used a different configuration of nozzle. In their experiments a comparative study was made to evaluate the performance of a flotation unit using three different gases with solubilities greater than air. The gases were a) off-gas from oxygen activated sludge (solubility: 466 mg/l.Atm), b) combusted digested gas (solubility: 203 mg/l.Atm) and c) sludge-incineration stack-gas (solubility: 352 mg/l.Atm). (BISWAS A.K. 1967). Despite the high solubility of these gases compared with 23mg/l.Atm for air, a full utilization of Dissolved Air Flotation using high soluble gases has reduced efficiency when compared to air due to the·fact that the main component of the above gases, CO_2 can interfere in many ways in the chemistry of

118

the system. For example CO_2 can change the surface potential of some minerals such as calcite. (PLASKIN I.N., 1959-BISWAS A.K., 1967). Also all the above gases require extra precautions for safe handling.

Apart from choosing a gas with higher solubility in water another method to enhance the flotation performance is the use of water than air at high temperatures (60^0-80^0). In this case for the same range of pressures (40-60psi) the amount of the precipitated air increases only for water temperatures above 60^0 (SHANNON W.T.,1980).

Effect of flowrate

TAKAHASHI T. et al (1979), in their experiments found that the amount of precipitated air in the flotation tank from a saturated in air water stream increases with the increase in liquid flowrate. Our data are in a good agreement with theirs. In some cases, as you can see from FIG 22, the amount of generated air is smaller than ours, which is probably due to the fact that they have used different nozzle configurations to ours.
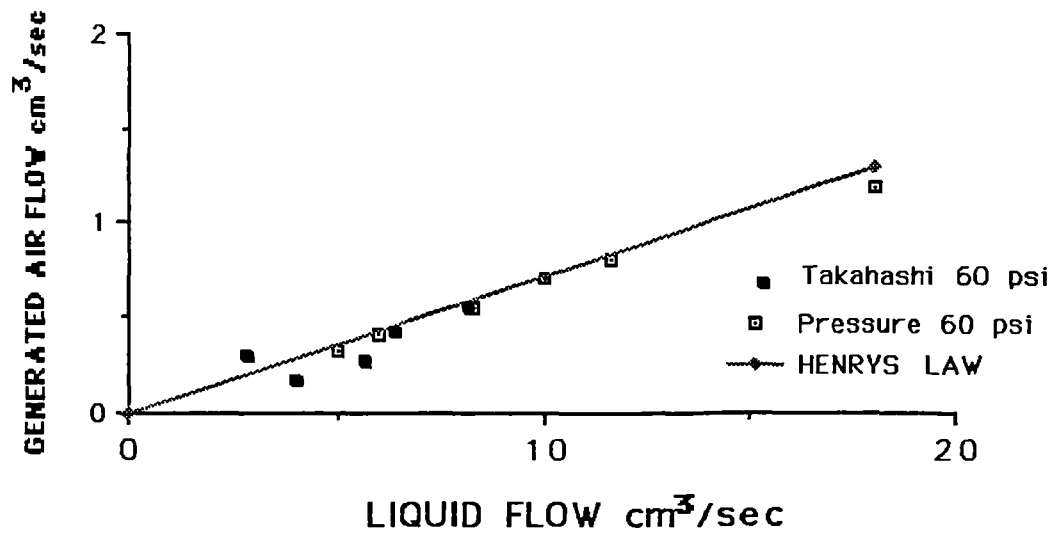
FIG 22

Effect of pressure

Finally BRATBY J. (1975) related the amount of the released air in the flotation tank with the pressure which was applied to the liquid with the following equations:

$$C=0.195 \ P \qquad\qquad [69]$$

for P > 45 psi

$$C=10^{(0.00773 \ P-0.548)} \qquad [70]$$

for P < 45 psi

where: P= Saturator gauge pressure (psi)

C= mass of air precipitated per litre of saturated
water (mg/lt)

FIG.23 shows the results and data points obtained by BRATBY J. (1975) and also with the thick line showing the empirical correlation which is the best fit of all these data given by Eq. (69-70). Superimposed on this line is our experimental points shown as big squares. It is clear that our results overlapped the BRATBY J. data points at low pressures, but due to the fact that we cannot work at higher pressures we could not confirm the straight proportion of the curve at high pressures.
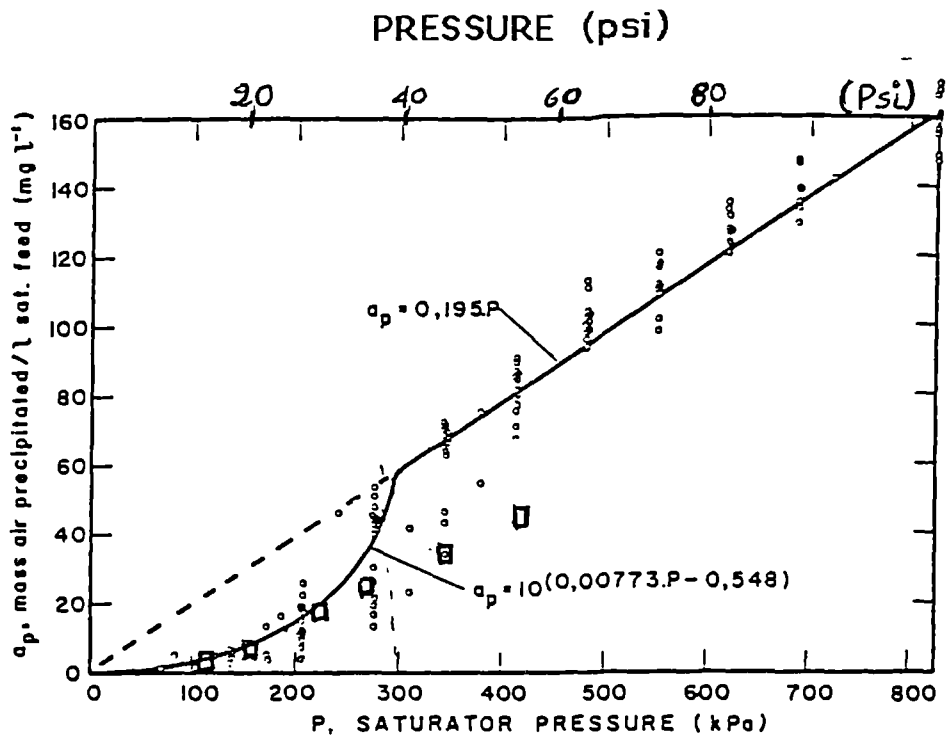
FIG. 23 EFFECT OF PRESSURE ON THE MASS OF PRECIPITATE
AIR

5.1.2. HIGEE ABSORBER

In the Higee apparatus the bulk of the liquid returns to the centre line in the non packed second chamber and flows over a weir into a large storage tank. A small sample tube dips below the liquid surface and scoops the aerated liquid and directs into a dissolved oxygen monitoring unit [ORBISPHERE LABORATORIES, Mod: 26072, sensor: 21152]. From these results the dissolved air can be calculated because both oxygen and nitrogen have nearly the same diffusivities.

Results were taken with packings of varying thickness, (2.5cm and 5cm), and also without packing. The packing was a rigid mesh made from polypropylene having a porosity greater than 95% and the width of the polypropylene mesh element was about 1mm; its commercial trade name was DECLON. The variables are the speed of rotation (which defines the "g" force at the outer periphery and thus the pressure of the absorbing gas), liquid flowrate and gas flowrate. All the packings had the same radial depth of 10cm but some runs were carried out with thinner axial length of packing (2.5cm) which increased the liquid velocities and also helped to reduce circulation within the packing. The gas and liquid flow were controlled for each set of runs. However, because of the high throughput the temperature could not be controlled but it was maintained in the range 10-20 $^{\circ}$C.

5.1.2.1 Obtained results, discussion and conclusion.

The results of all the runs for different conditions are tabulated in Appendix 3. The results were classified in various groups and and the parameters which we examined were:

1) Effect of Plenum pressure on the amount of released air (which for a fixed radial length of packing is directly linked to the speed)

2) Effect of liquid flowrate on the amount of released air for different settings of gas flowrate, packings and rotation speed.

3) Effect of gas flowrate on amount of released air

Effect of pressure

FIG.24 shows the results of two runs one using thick DECLON as packing material and the other no packing at all. It can be seen, therefore, that in the case where packing was used, the amount of air released is smaller than when no packing is used. The varying pressures produced as a result of the different rotation speeds do not appear to influence the final concentration of released air. It is expected that when packing is present the gas bubbles continually coalesce and split as they migrate through the packing, this should produce a more efficient degree of saturation, however the results prove otherwise. This is probably due to the very high gas/liquid flow used for these runs and the initial bubbles formed by jet action without the packing, are very small.

The runs in FIG. 24 were carried out at low liquid flows, therefore a series of runs were undertaken at high liquid throughputs. FIG.25 shows that the efficiency is improved at lower pressures and unlike FIG. 24 the generated air increases with pressure, this can be economically advantageous because better saturation levels can be obtained with lower energy consumption.

For this type of saturator, pressure is linked to speed and effective gravity, thus at high pressure (high speed), although the bubbles should be smaller, the higher centrifugal speeds mean that the bubbles move faster and spend less time in the liquid and will give poorer performance.
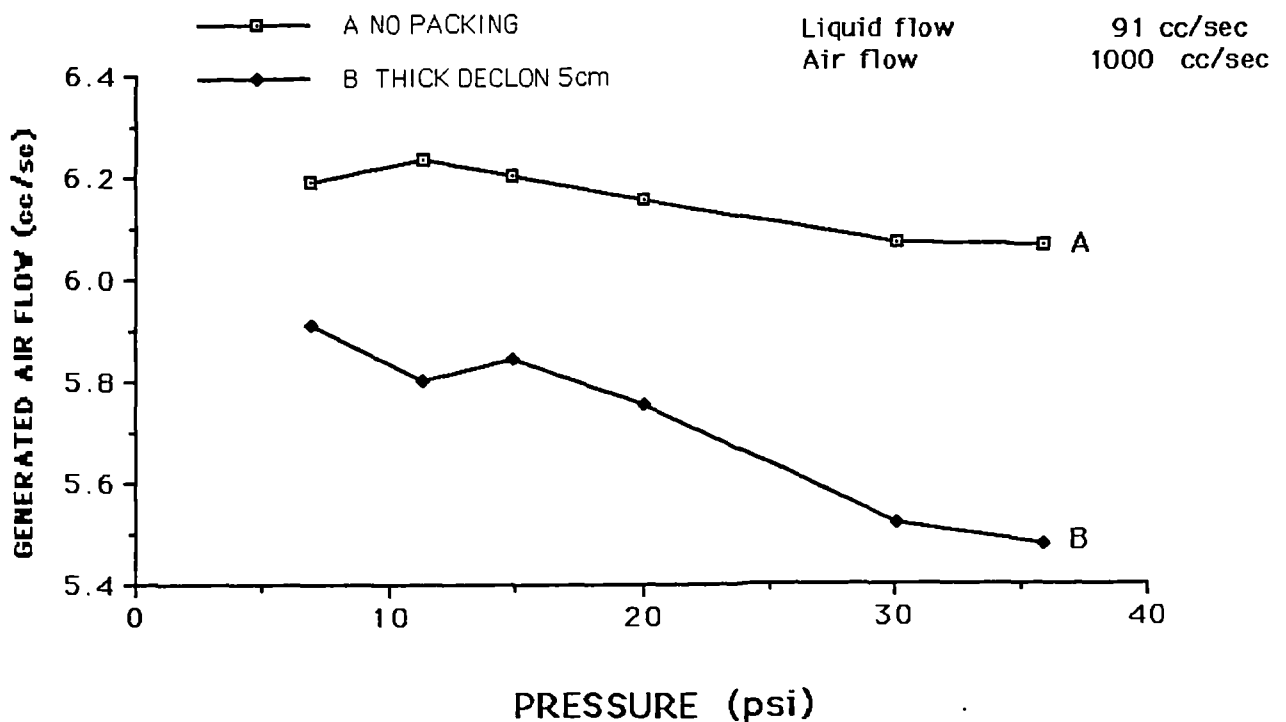
FIG. 24 EFFECT OF PLENUM PRESSURE ON RELEASED AIR
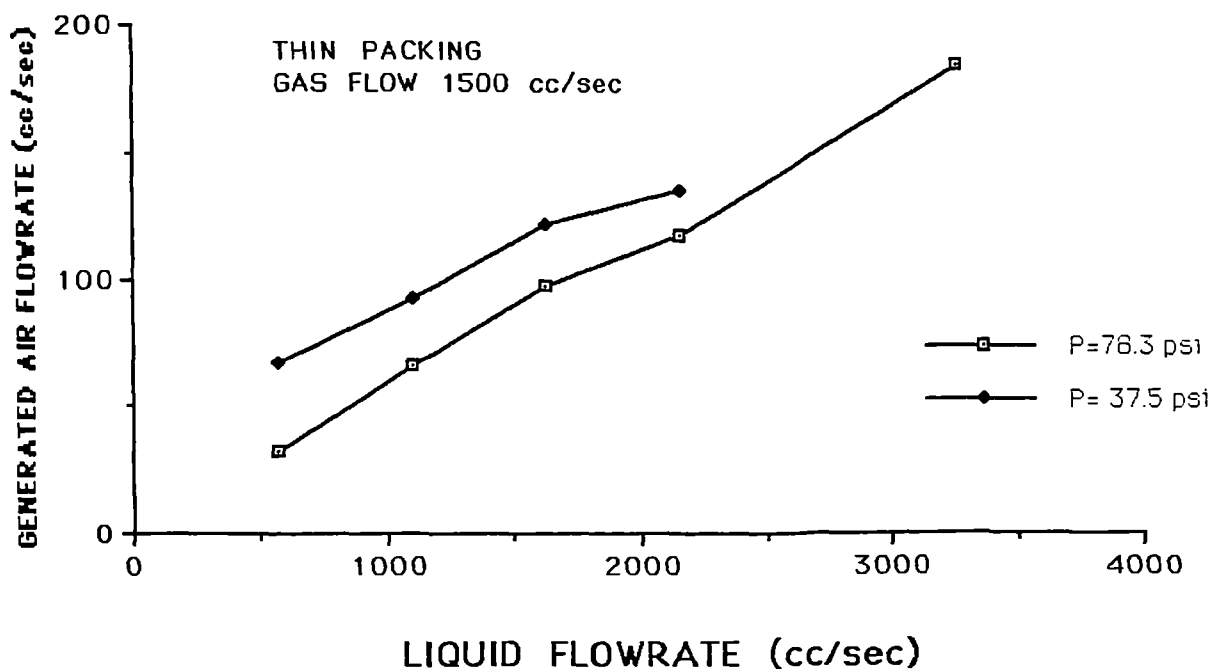
FIG.25 EFFECT OF LIQUID FLOWRATE ON THE AMOUNT OF RELEASED AIR

Effect of liquid throughput

To examine how important high liquid throughput and the presence of the packing was during the operation, two types of packing were used, thin and thick DECLON. FIG.26 reveals that thin packing gives slightly better absorption of air. This happens because the thin packing produces a higher mean liquid velocity and probably near plug flow conditions without back mixing. It is

well known that back-mixing must be avoided in absorption columns.

It is interesting to note that the gas liquid ratios used for these measurements was in the range 1-0.4 whereas in FIG. 24 the gas/liquid ratio was 11:1 which accounted for the poorer performance with packing present.
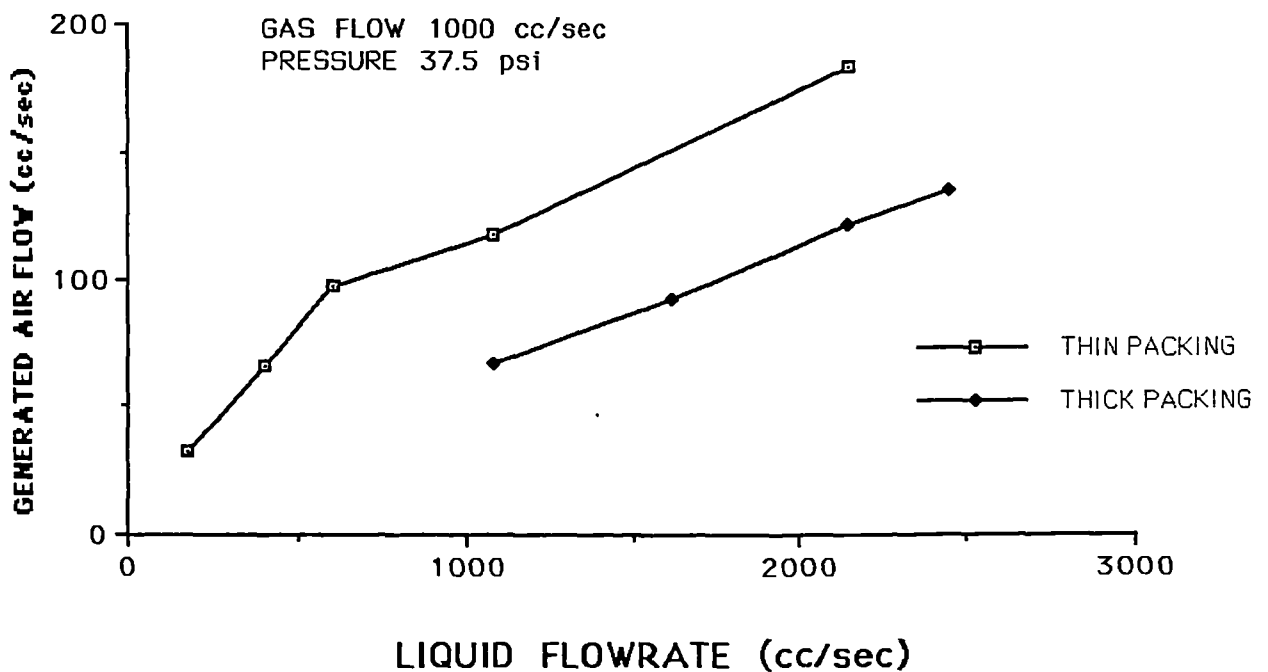
FIG.26 EFFECT OF LIQUID FLOWRATE ON THE AMOUNT OF RELEASED AIR

126

Effect of gas flowrate

FIG. 27 shows that in general the higher gas flows produce a better performance but the interaction between gas and liquid flow is complex as is expected because the retention time is interralated. Proof of this is provided by FIG.27 which appears to show that for this one speed (one pressure) there appears to be in optimum liquid throughout (greater than 2000 cc/sec) when the effect of gas flow does not appear to be important.
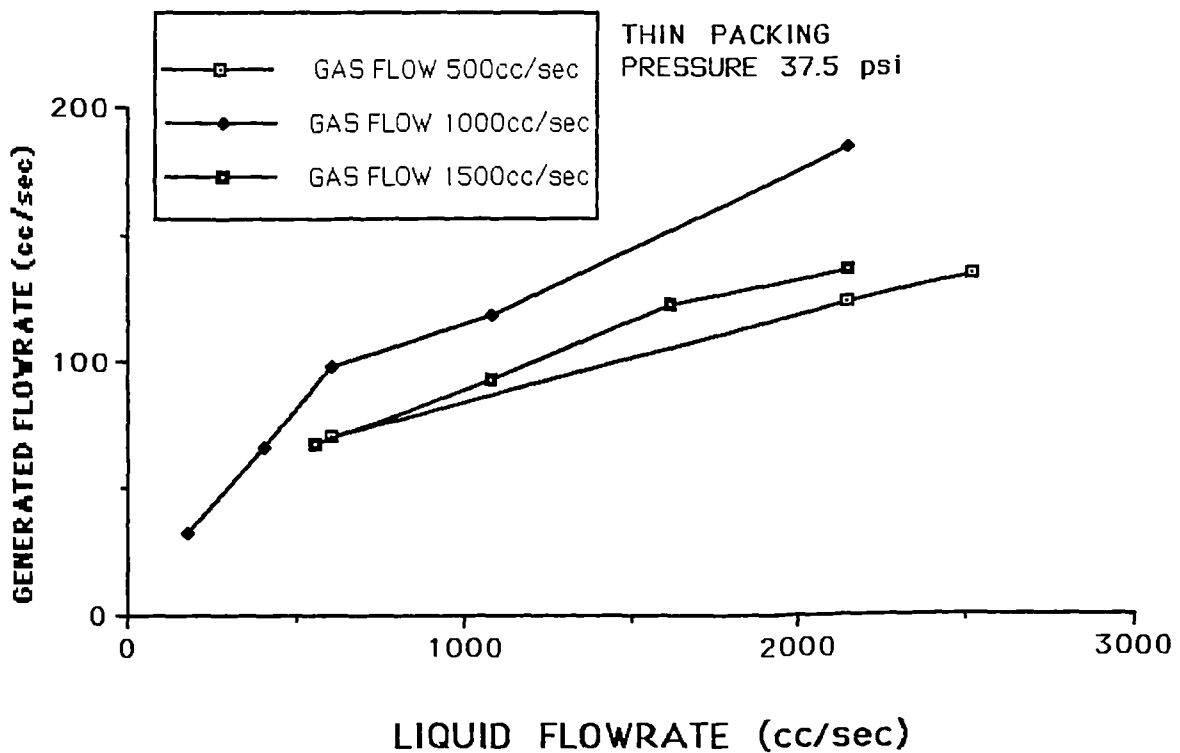
FIG.27 EFFECT OF LIQUID FLOWRATE ON THE AMOUNT OF THE RELEASED AIR

127

Experiments were also carried out for the low liquid flows and when no packing is present, the gas flow, as shown in FIG. 28, has no important role on the performance of the Higee absorber. On the other hand, pressure seems to be the dominant factor for enhancing performance at these conditions. Without packing the bubbles are not impeded as they migrate towards the centre line and thus the gas flow effect should only effect the initial bubble size. For single nozzle and one "g", the bubble size decreases with gas flow and in theory the mass transfer should be improved, however more bubbles are produced per unit volume and the potential for coalescence increase which reduces the mass transfer. Without packing coalescence will occur with the net result that the two mass transfer effects cancel each other out, resulting in only a marginal gas flow effect as seen in FIG.28.
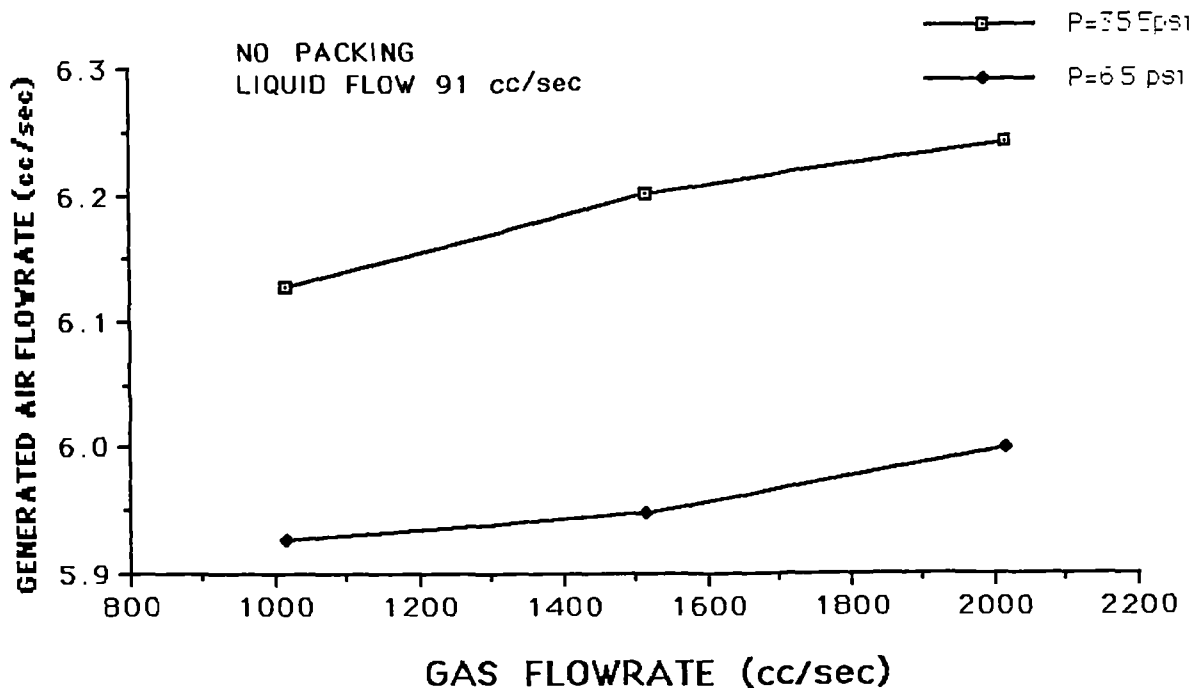
FIG.28 EFFECT OF GAS ON THE AMOUNT OF RELEASED AIR

Comparative study of saturation levels

It is obviously important to compare the performance of the two saturators.

For comparison reasons the theoretical values obtained from Henry's Law and the experimental results which were obtained from both the experimental devices used in this work. The comparison is shown in FIG. 29. It is apparent that the liquid in the sample point was still supersaturated in air. Obviously, the saturation levels which were achieved with the Higee absorber are much higher than those obtained from the conventional systems.
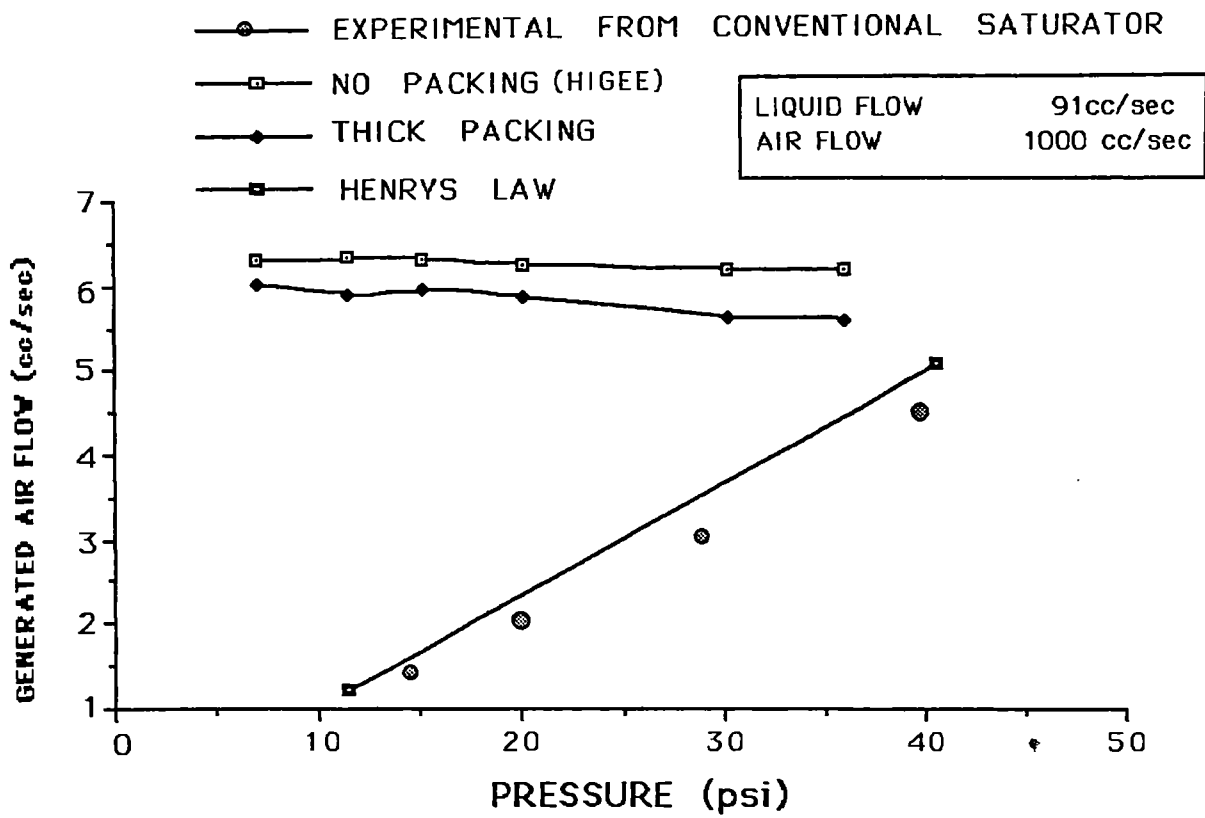
FIG. 29 EFFECT OF PRESSURE ON THE AMOUNT OF GENERATED AIR FLOW WITH THE CONVENTIONAL AND HIGEE TECHNIQUES

130

5.2 Bubble size measurements

5.2.1 Conventional saturator results

The resulting negatives from the photographs were projected on a large screen and for comparison reasons an object of known size was protruded.

The photographs (1-18) show that the bubbles appeared spherical but, due to their velocity sometimes they appeared blurred which was attributed to imperfect flash conditions and the large scale of magnification which was achieved through the arrangement of lenses.

In all the runs a number of bubbles were photographed to within a zone 2cm from the level of the water in the perspex tank and the average bubble diameter was evaluated. The experimental program can be divided into the following experiments:

1) Effect of liquid flowrate on bubble size.

2) Effect of pressure on bubble size.

A statistical analysis was performed to evaluate the validity of the observed bubble diameters. The results of the photographs were shown in histograms 30a-30r. (see APPENDIX 1)

The results of the analysis were plotted in FIG.31-33 against the calculated results which derived from Eq.(55). (see APPENDIX 2)

The standard deviation of the obtained results was in the range of 15-30μm. 95% of the generated bubbles lay between 30-200μm. Also during the experiments at higher liquid flowrates (18cc/sec) large bubbles were observed but they were not captured in the film. These were probably formed by the growth of bubbles in corners or, attached to the outlet pipes for here the water is still supersaturated. Of course the formation of this size of bubbles is undesirable due to the fact that air is wasted for their formation and also, they can cause turbulence in the system where fragile flocs appear.

5.2.2 Higee Saturator results

The saturated liquid which returned to the central axis, and then flowed over the collection weir, from which a small sample was directed into the same bubble visualization chamber as described in Chapter 4. The appearance of the liquid when viewed with the borescope was of a slight cloudiness but it was not possible to photograph or observe any bubbles. This could be either because the bubbles are too small or because the pressure of the liquid had reduced to atmospheric by the time it reaches the weir and all the bubbles had come out of the solution before reaching the measurement cell. The latter concept is unlikely to

be true as the absorbed gas results show in section 5.1.2.1 there is clearly a large quantity of dissolved gas present by the time the liquid gets to the oxygen meter. The Higee unit was only available for a limited time and it was not possible redesign the liquid take-off section to enable any bubbles present to b e examined. Further more if the bubbles are very small a much more expensive and complex bubble size monitoring system required.

PRESSURE 10 (psi)

LIQUID FLOWRATE   5cc/sec

PHOTOGRAPH 1

PRESSURE 20 (psi)

LIQUID FLOWRATE   5cc/sec

PHOTOGRAPH 2
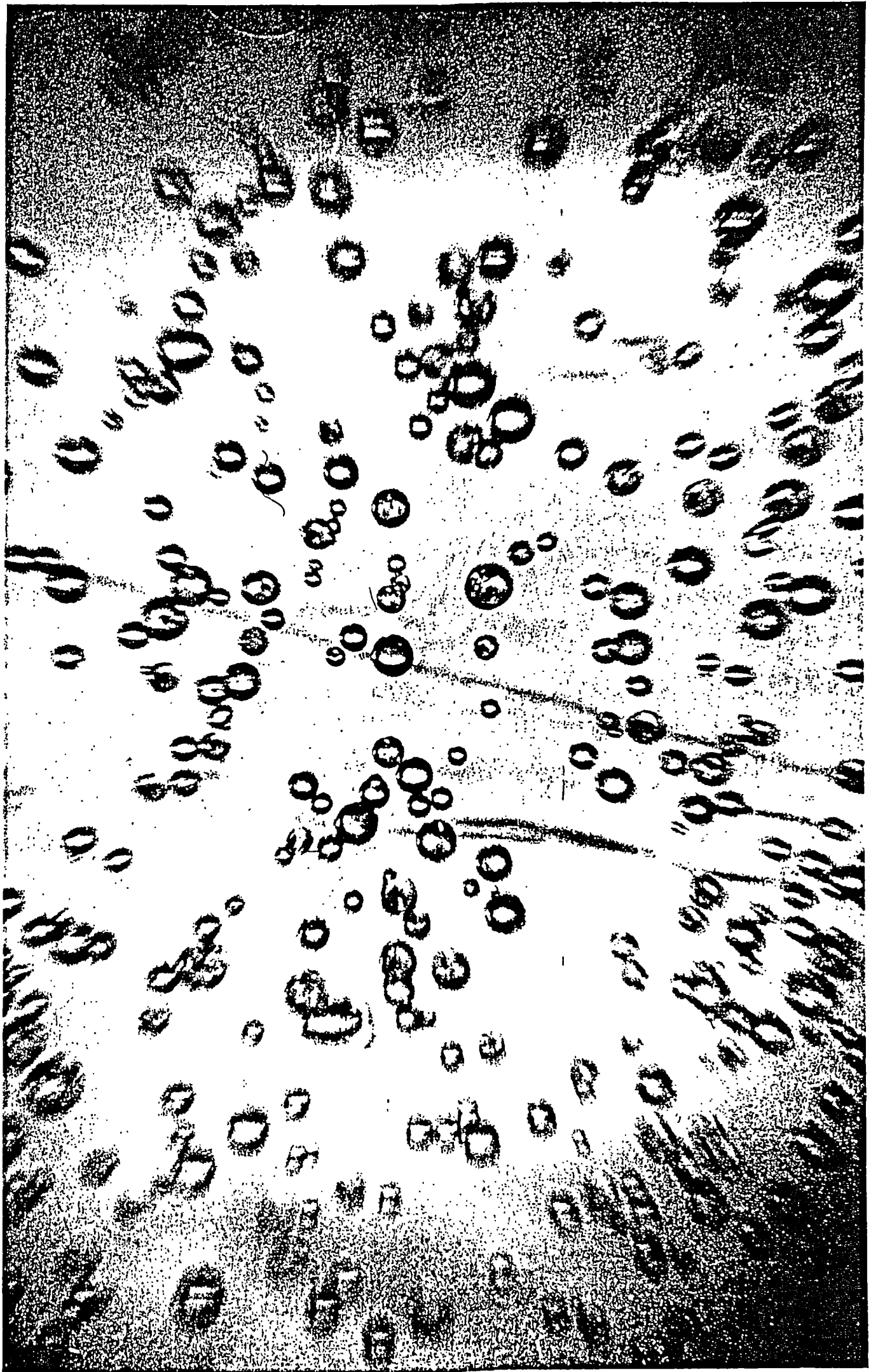
PRESSURE 30 (psi)

LIQUID FLOWRATE 5cc/sec

PHOTOGRAPH 3
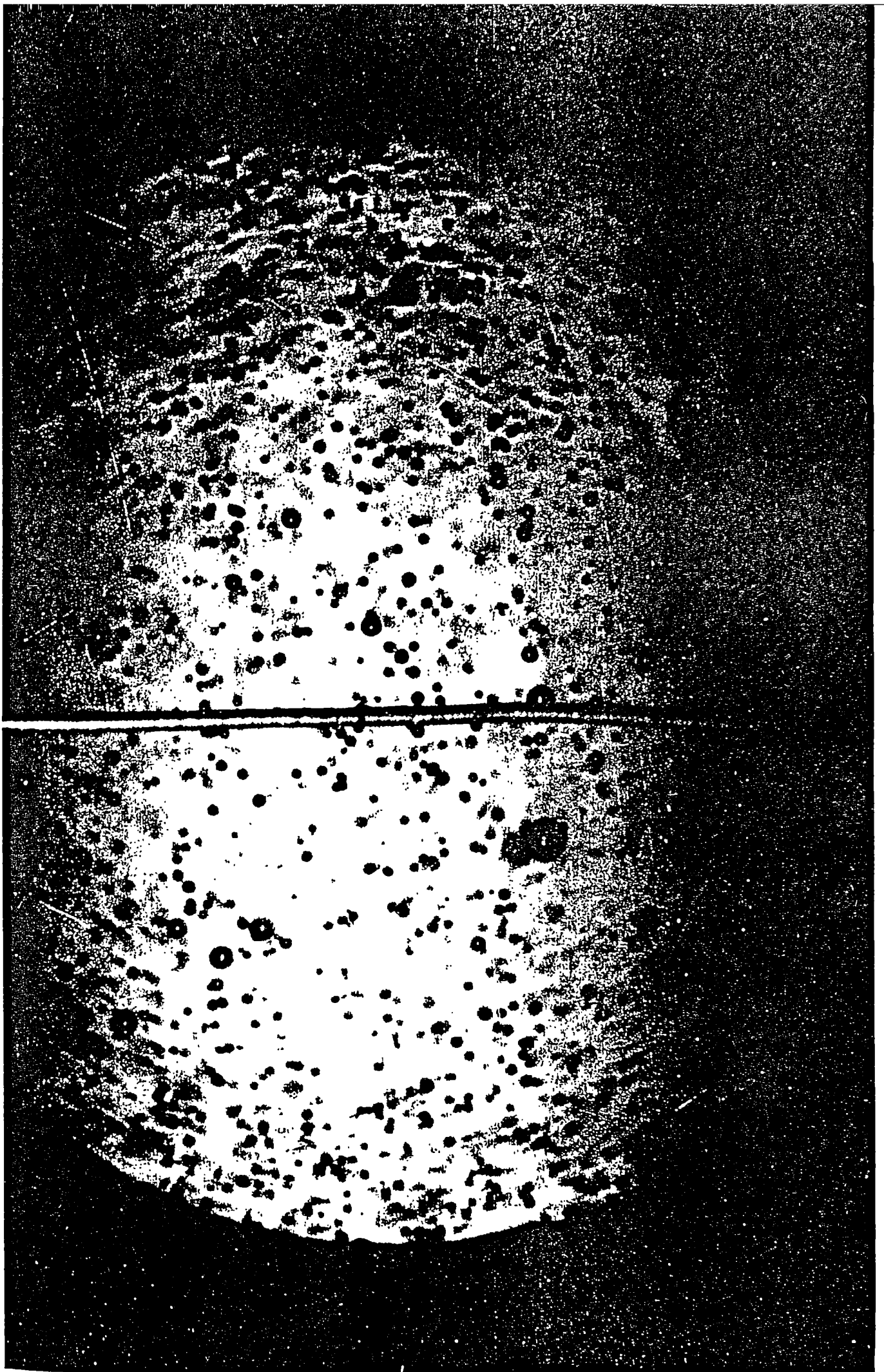
PRESSURE 40 (psi)

LIQUID FLOWRATE   5cc/sec

PHOTOGRAPH 4
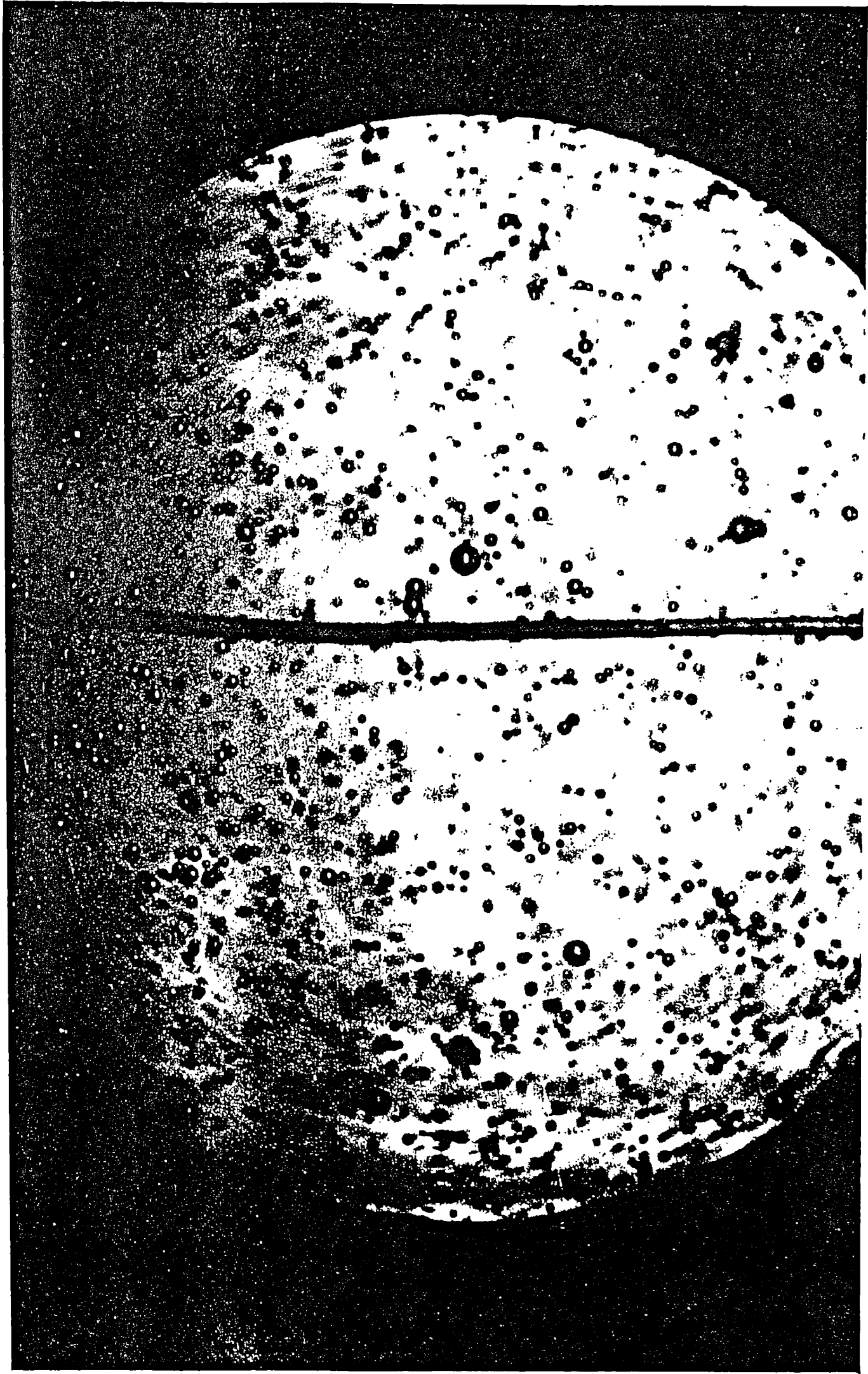
PRESSURE 50 (psi)

LIQUID FLOWRATE   5cc/sec

PHOTOGRAPH 5
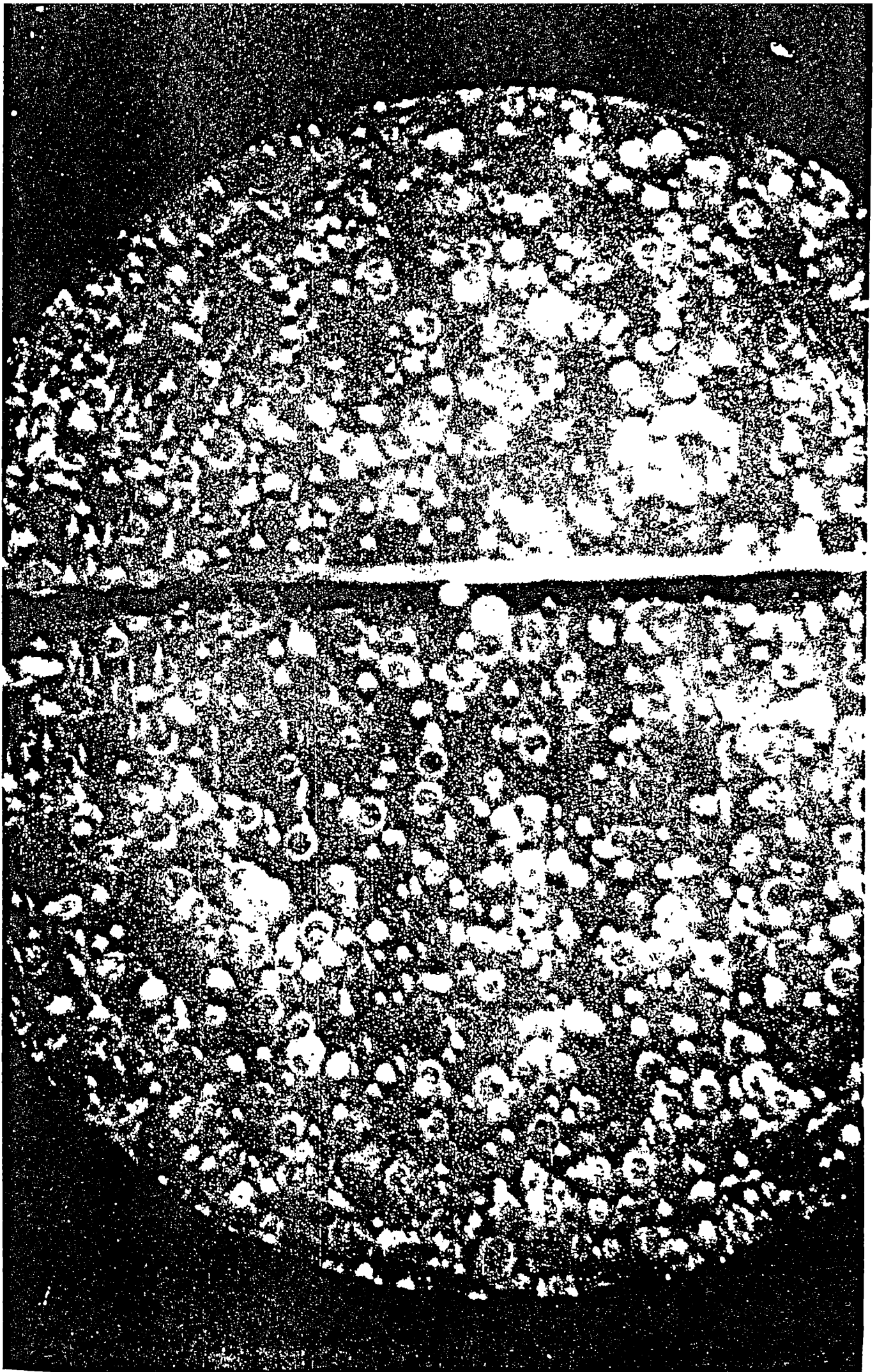
PRESSURE 60 (psi)

LIQUID FLOWRATE   5cc/sec

PHOTOGRAPH 6
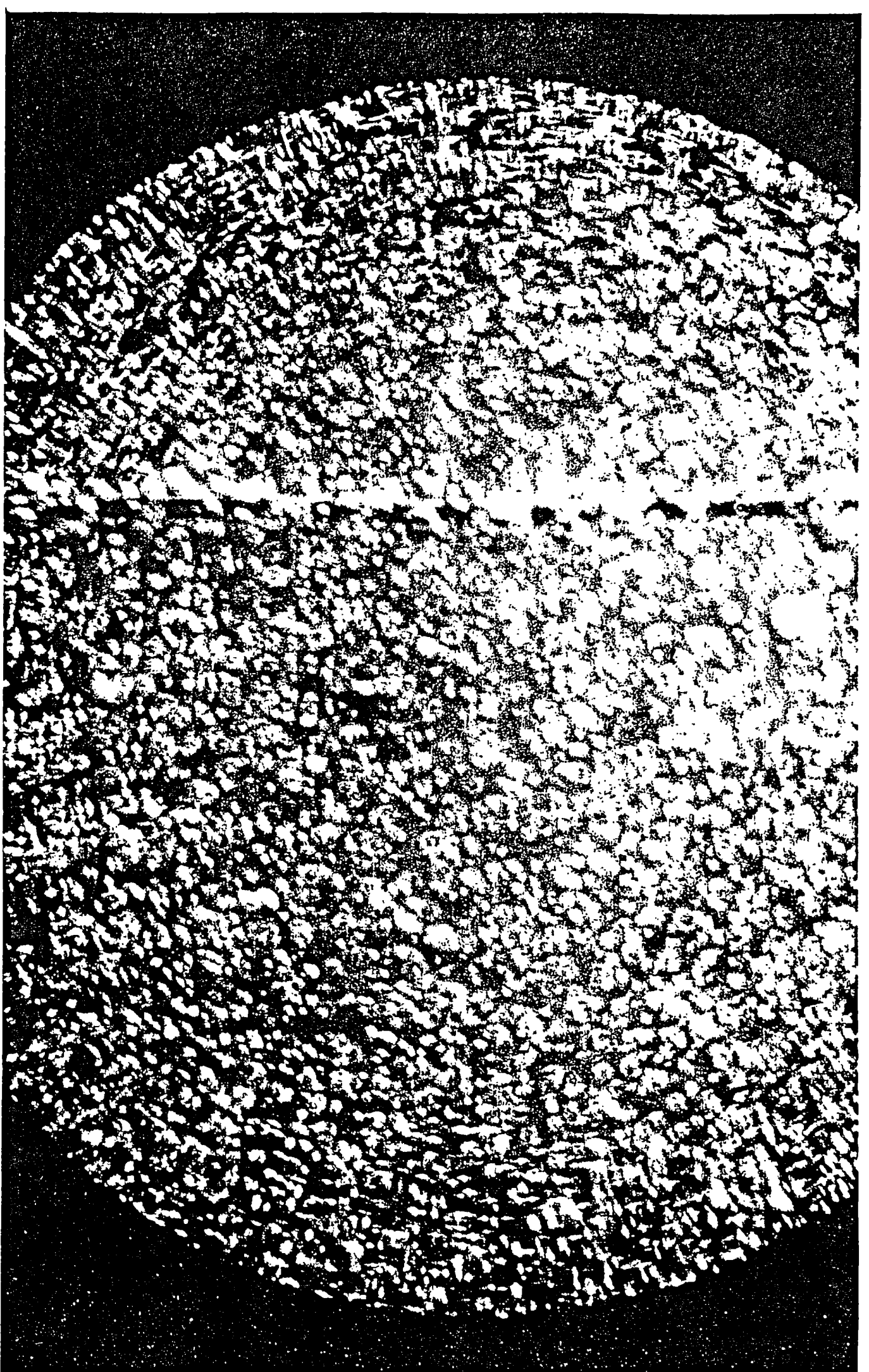
PRESSURE 10 (psi)

LIQUID FLOWRATE   10cc/sec

PHOTOGRAPH 7
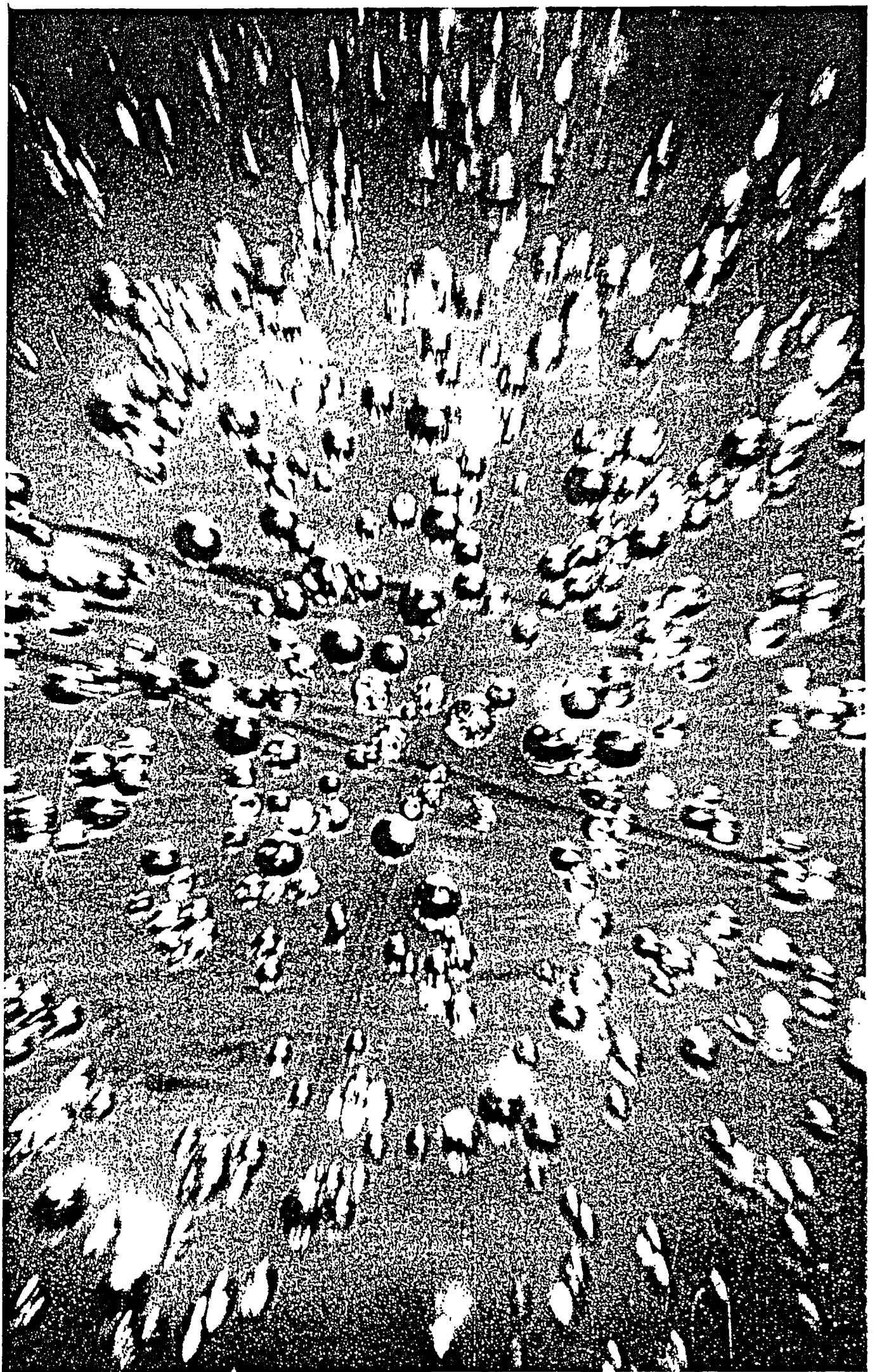
PRESSURE 20 (psi)

LIQUID FLOWRATE   10cc/sec

PHOTOGRAPH 8
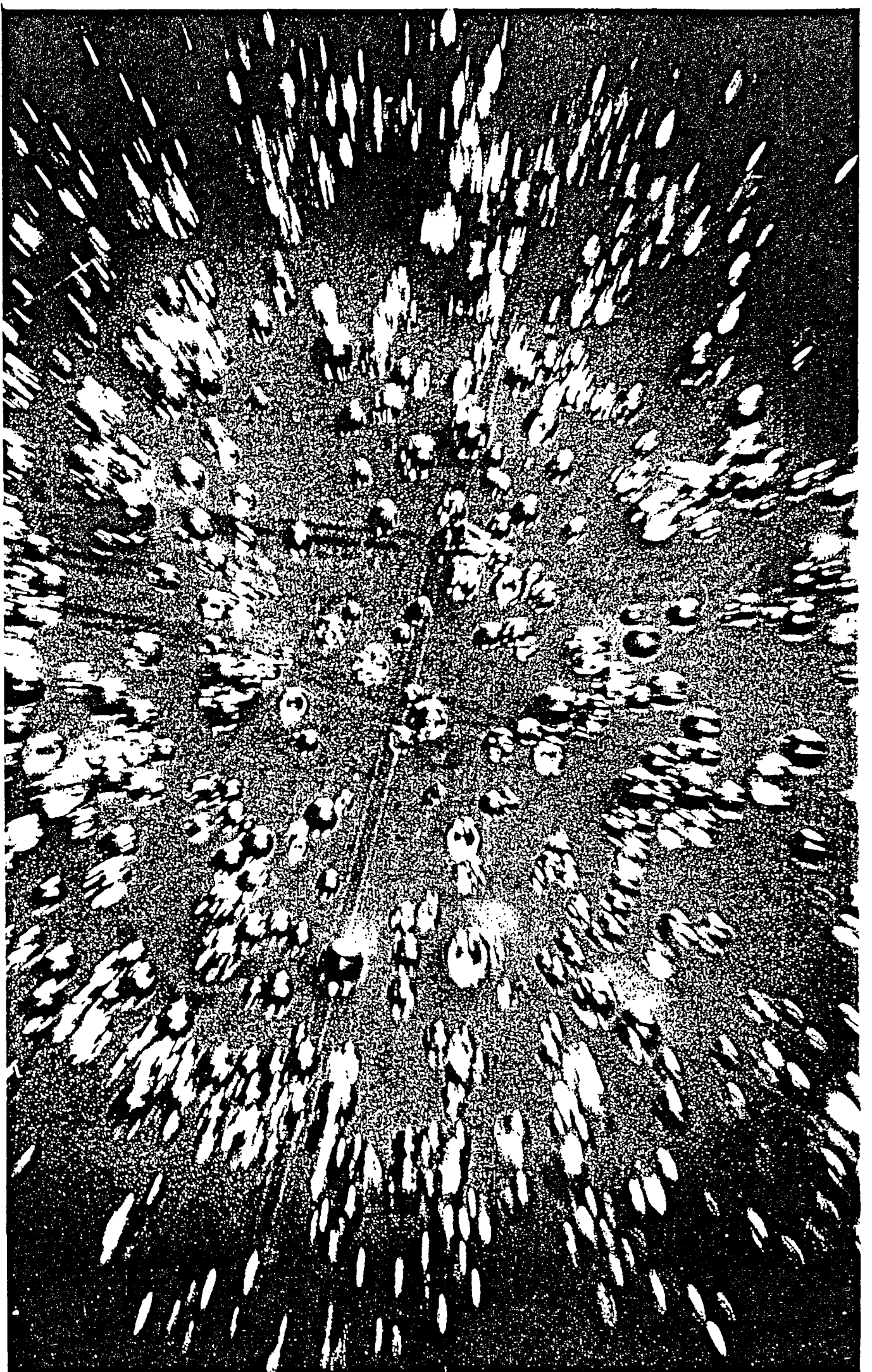
PRESSURE 30 (psi)

LIQUID FLOWRATE   10cc/sec

PHOTOGRAPH 9
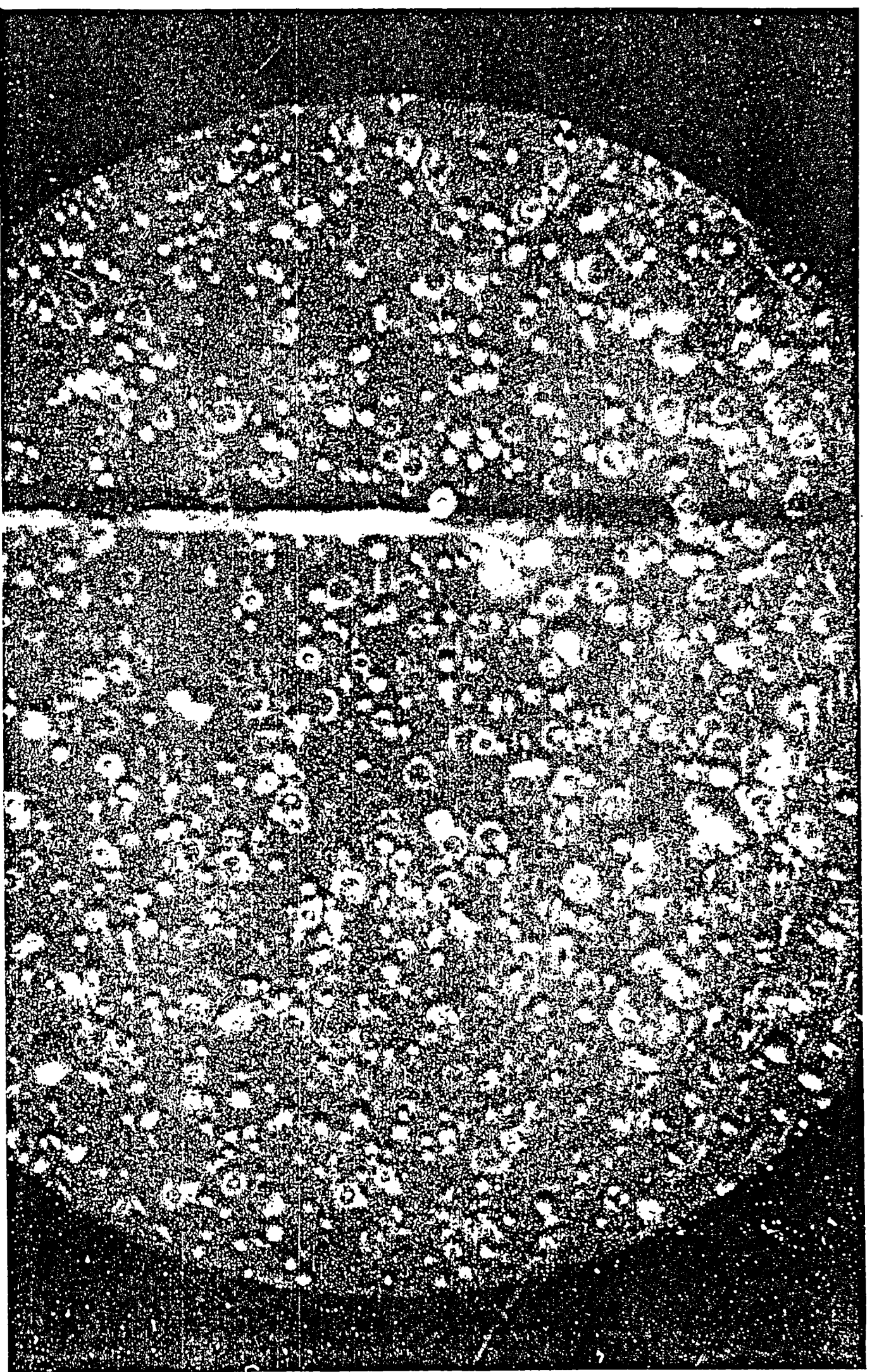
PRESSURE 40 (psi)

LIQUID FLOWRATE   10cc/sec

PHOTOGRAPH 10
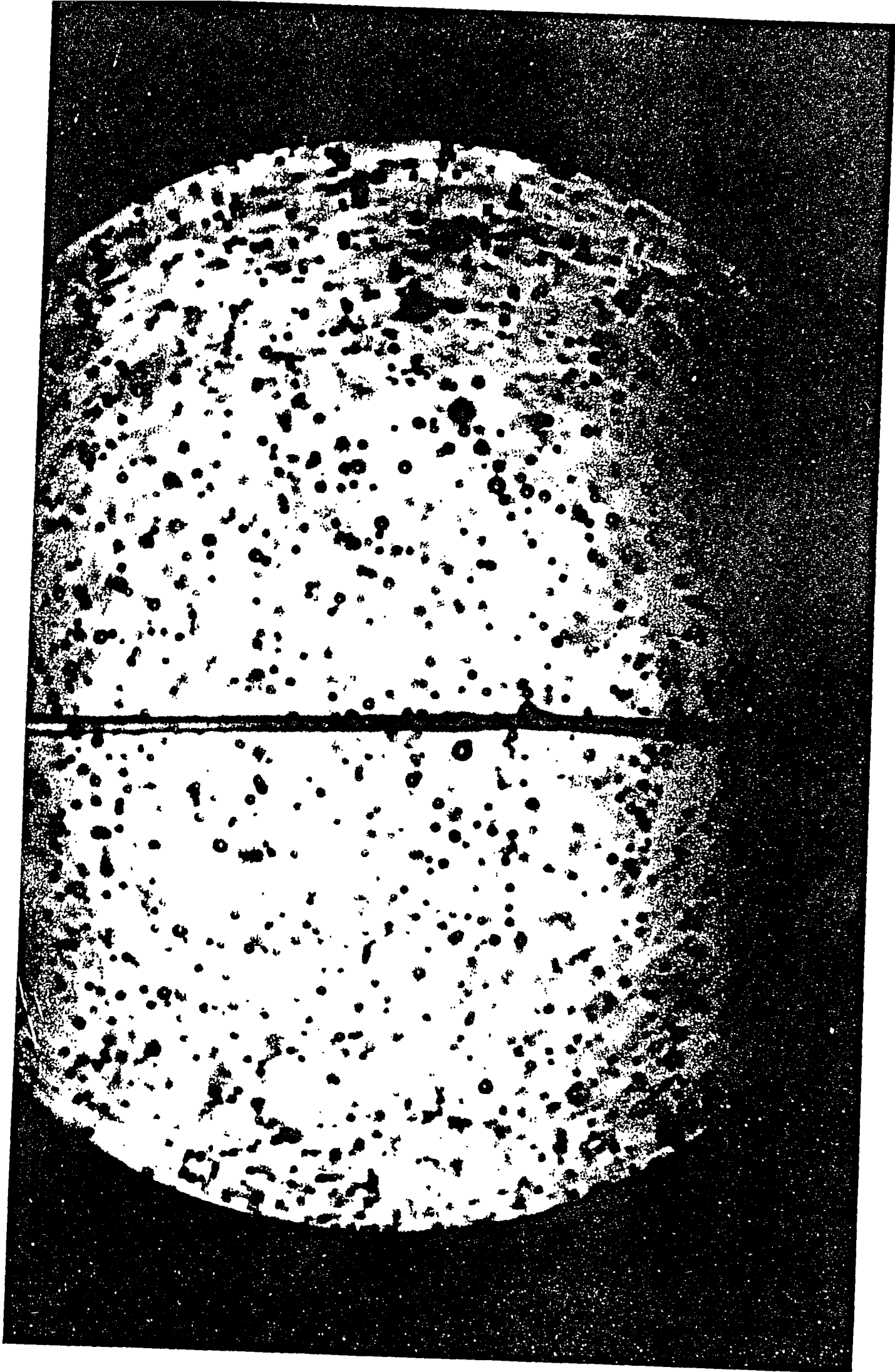
PRESSURE 50 (psi)

LIQUID FLOWRATE 10cc/sec

PHOTOGRAPH 11
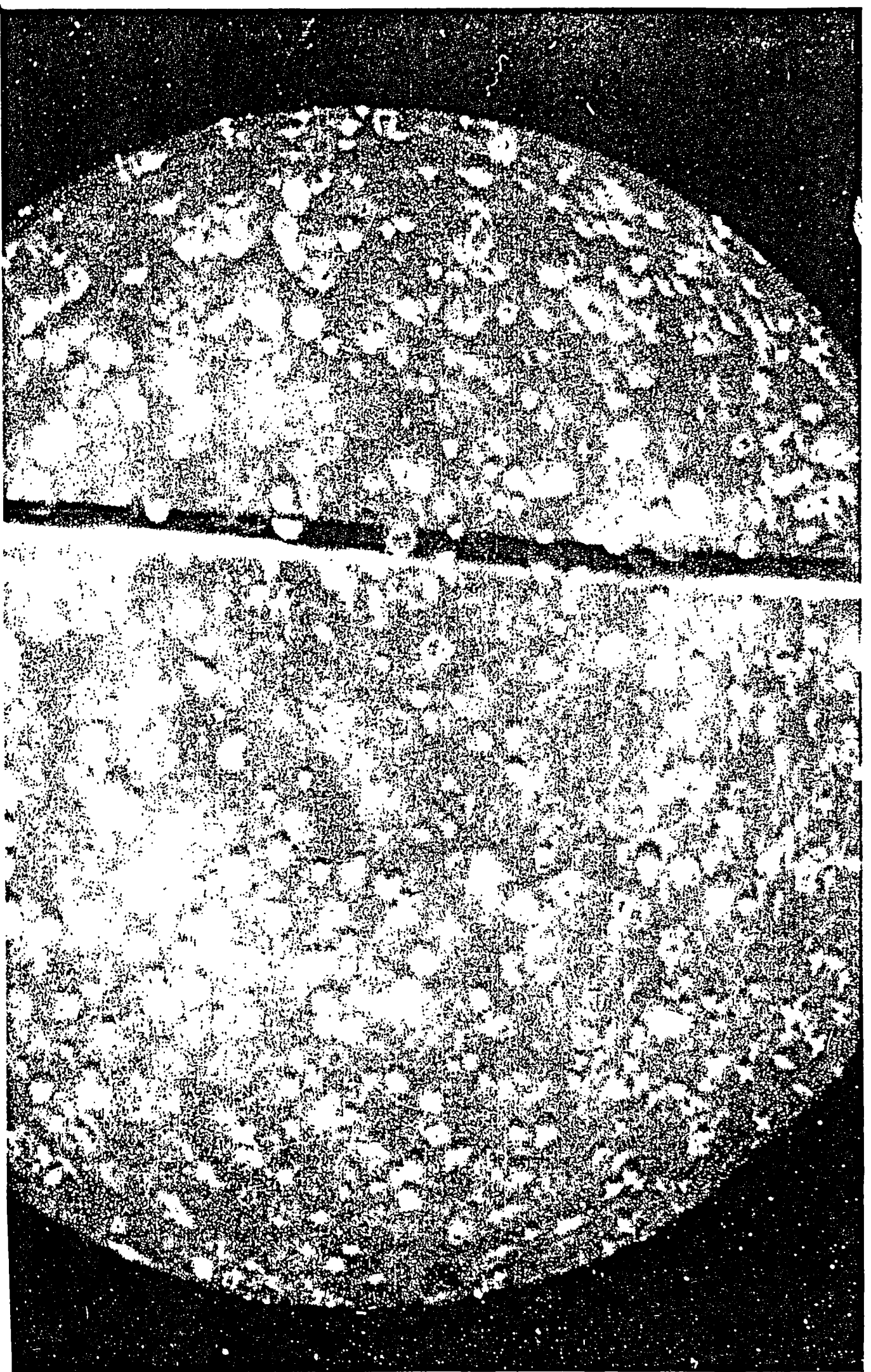
PRESSURE 60 (psi)

LIQUID FLOWRATE 10cc/sec

PHOTOGRAPH 12
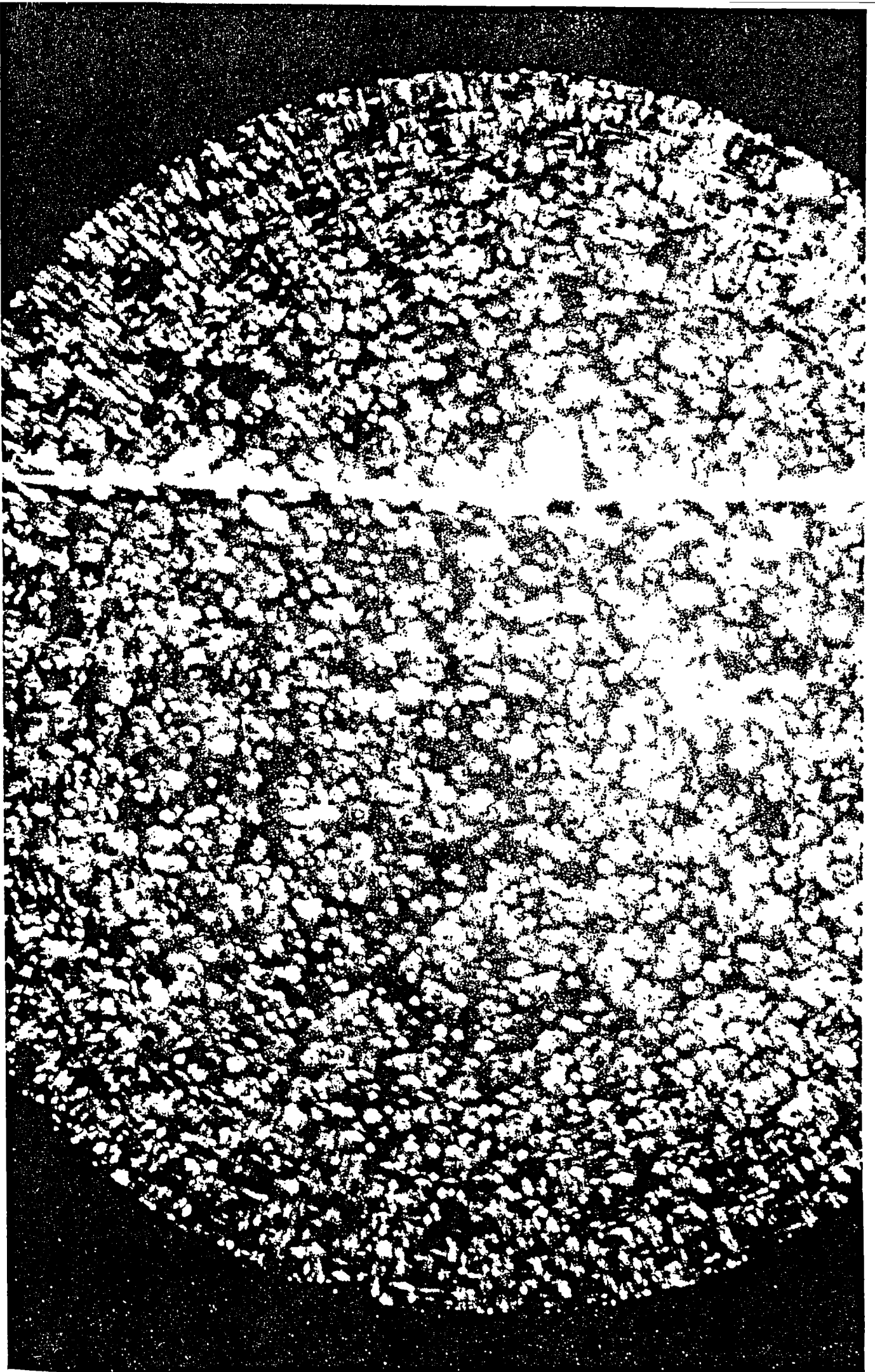
PRESSURE 10 (psi)

LIQUID FLOWRATE   18cc/sec

PHOTOGRAPH 13
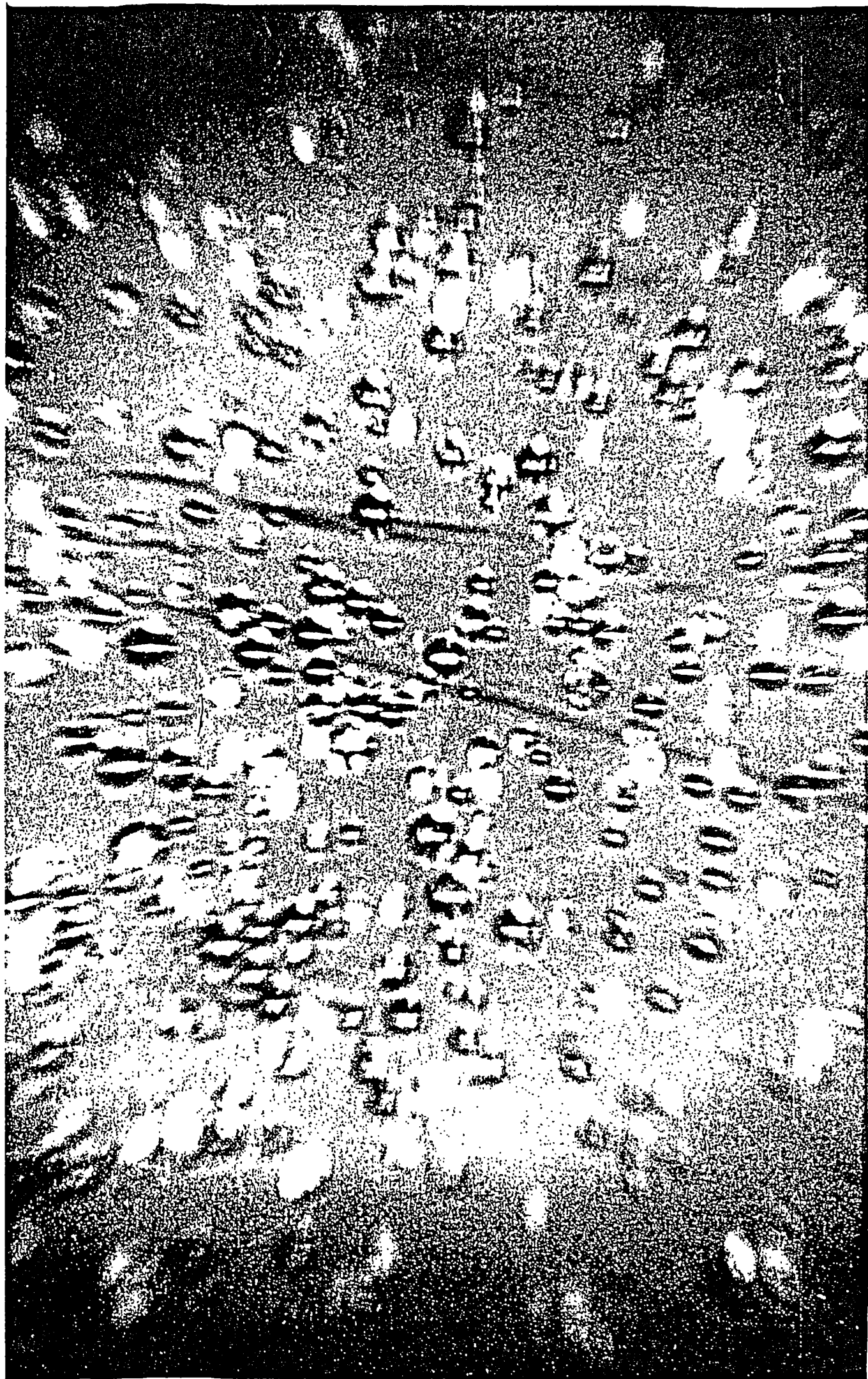
PRESSURE 20 (psi)

LIQUID FLOWRATE 18cc/sec

PHOTOGRAPH 14

PRESSURE 30 (psi)

LIQUID FLOWRATE   18cc/sec

PHOTOGRAPH 15
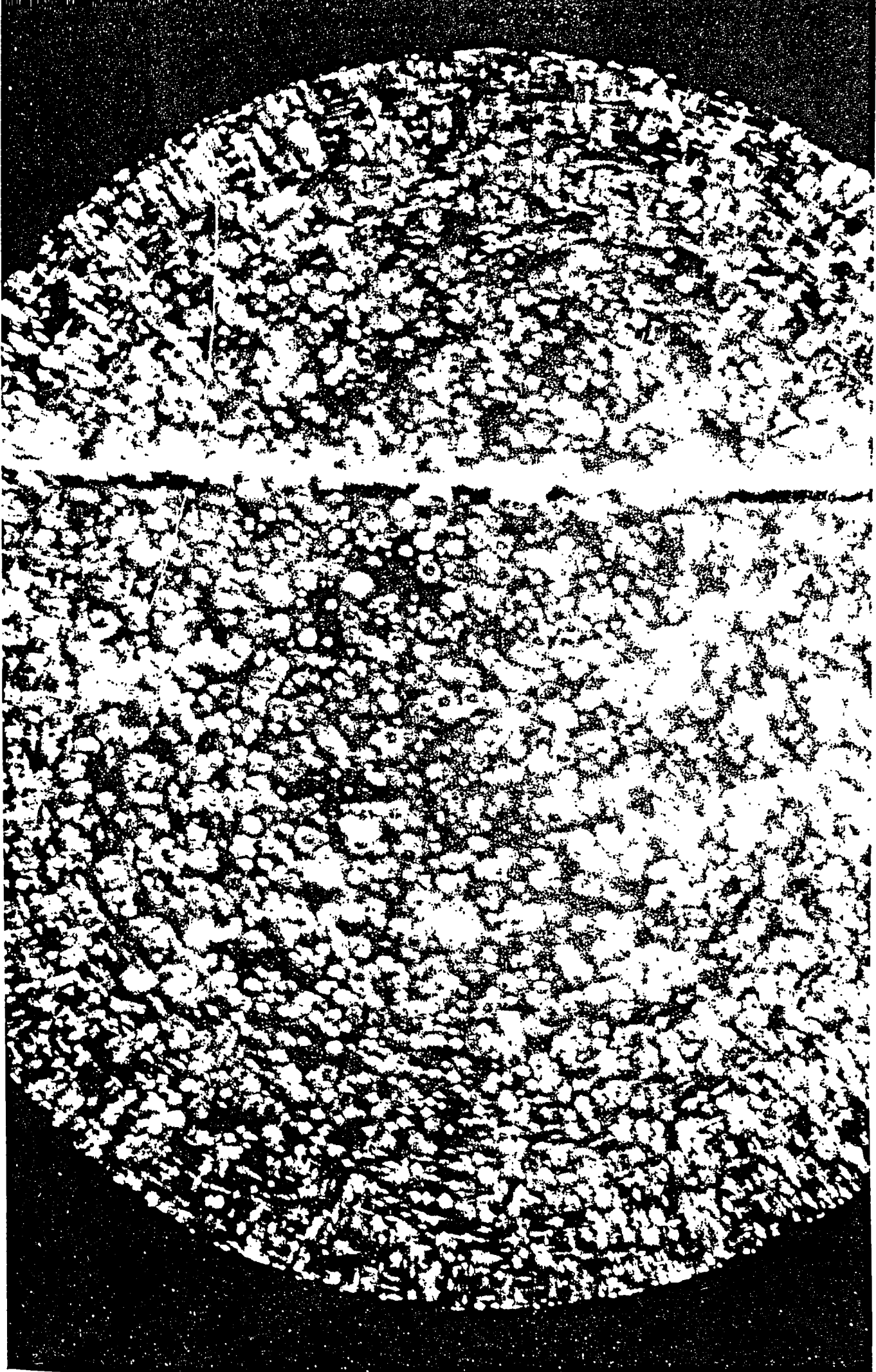
PRESSURE 40 (psi)

LIQUID FLOWRATE   18cc/sec

PHOTOGRAPH 16
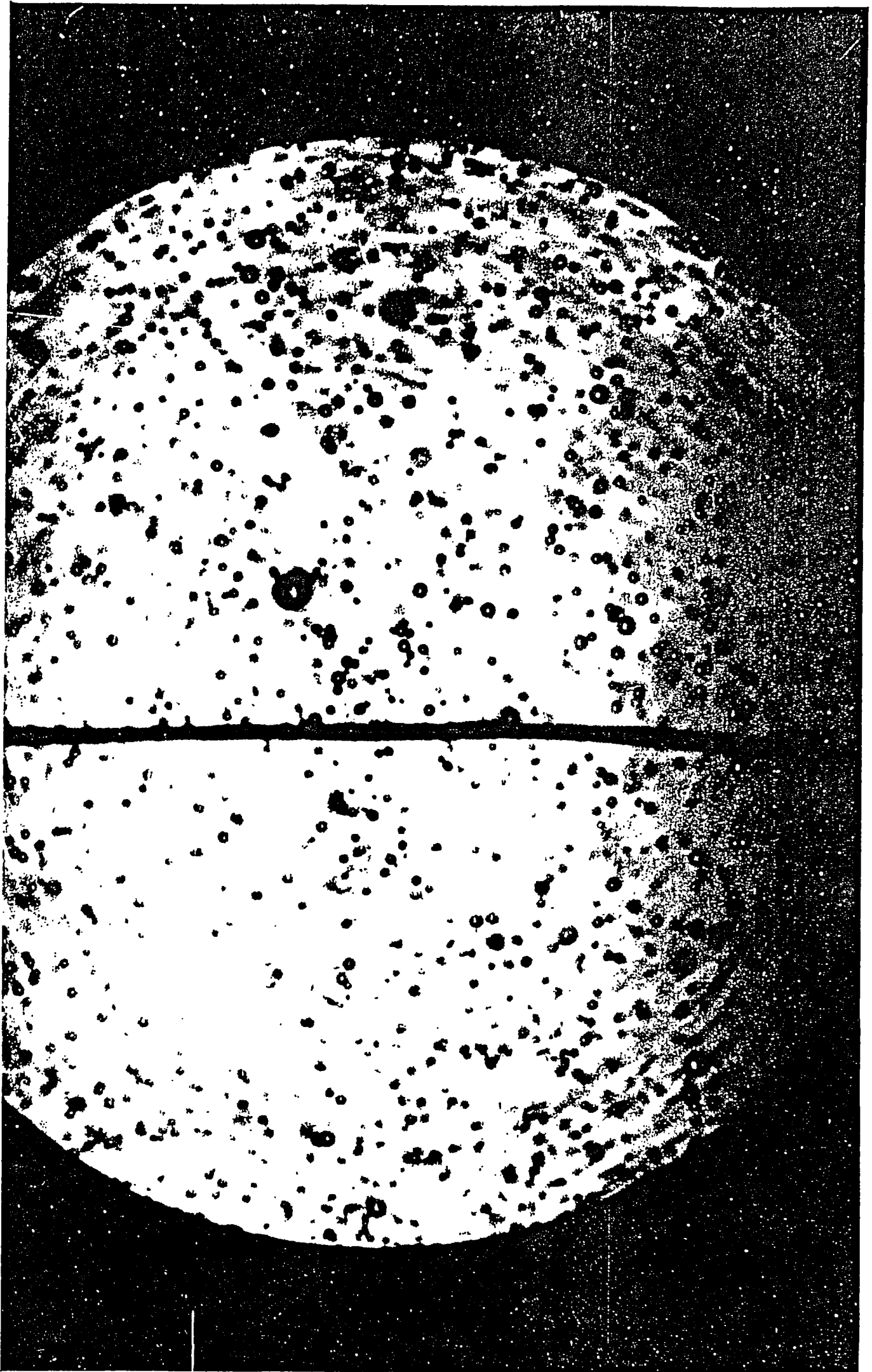
PRESSURE 50 (psi)

LIQUID FLOWRATE   18cc/sec

PHOTOGRAPH 17

PRESSURE   60   (psi)

LIQUID   FLOWRATE   18cc/sec
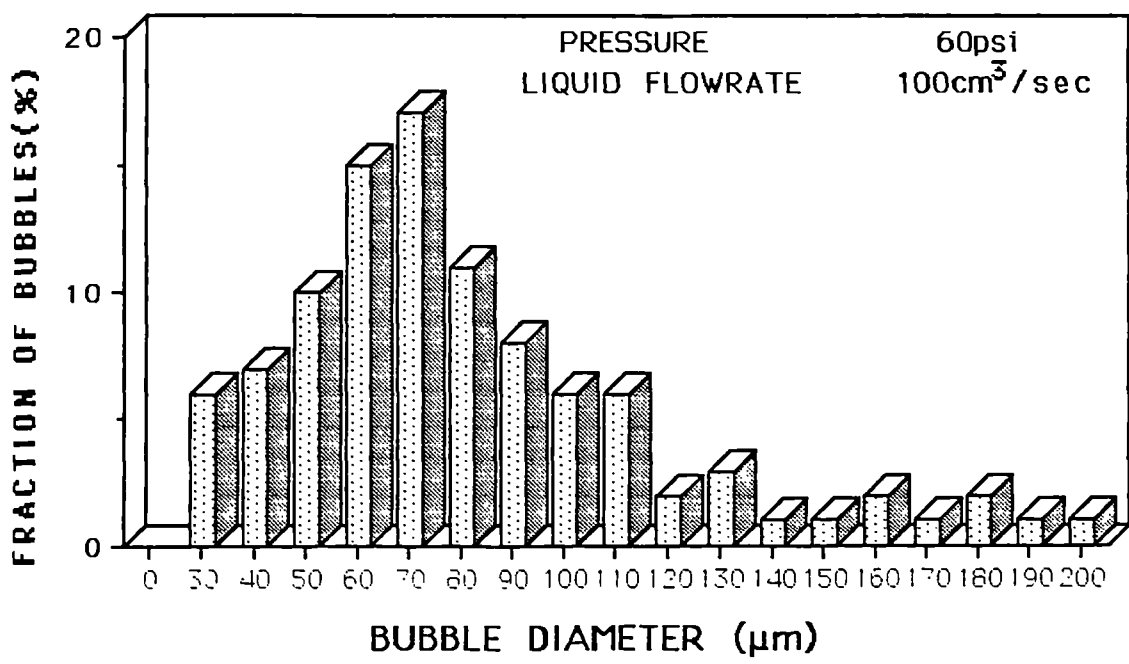

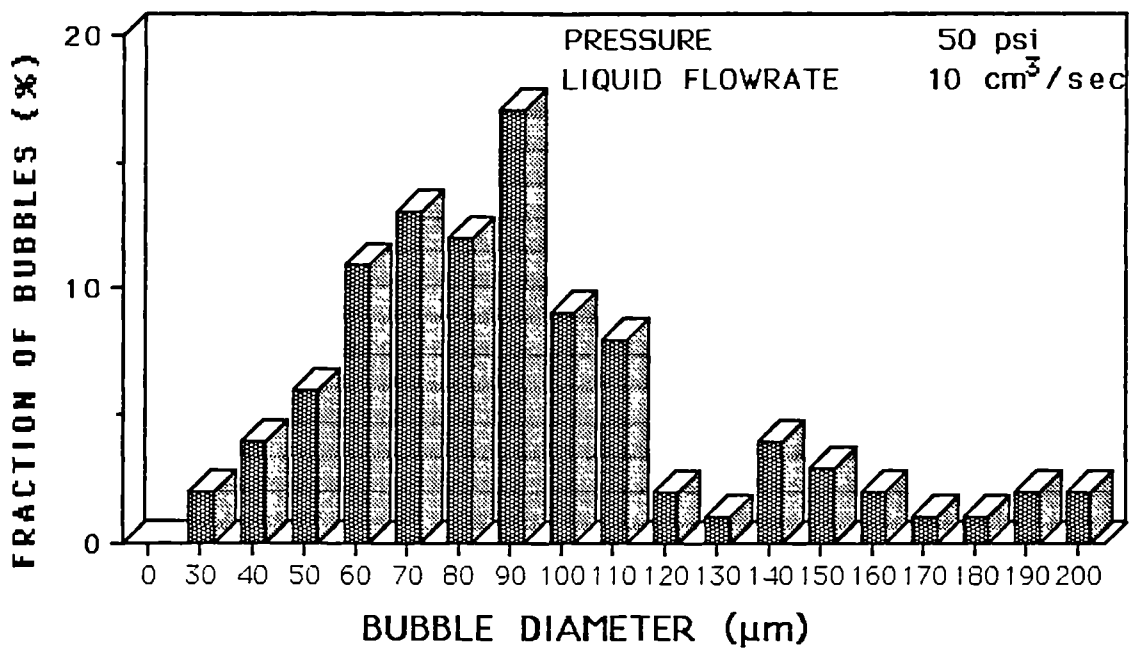PHOTOGRAPH   18

FIG. 30a-30b
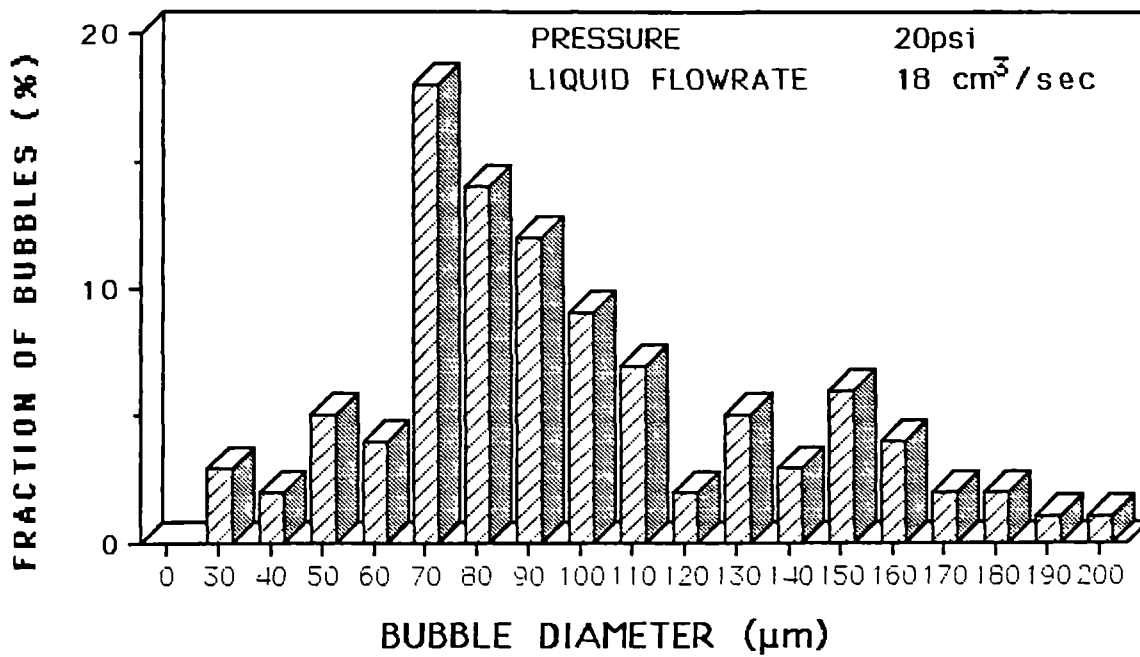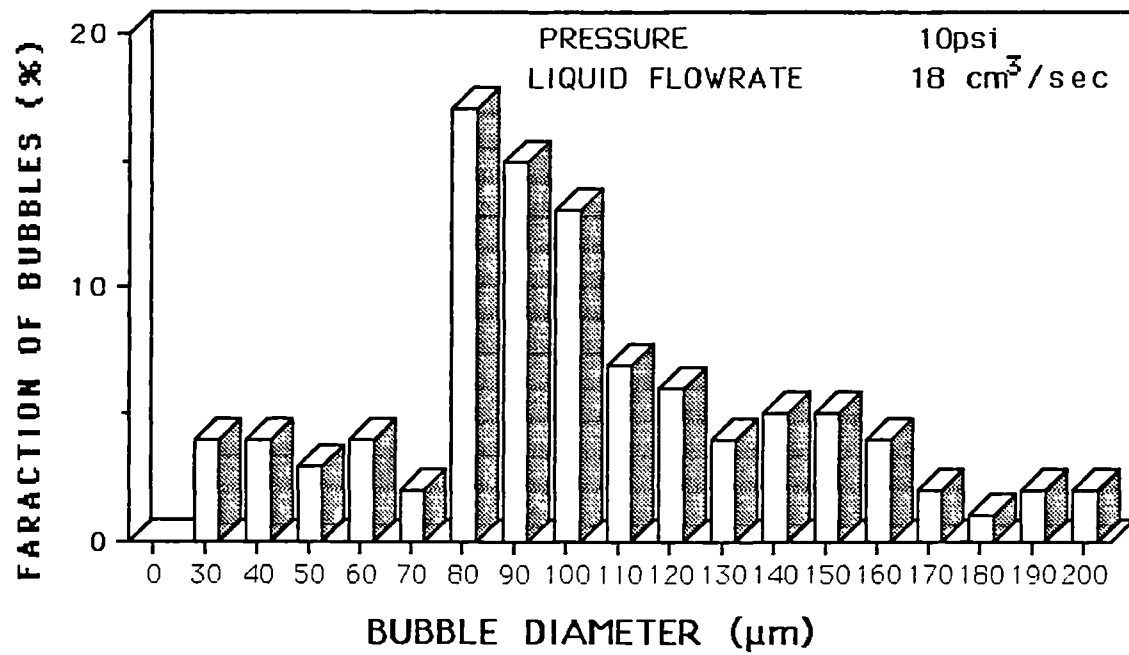
134

FIG. 30c-30d

135
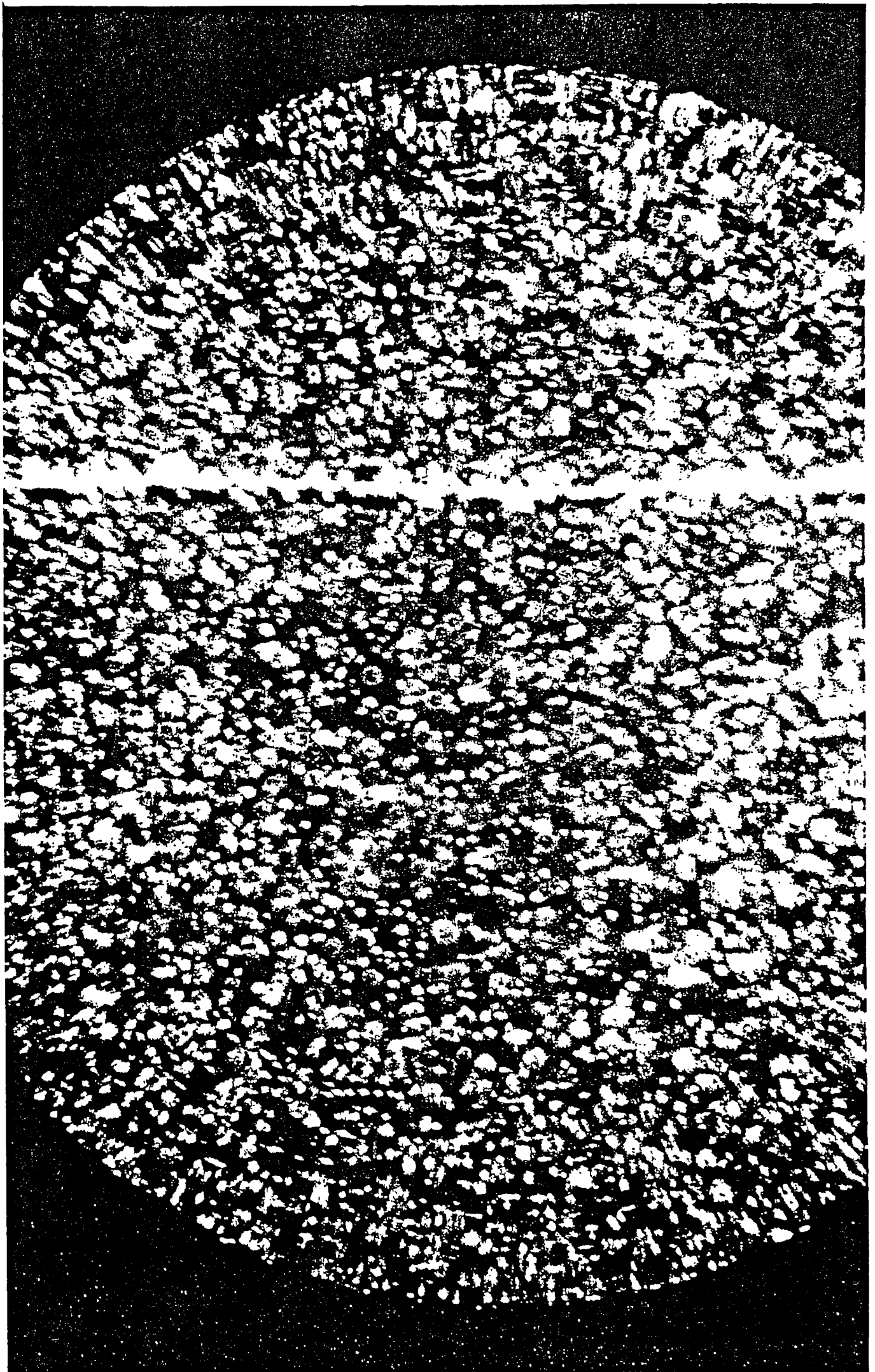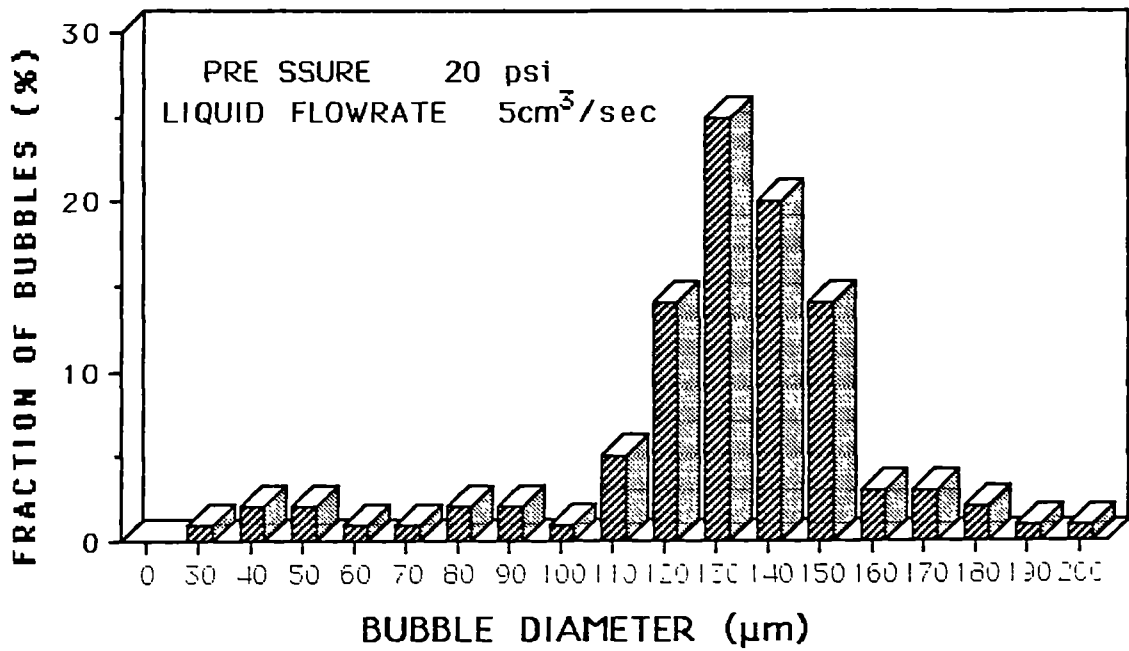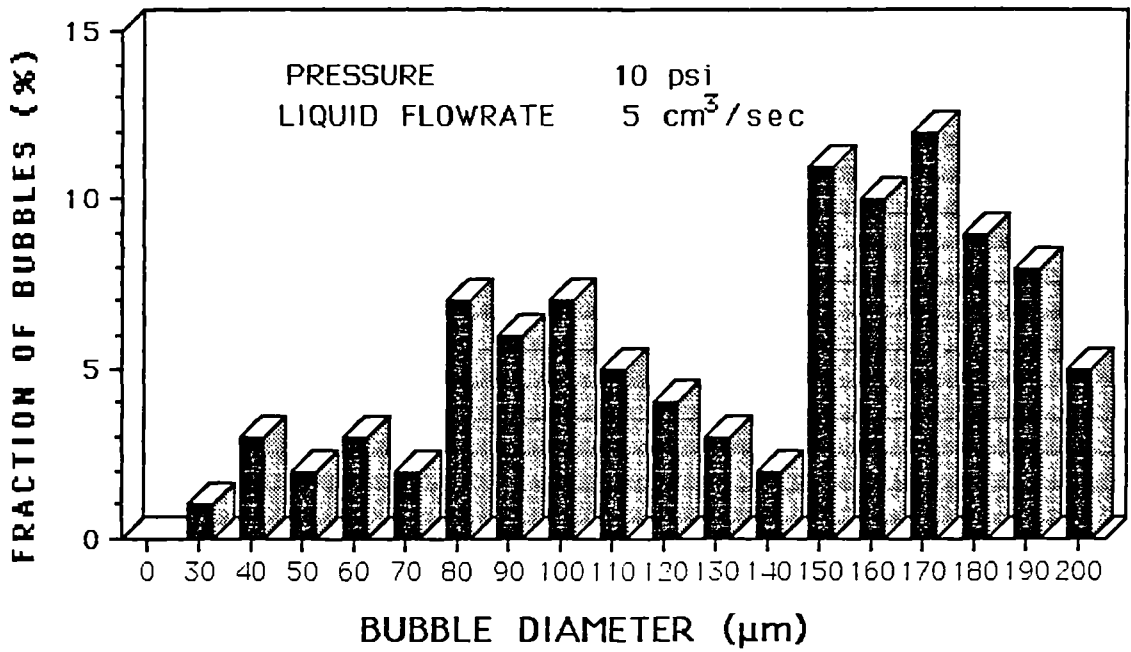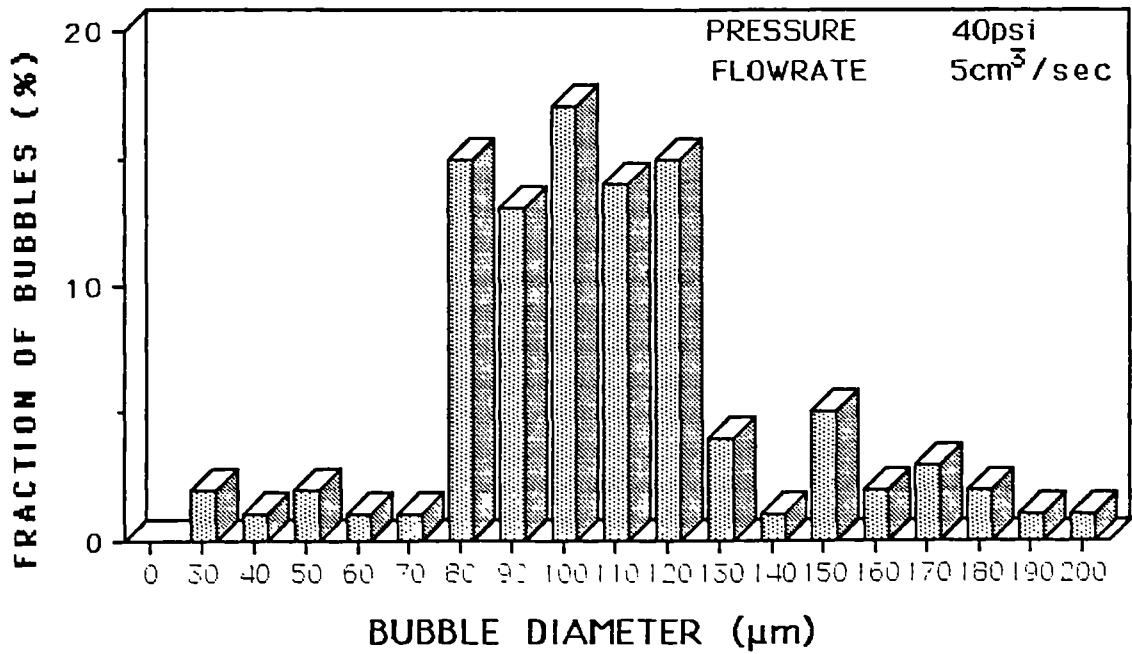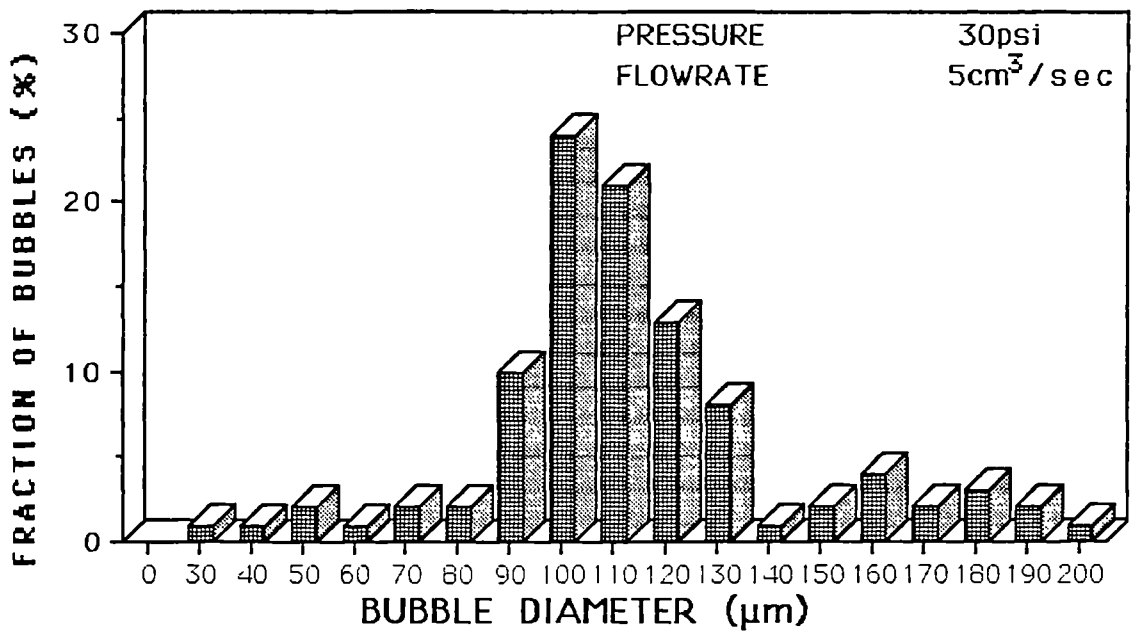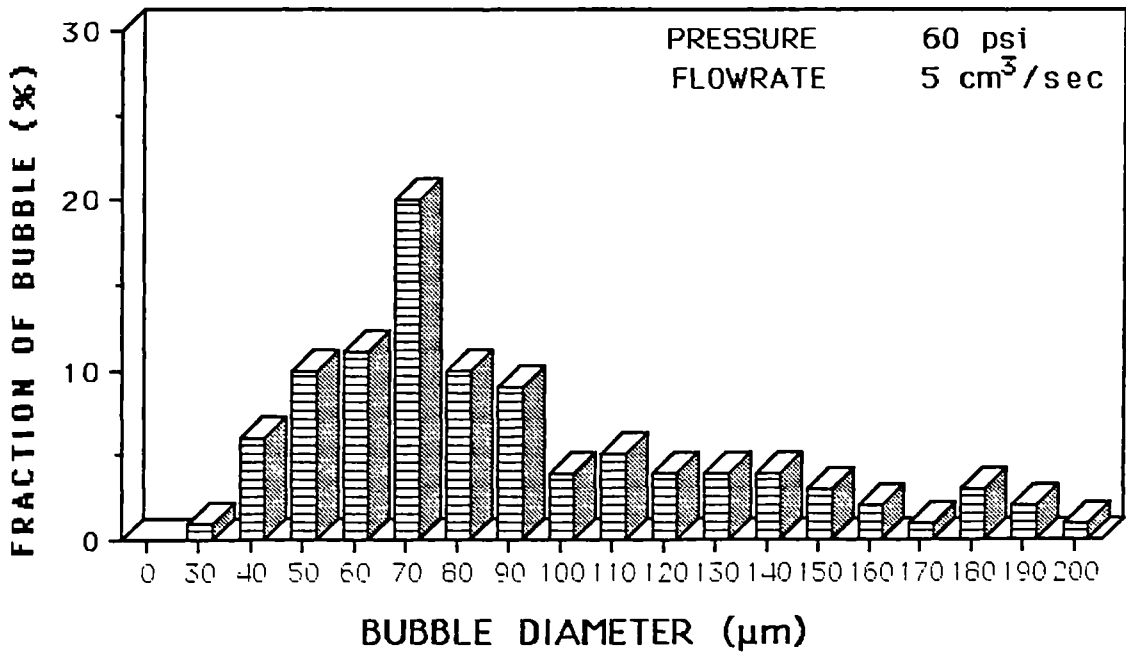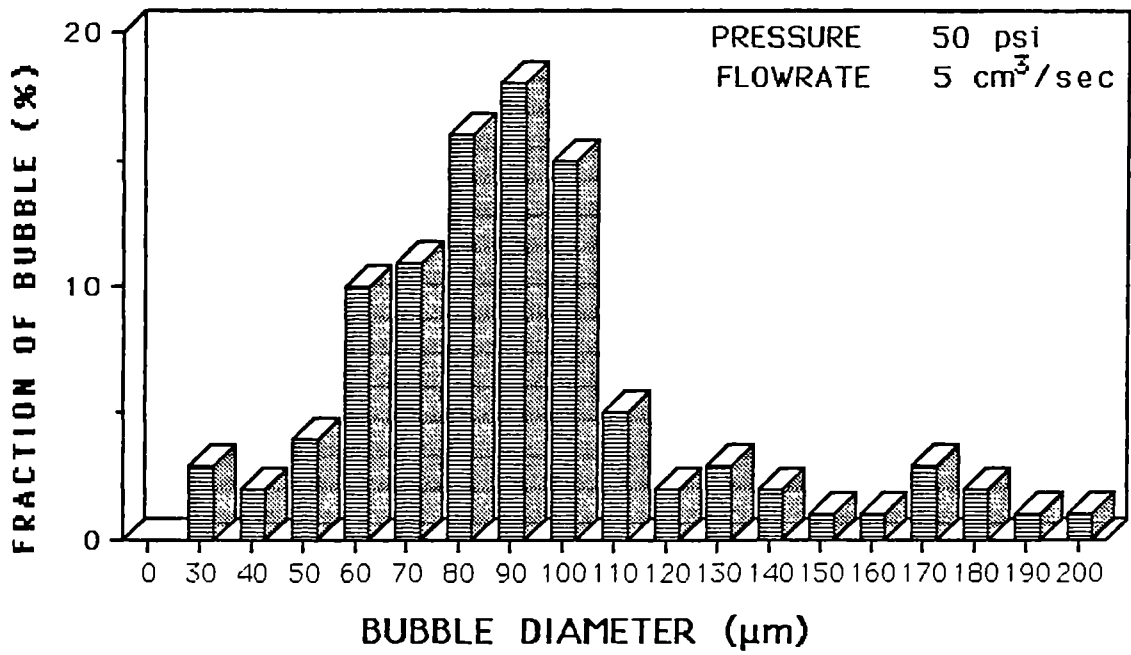
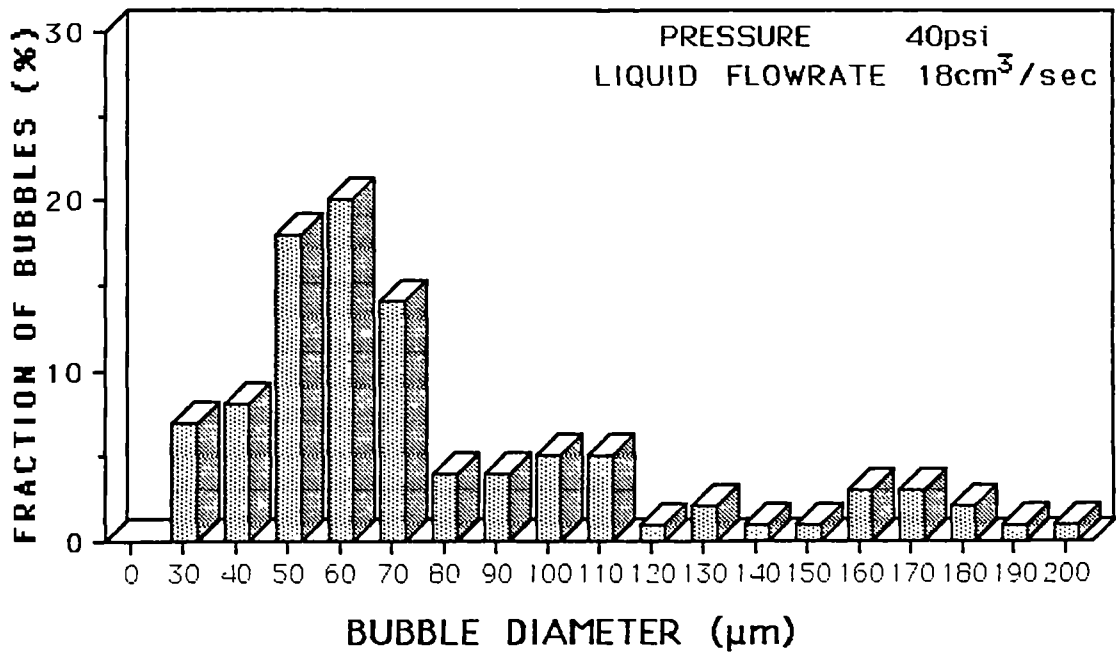FIG. 30e-30f
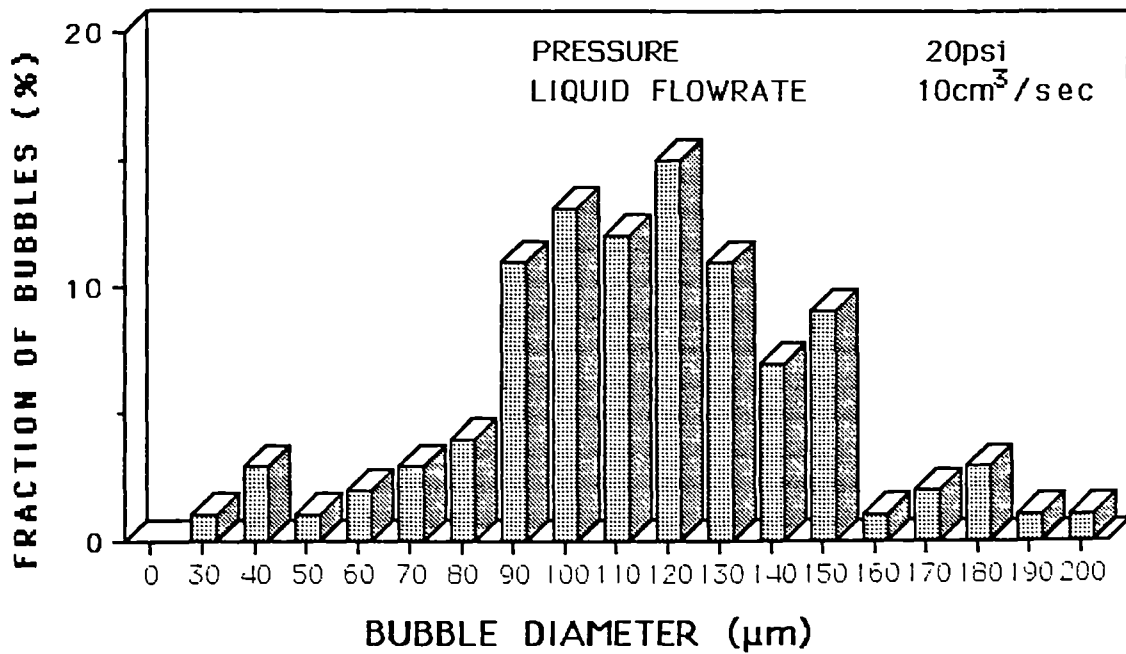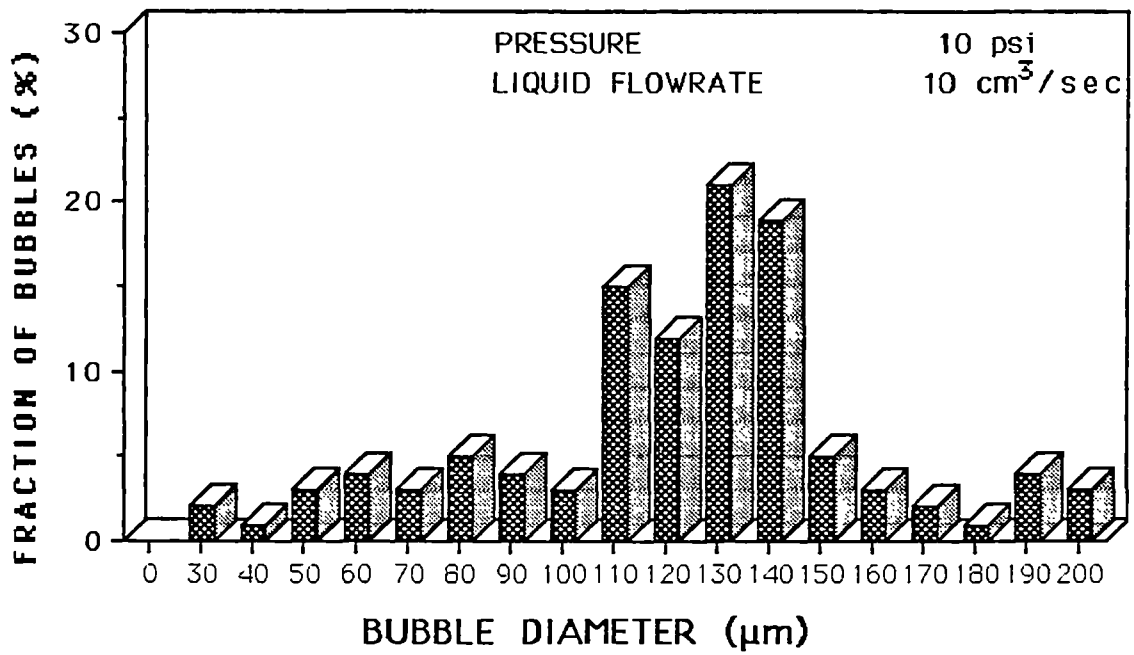
FIG 30g-30h

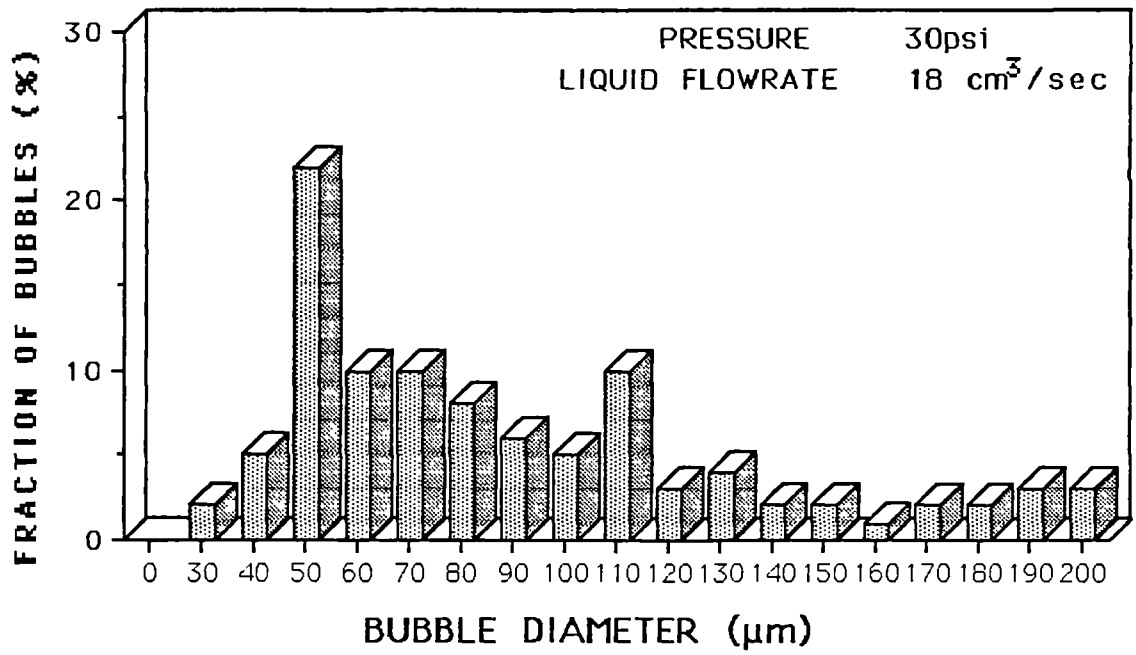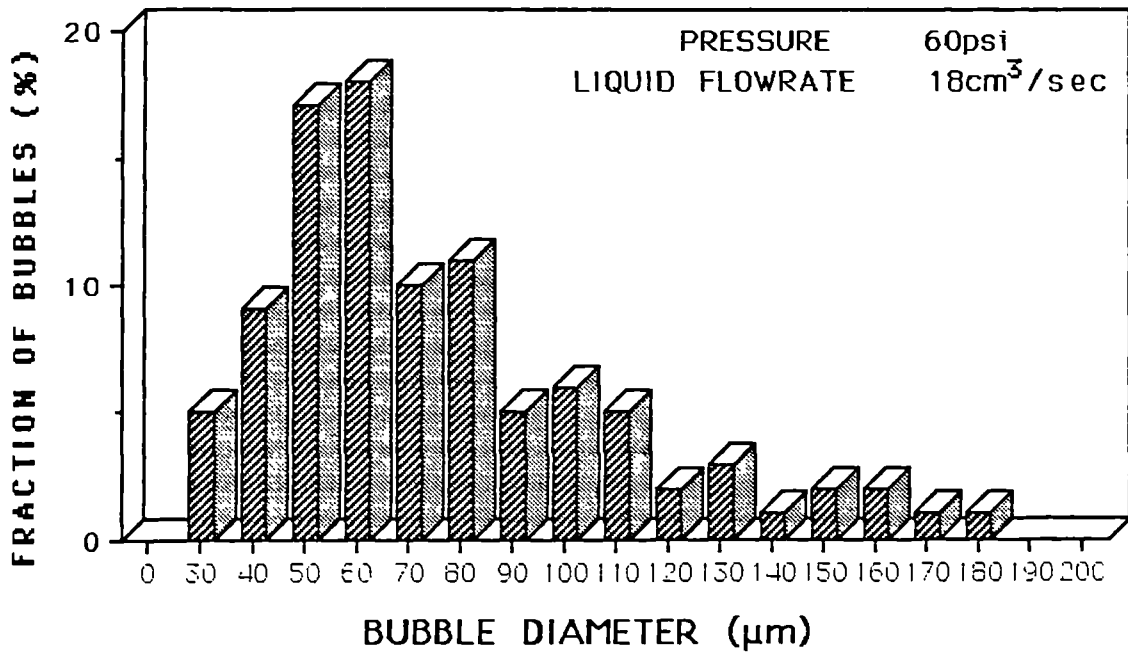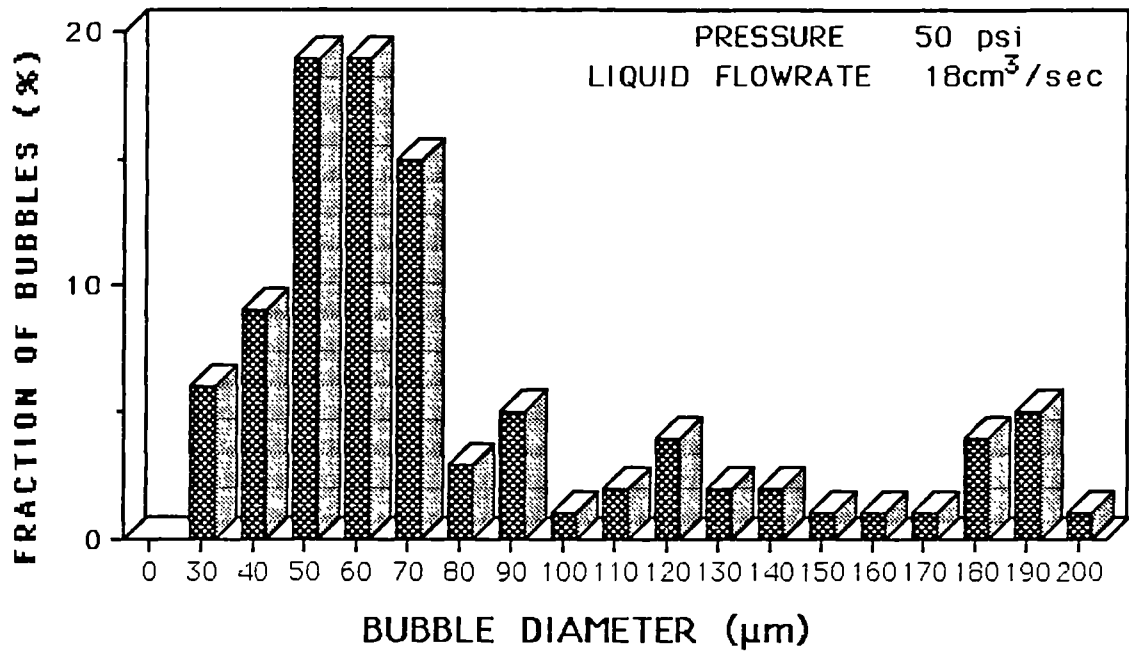FIG.30i-30j

138
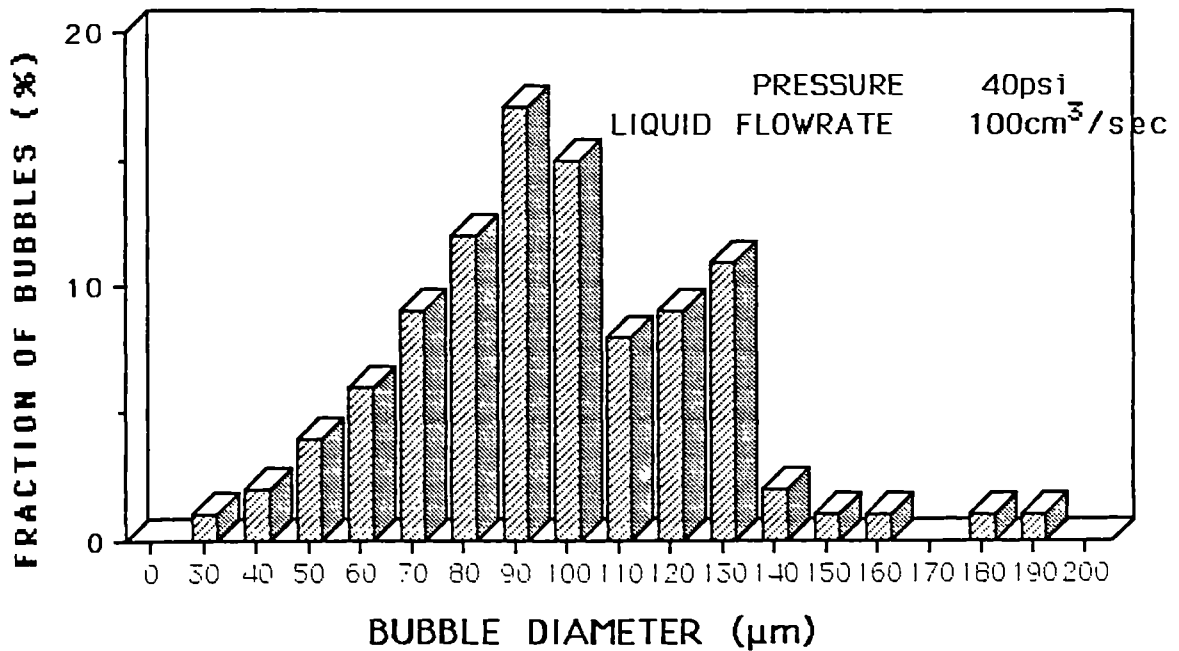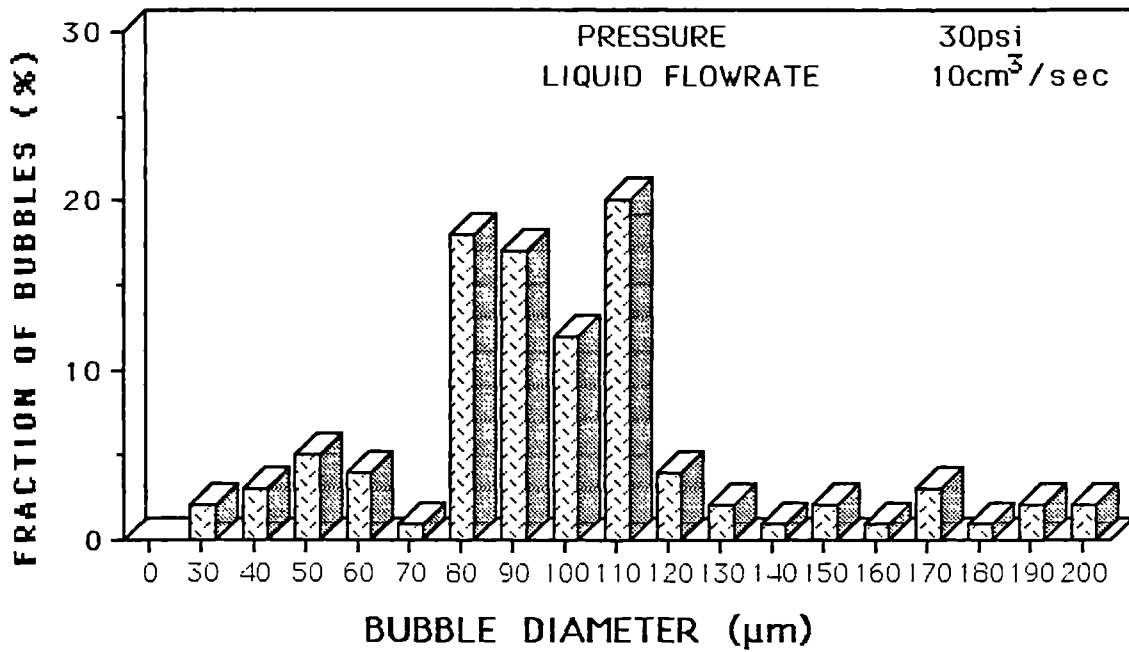
FIG. 30k-301

FIG. 30m-30n

FIG. 30o-30p

FIG 30q-30r

5.2.3. DISCUSSION AND CONCLUSIONS

5.2.3.1 EFFECT OF PRESSURE ON BUBBLE SIZE

As was mentioned the bubble size in the DAF influences the performance of the process. For the same volume of released air it is preferable to form a larger number of small bubbles rather than large bubbles. Great kinetic advantages, such as increasing the surface area and also the residence time which are important where collision phenomena are required to form a bubble-aggregate, can be achieved by having a large number of small bubbles. Gas precipitation and bubble formation proceeds by two stages. The formation of a nuclei and the growth of the nuclei. If the size of nuclei is controlled the size of the air bubble may also be controlled. This is feasible because as we saw in Chapter Three the diameter of the nuclei is a function of pressure and surface tension. Keeping the surface tension constant and increasing the pressure decreases the size of the nuclei. Our results in FIG. 31(A,B,C) indicate that for a given flowrate the size of the generated bubble decreases with the dissolved pressure.

The opinions and the results of different workers are contradicting. VRABLIK (1959) found out that by increasing the pressure the bubble size increases as well, but on the other hand TAKAHASI et al reported that only small changes in bubble size can occur with pressure variation but these changes are the opposite of those proposed by Vrablik. FIG.32 shows that is a close correlation between the obtained and the experimental data.
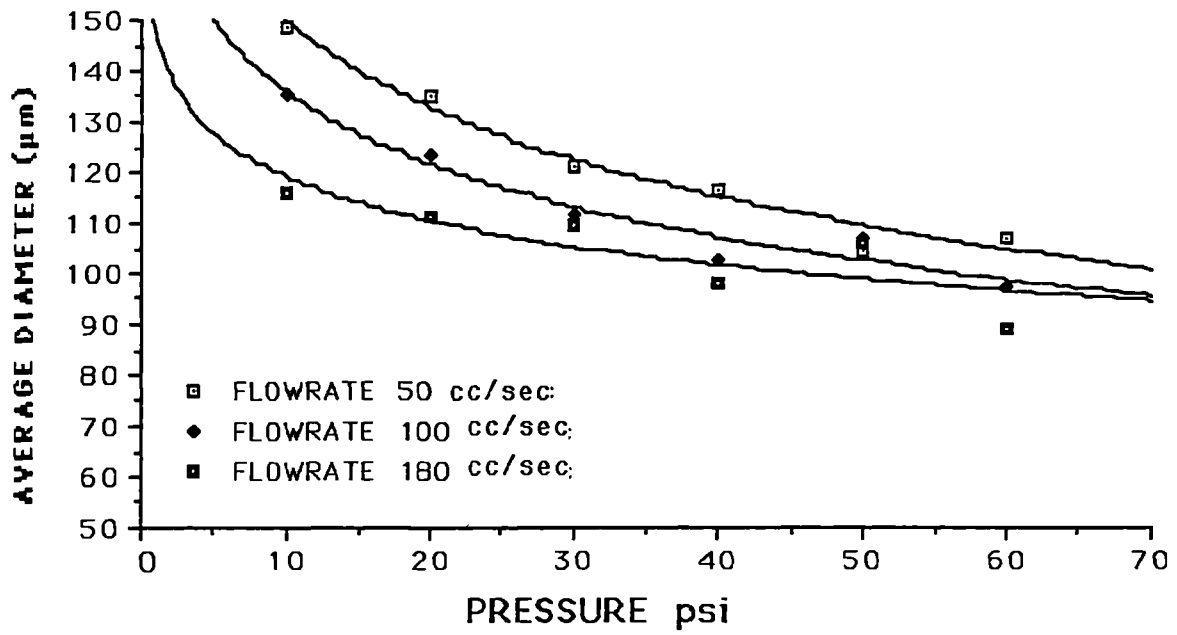
143

FIG.31(a)   EFFECT OF PRESSURE ON ESTIMATED AVERAGE DIAMETER FOR THREE DIFFERENT FLOWRATES
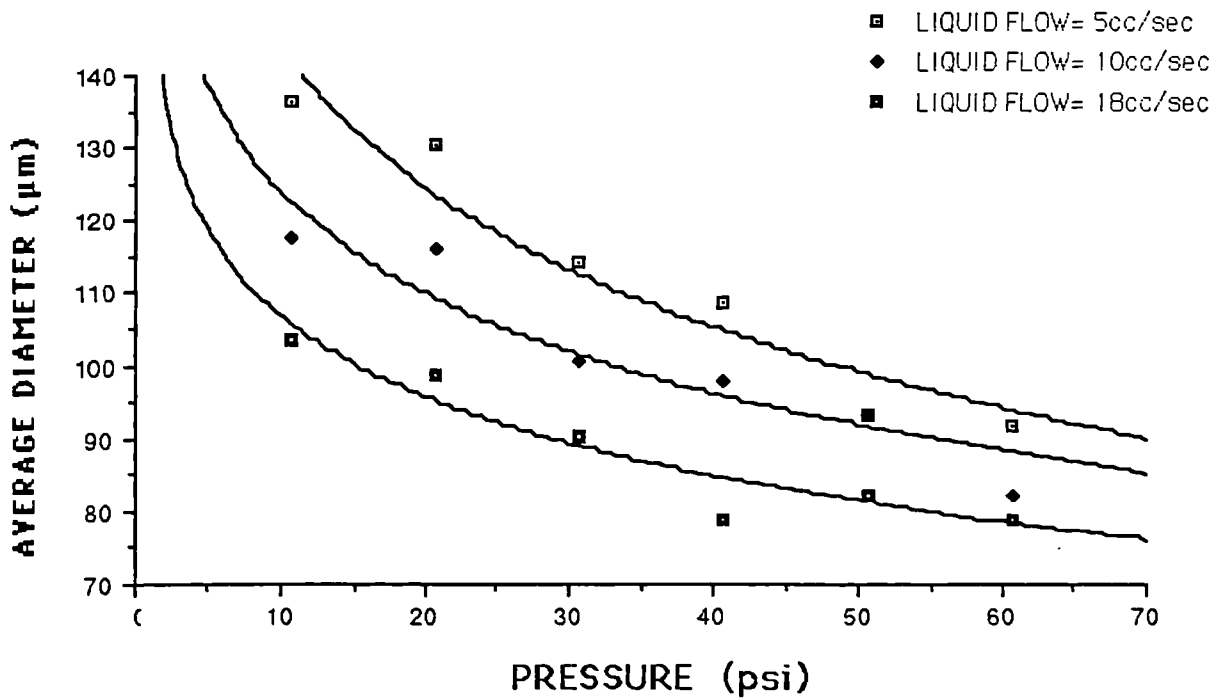

FIG. 31(b)   EFFECT OF PRESSURE ON EXPERIMENTAL AVERAGE BUBBLE DIAMETER FOR THREE LIQUID FLOWRATES
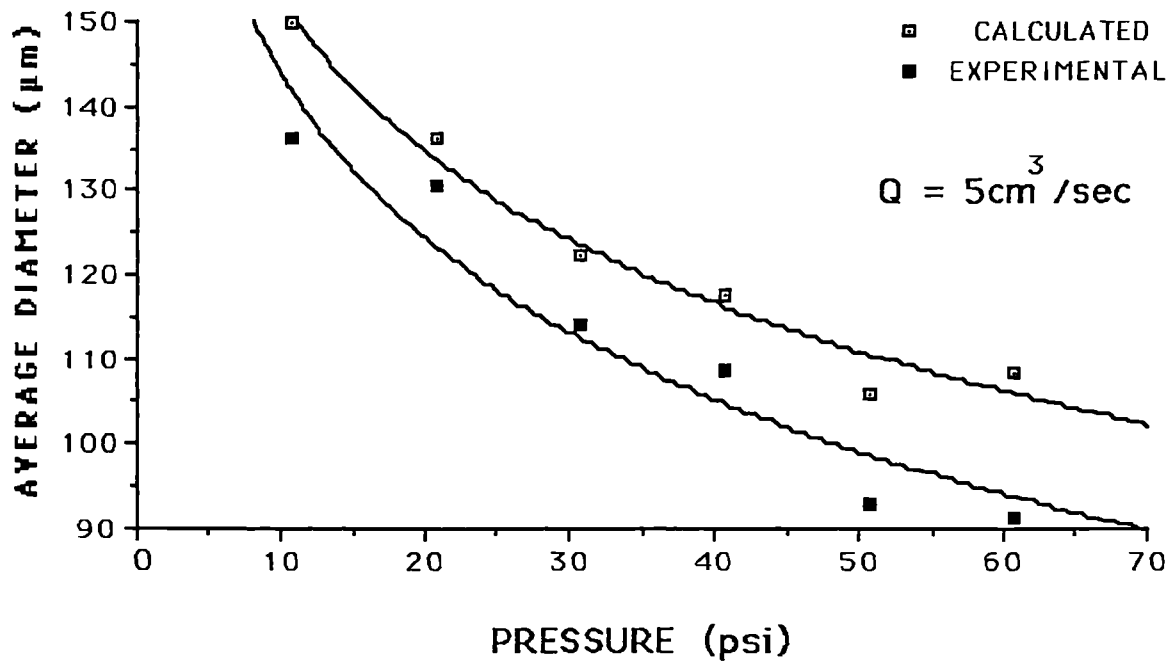
FIG.32 (a) EFFECT OF PRESSURE ON AVERAGE BUBBLE DIAMETER
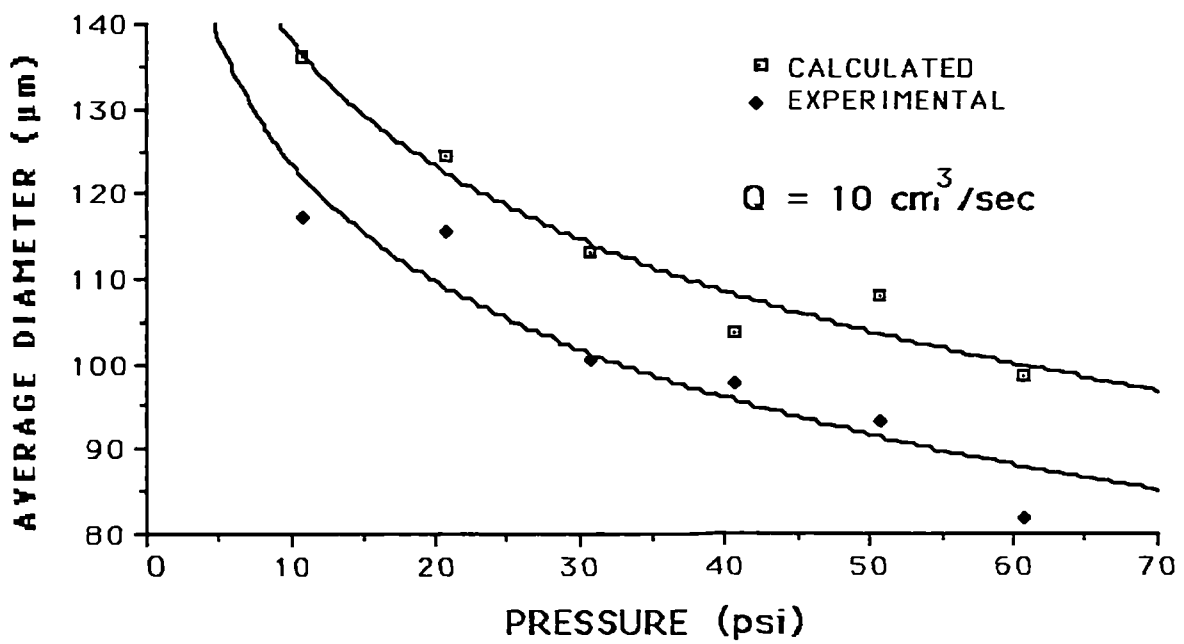
FIG.32(b) EFFECT OF PRESSURE ON AVERAGE BUBBLE DIAMETER
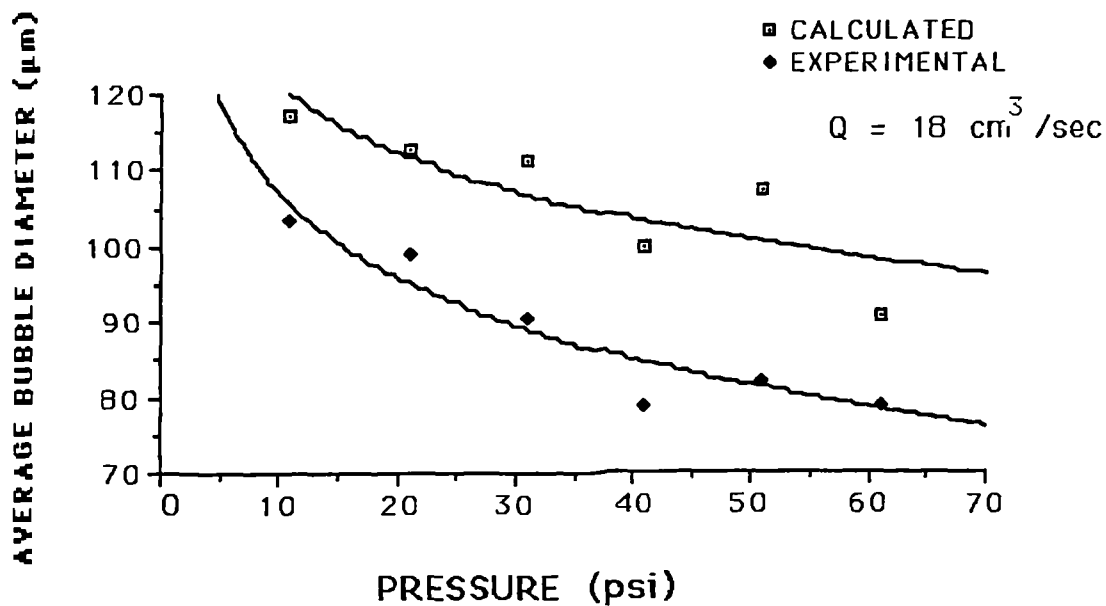
FIG.32(c) EFFECT OF PRESSURE ON AVERAGE BUBBLE DIAMETER

Effect of liquid flowrate on bubble size

Another parameter which affects the performance of the flotation process is the liquid flowrate. It was, therefore, appropriate to carry out experiments under constant dissolved pressure and vary the liquid throughput. From our results in FIG. 33 it becomes obvious that the liquid flowrate has only a small influence on bubble diameter hence the flotation efficiency, especially when the stream of saturated water is under high pressures (40-60psi). Only at lower values of pressures there is a tendency for bubble size to decrease more rapidly with flowrate.

Takahasi et al (1979) found that the bubble size tends to be smaller with an increase in flowrate, which. are similar findings to ours. Their results do not appear on the graphs because they

have worked in a range of liquid flowrates much smaller than ours (0-2cc/sec).

In contrast with Takahashi, PINFOLD (1970) in his report observed an increase in bubble diameter with increasing the liquid flowrate.
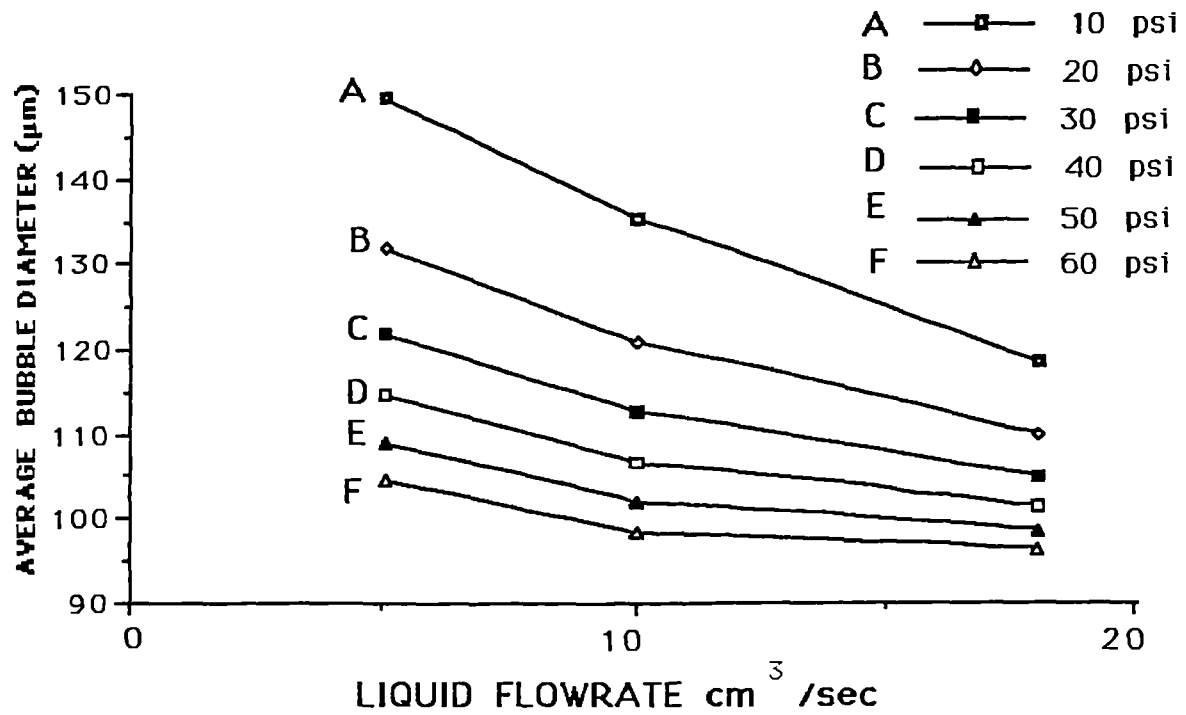
FIG.33a   EFFECT OF FLOWRATE ON CALCULATED
AVERAGE BUBBLE DIAMETER

147
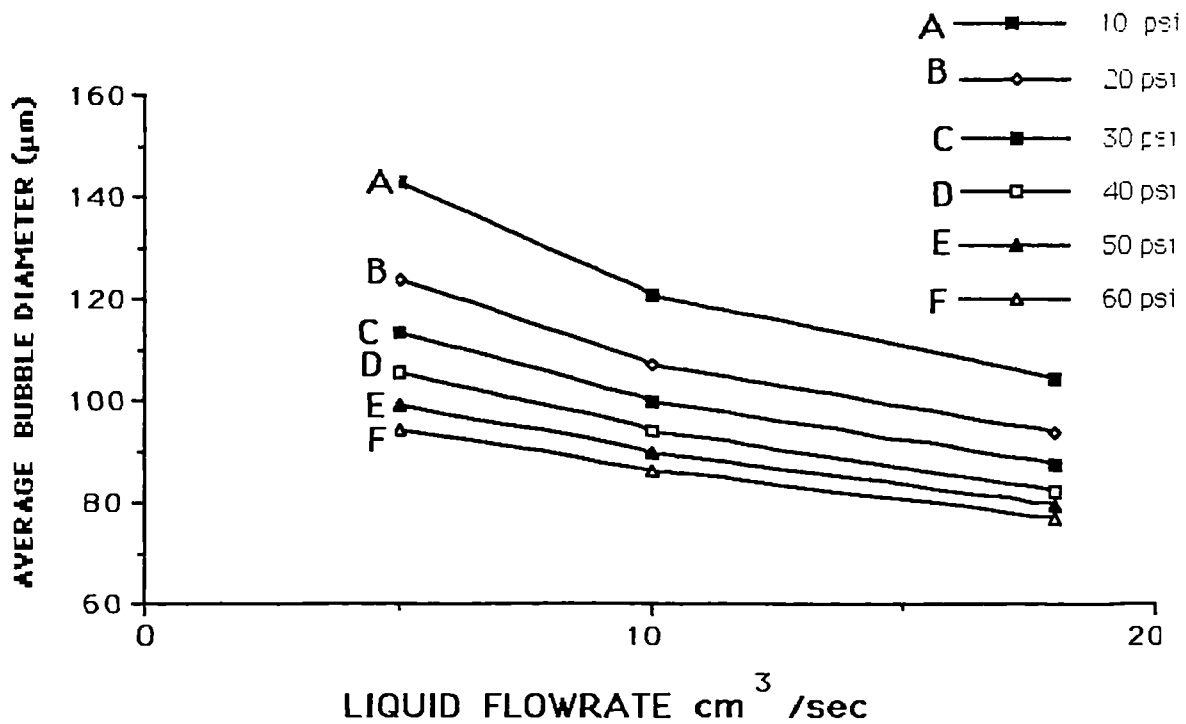
FIG.33b   EFFECT OF FLOWRATE ON EXPERIMENTAL
AVERAGE BUBBLE DIAMETER

Derivation of an equation relating pressure with bubble numbers

Obviously the number of bubbles per unit volume will have a strong influence on flotation efficiency thus the number of bubbles was estimated from our experimental results using Eq. 56. These results are shown in the log-scale plot. In FIG.34. A log-scale plot was chosen because a linear scale produce a wide spread and an attempt to generate a design equation was made. It is obvious that the effect of pressure is important and that the number of bubbles per cm^3 increases as we increase the pressure. The liquid flowrate seems to play an unimportant role. As has been revealed through out our analysis, the pressure is the variable which most

148

affects the bubble size. At this point it is important to derive an empirical equation which will relate the number of the formed bubbles and the imposed pressure. With the help of regression analysis from FIG. 34 we derived that the equation for the line of best fit is:

$$N_b = a * P^c \qquad [71]$$

where : $a = 175$

$c = 1.64$

$P =$ pressure (psi)

$N_b =$ number of bubbles /cm^3

This equation can be a useful guide in applications where a certain amount of bubbles of a known diameter would be important for the subsequent removal of particles of a known size.
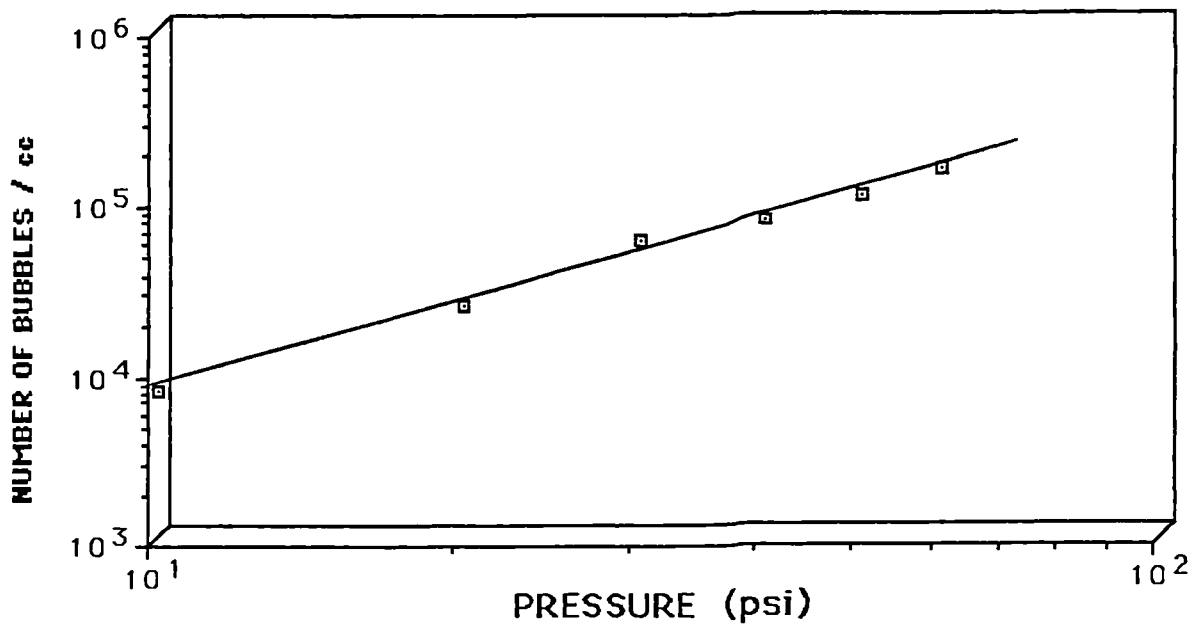
FIG 34 EFFECT OF PRESSURE ON THE NUMBER OF BUBBLES

Effect of pressure on the uniformity of bubbles

Another important parameter for good flotation is the uniformity of bubble sizes.

In our literature survey Section (3.2.2.3) an index which describes the uniformity of the bubbles. (Eq.58). In our experiments this index was calculated and plotted in FIG.35(a,b) against the pressure and liquid flowrate respectively. It is clear that at large pressures and high flowrates, the uniformity of bubbles is better. The pressure is evident and it is also clear that the liquid flowrate plays a lesser role. The value of the index

decreased and reached a limited value when at high pressure causing the generation of bubbles with a more uniform size.
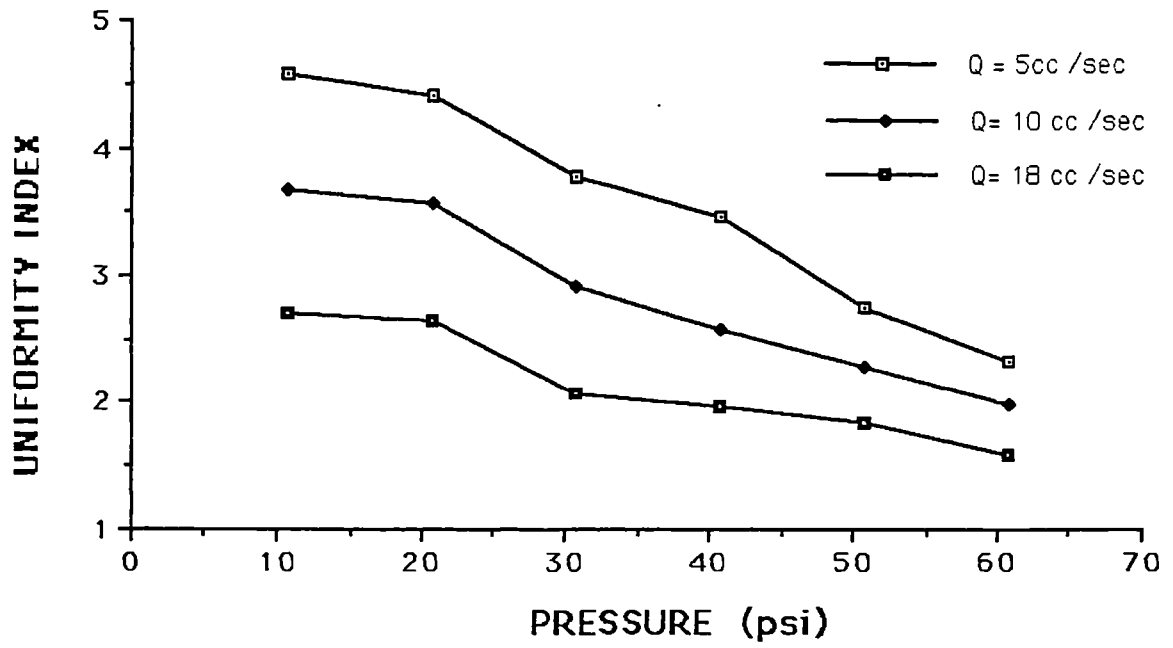
FIG.35(a) EFFECT OF PRESSURE ON THE UNIFORMITY INDEX
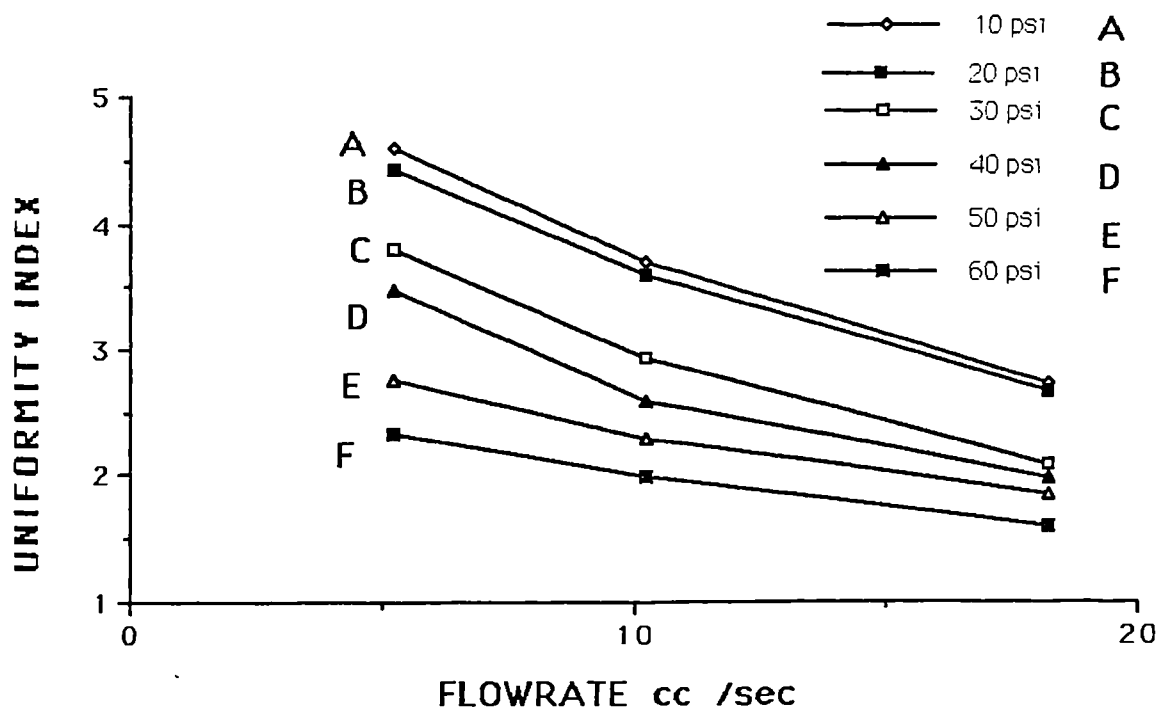
FIG.35(b) EFFECT OF FLOWRATE ON THE UNIFORMITY INDEX

5.3 HYDRODYNAMIC STUDIES

It is clear from the Higee studies that high volumes of supersaturated liquid can be produced and, provided the bubbles can be nucleated, this should provide a useful way of ensuring a better distribution of the liquid and any associated bubbles than the conventional high velocity single nozzle system.

Since the bubble size and the flow patterns into flotation tank is an important issue, a computer fluid dynamic package ,"FLUENT", was adapted to study the following.

a) Flow patterns with experimental nozzle.

b) Flow patterns with multi-nozzle configuration.

FLUENT has been useful in modelling the complex of bubble trajectories encountered in flotation processes. The programme uses finite difference numerical procedures to solve Navier-Stokes. Equations, governing fluid flow. The numerical technique involves the subdivision of domain of interest into a finite number of control volumes and cells to obtain the set of simultaneous algebraic relation. Due to non linearity and the interdependence of the differential equation, an iterative procedure had to be adapted. The number of iterations depended upon the complexity of the initial conditions and boundary conditions.

The package was limited to 2251 finite elements nodes which is the product of the cells of the co-ordinates. To develop the geometry of the flotation tank having a narrow inlet of order of mm it was necessary to use a modified version having its upper limit of 40000 nodes. By changes in the actual package routines the distribution of number of modes for x-y-z co-ordinates were 41-11-13 respectively.

5.3.1 Single experimental nozzle

Fig.36 shows a simulated tank with the same dimensions as the flotation tank in our experiments. The inlet nozzle and the outlet pipe are also shown. Fig.37 shows the v-velocity vectors of a stream of water saturated with air entering the tank through the nozzle which had the same diameter as ours. Fig.38-39-40 are the

153

cross sections of the v-velocity in the 8th plane namely near in front of the nozzle, (10cm), 5th plane in the middle of the tank (35cm from the nozzle) and 2nd plane close to outlet respectively (80 cm from the nozzle).

5.3.2 Multi nozzle system

Alternatively Fig.41 shows a simulated tank with the same dimensions as ours but having this time 4 inlets along one side each having the same diameter with our experimental nozzle but as the throughput is the same, the velocity vectors are smaller than in the single nozzle case.

Fig.42 represents the vectors of velocity throughout the vessel and FIG. 43-44-45 show the cross sections of v-velocity in the same planes as in FIG.38-39-40.

5.3.3 Analysis and conclusions

From FIG. 37 and 42 the vectors of the jet velocity seem to have the highest values as they enter the vessel as expected however, they remain constant until the jet hits the opposite wall. In case where there is one nozzle in the tank, there seem to be stagnant points close to the corners while in the multi nozzle system the velocity vectors distributed uniformly in the tank. The minimum and maximum values in m/sec are given in the corresponding graphs. As we examine the contours of v-velocity in the 8th plane which is close to the inlet area in the single nozzle system, we can observe that the bubbles tend to move perpendicular to the flow.(FIG.38). In the case of multi-nozzle

154

system a more uniformly contoured picture is revealed.(FIG.43) The picture changes in the middle of the domain where in the four nozzle system a larger number of bubbles have tend in a circular motion. This area seems to be effected by turbulence for both systems. Finally in the 2nd plane, the one, furthest away from the inlet area the contours of u-velocity were examined. With the single experimental nozzle, the stream enters the basin, reaches its maximum velocity at the far wall, it hits on the wall and as a result the bubbles move in all directions. The multi-nozzle system appears to be more uniform as the bubbles move along the bottom and side walls of the basin.

The distribution of the velocities was shown in colour on the monitor. But this can not be seen clearly from the printed graphs. As we have observed the maximum velocities are appeared in the centre of the domain for both the nozzle systems and the lowest are close to the walls.

The minus sign of velocity also, which appears in FIG. 38-39-40-43-44-45 means that the $\underline{v}$ or $\underline{u}$-velocity that moment is opposite to the direction in which the jet stream enters the vessel through the nozzle vessel

The above data conclusively, shows that a better distribution of $\underline{u}$ an $\underline{v}$ velocities achieved using a multi-nozzle system. The lack of stagnant points and the uniform distribution of the contours of the velocity throughout the basin are the basic features of the multi-nozzle system.

FIG.36   3-D OUTLINE OF SIMULATED FLOTATION TANK WITH ONE
NOZZLE

FIG.37   DISTRIBUTION OF VELOCITIES VECTORS IN A
SIMULATED TANK WITH ONE NOZZLE

FIG. 38 VIEW OF CONTOURS OF V-VELOCITIES FOR THE 8th
PLANE IN ONE NOZZLE SYSTEM

158
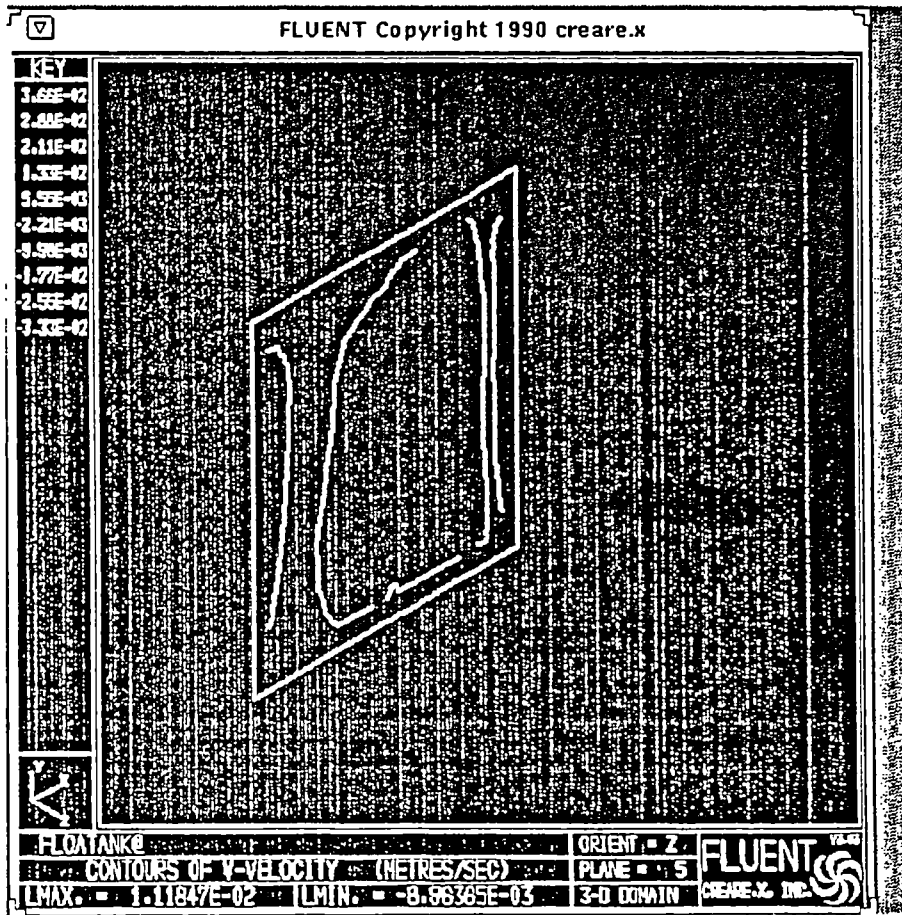
FIG. 39 VIEW OF CONTOURS OF V-VELOCITIES FOR THE 5th
PLANE IN ONE NOZZLE SYSTEM

159
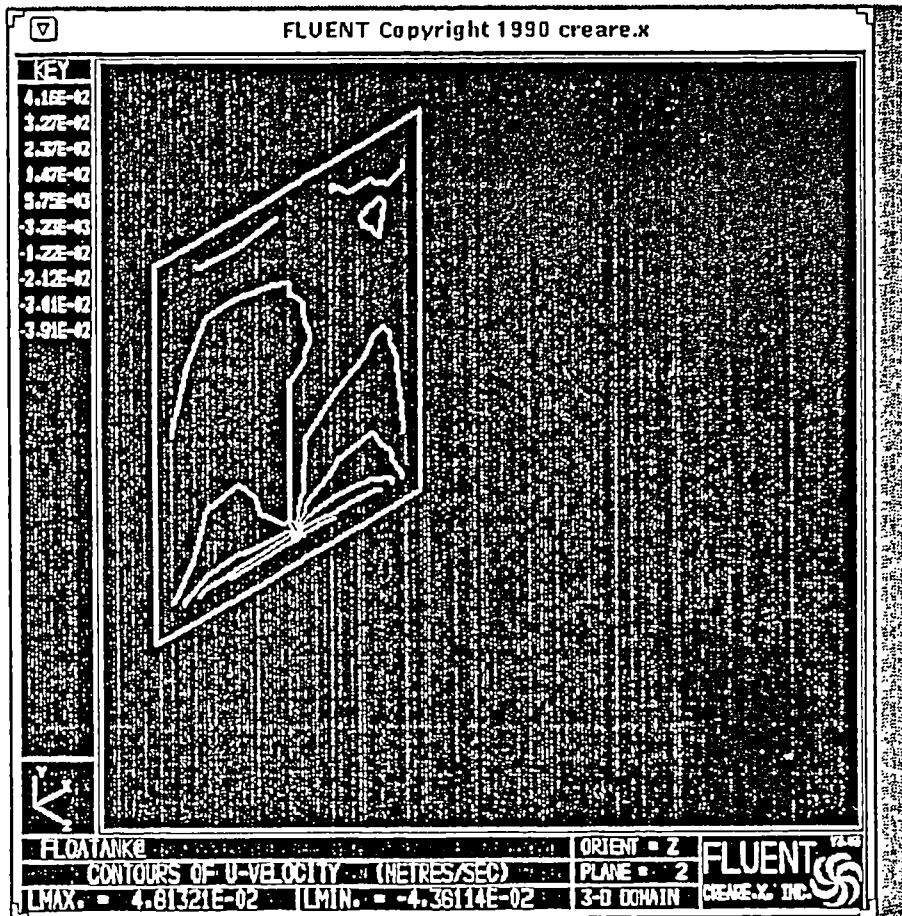
FIG. 40 VIEW OF CONTOURS OF U-VELOCITIES FOR THE 2nd
PLANE IN ONE NOZZLE SYSTEM
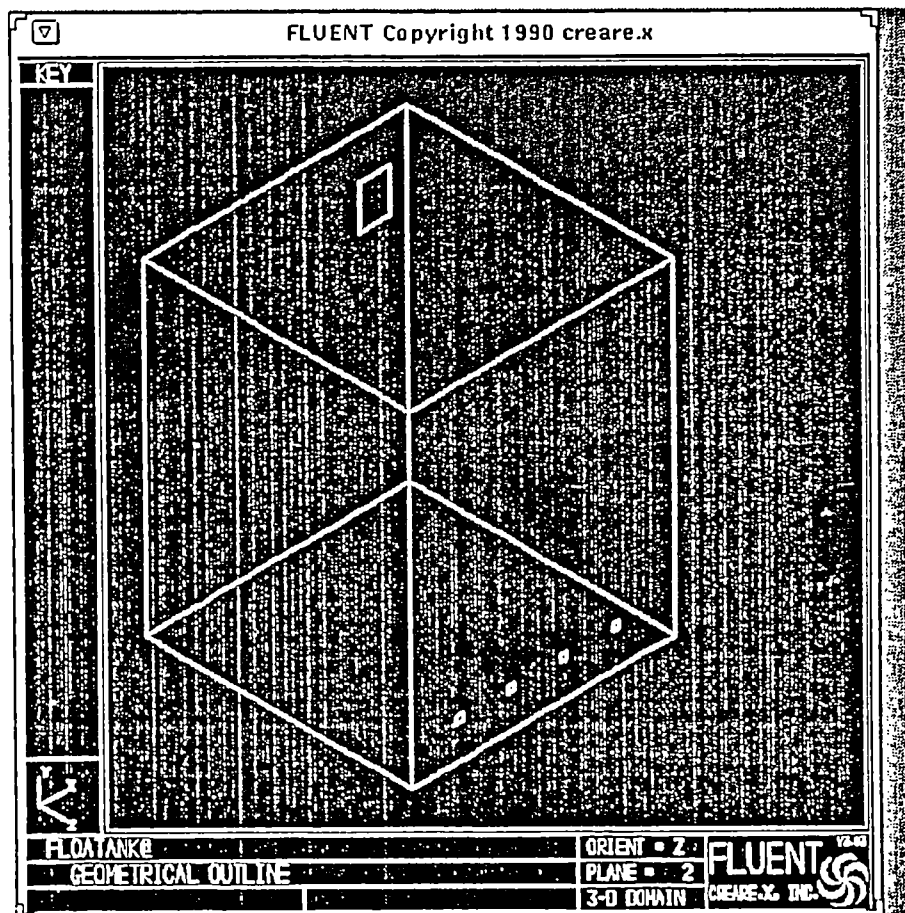
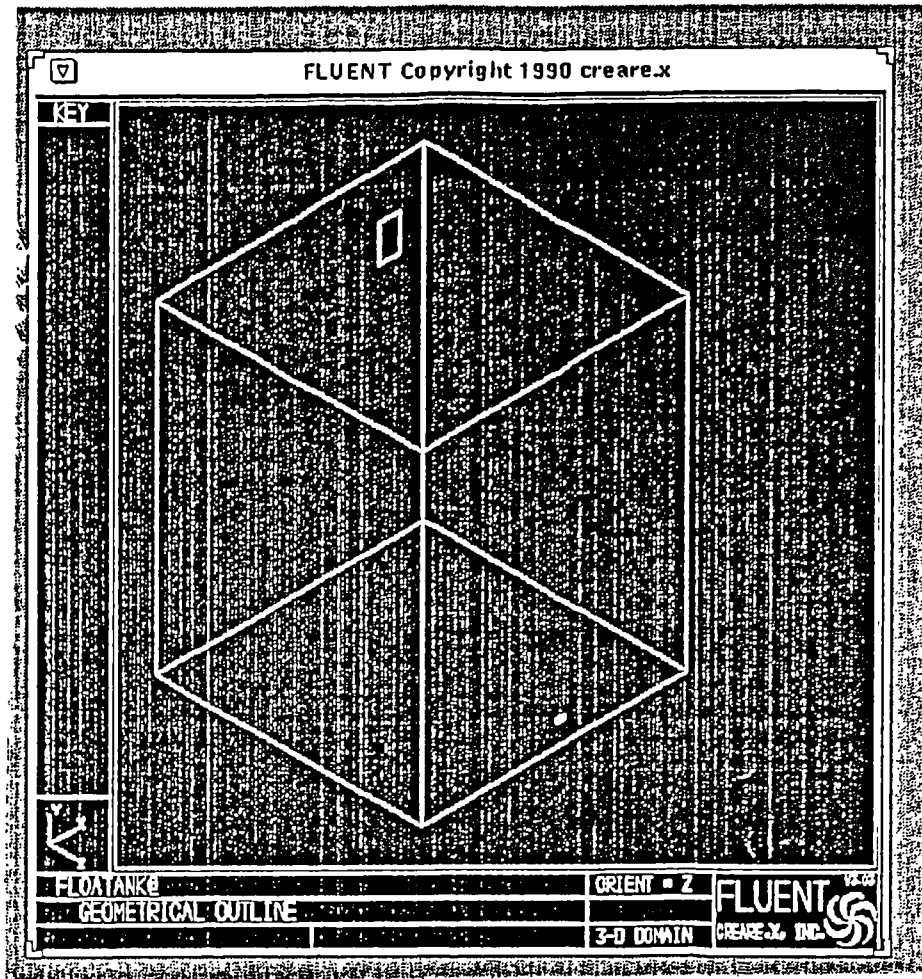FIG.41   3-D OUTLINE OF. SIMULATED FLOTATION TANK WITH
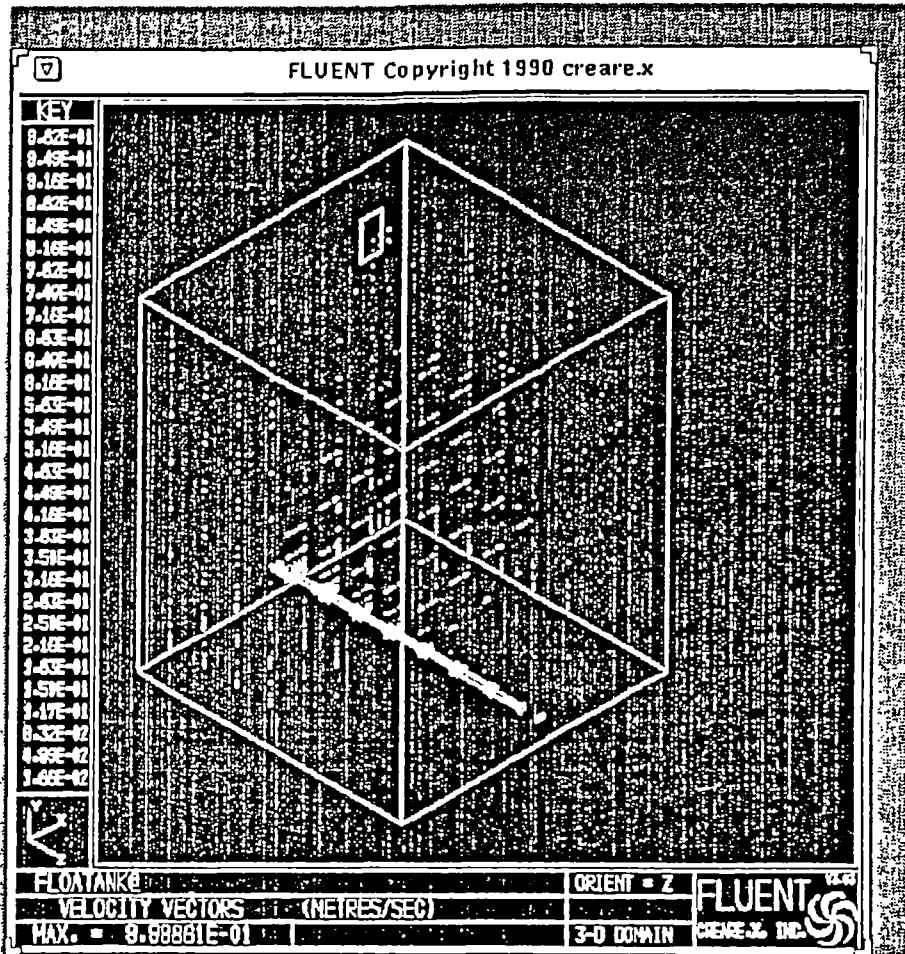FOUR NOZZLE
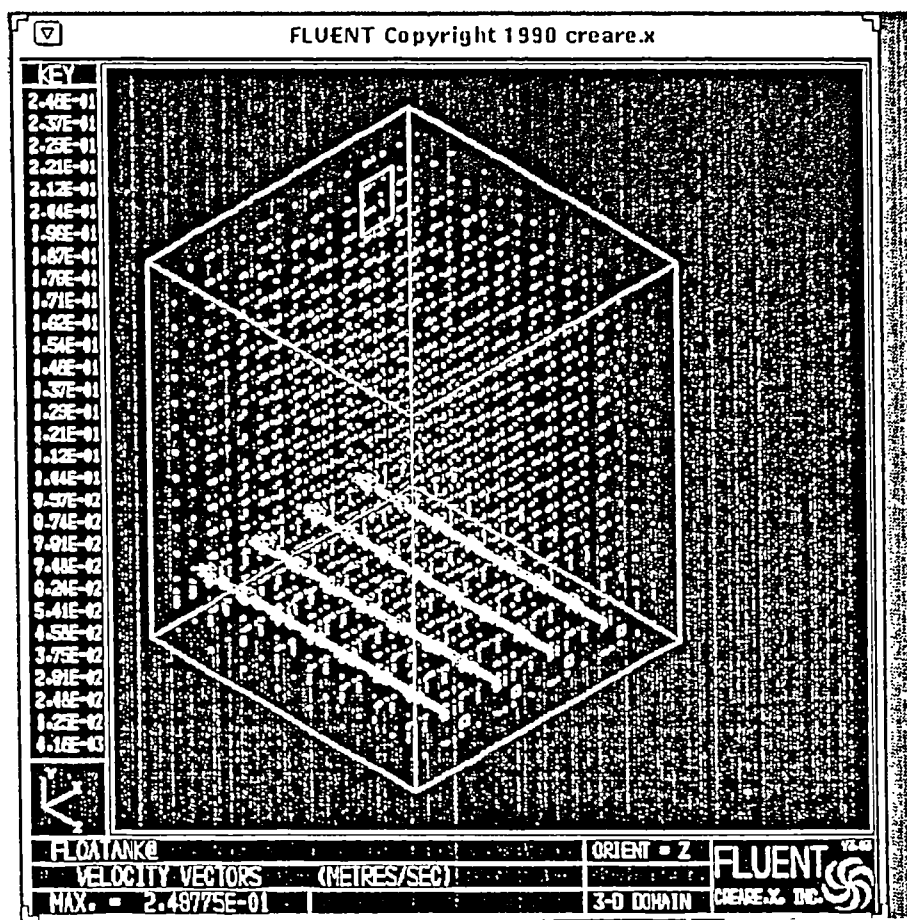
FIG.42   DISTRIBUTION OF VELOCITIES VECTORS IN A
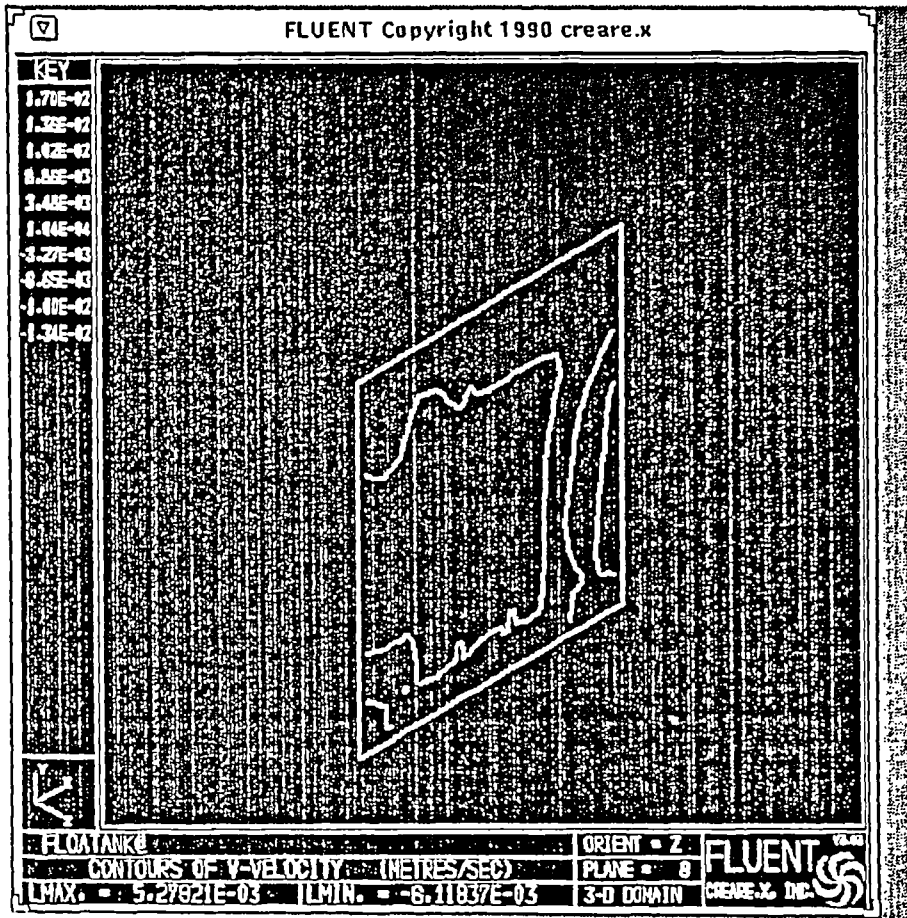SIMULATED TANK WITH FOUR NOZZLES

162
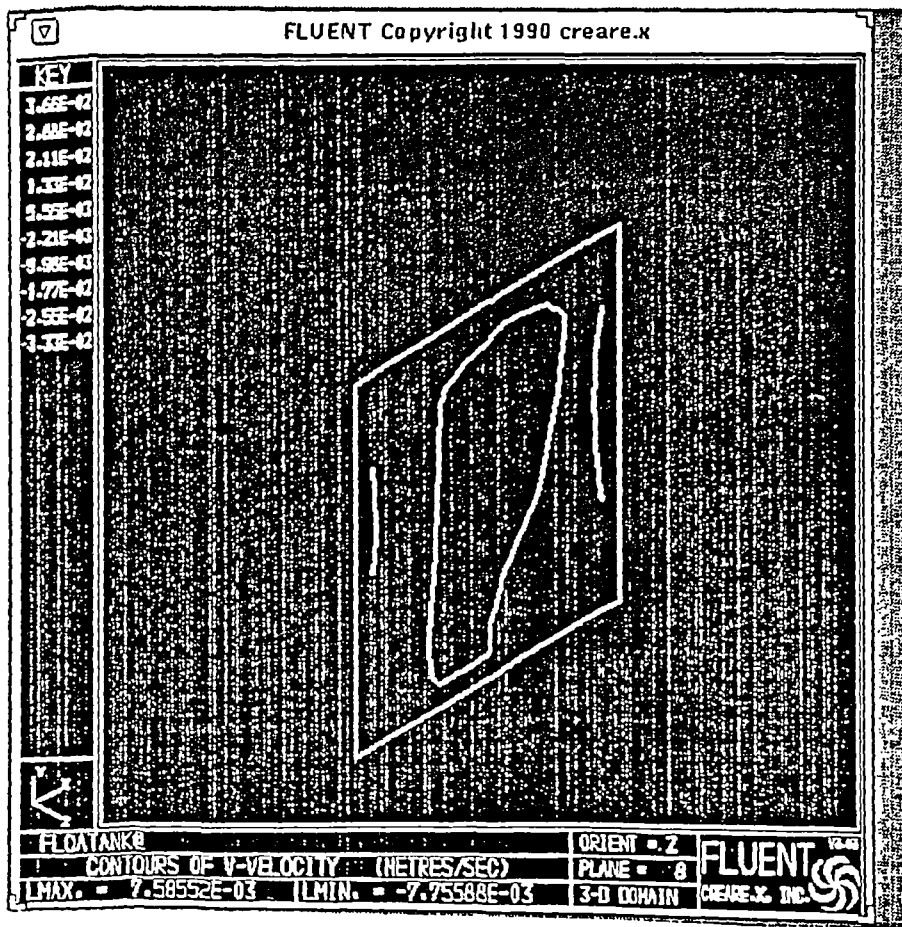
FIG. 43 VIEW OF CONTOURS OF V-VELOCITIES FOR THE 8th
PLANE IN FOUR NOZZLE SYSTEM

163

FIG. 44 VIEW OF CONTOURS OF V-VELOCITIES FOR THE 5th
PLANE IN FOUR NOZZLE SYSTEM
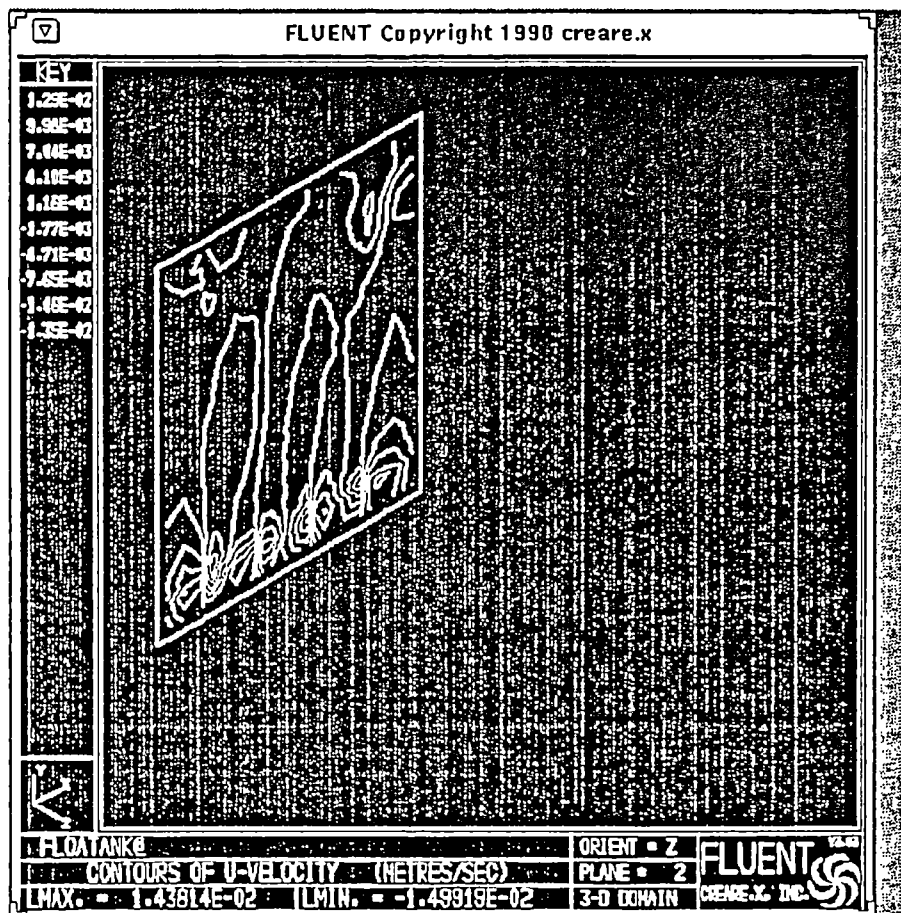
FIG. 45 VIEW OF CONTOURS OF U-VELOCITIES FOR THE 2nd
PLANE IN FOUR NOZZLE SYSTEM

165

CHAPTER 6

CONCLUSIONS

6.1 Conventional saturation system

1) Using the conventional saturator the obtained values of released air practically obeyed Henrys Law.

2) In conventional systems a better uniformity of bubble size is achieved with high pressures and a high liquid throughput.

3) An increase in pressure decreases the size of the generated bubbles in the conventional saturator. The size of bubbles produced in a conventional saturator varies in between 75-120μm.

4) The effect of liquid flowrates on bubbles sizes in the conventional systems seems to be unimportant for low values but it becomes slightly significant when applying higher liquid flowrates by causing a decrease in the bubble size.

5) An empirical correlation between number of generated bubbles per cm^3 and applied pressure was derived as:

$$N_b = a * P^c$$

The effect of liquid flowrate on this was not large, therefore it did not appear in the correlation. This equation could be useful for designing flotation tanks.

6.2 Higee Saturator results

6) In the Higee Absorber the effect of packing was found not to be beneficial at low liquid flowrates (<1000cc/sec) and high gas/liquid ratios (>10). Under these operating conditions a very high degree of saturation was found.

7) When compared at the low flowrate conditions, in the Higee Absorber, we can achieve a higher degree of saturation at lower pressures compared with the conventional saturator.

8) The effect of pressure (linked to rotational speed) is not marked in the Higee Saturator and in particular at low throughputs the degree of saturation is higher than Henry's Law and remains constant with the pressure. It is clear from this result that supersaturation is occuring.

9) Bubbles were not observed in the saturated solution coming from the Higee system.

10) The effect of the thickness of a packing was investigated for high liquid throughputs. When a thin packing is used in conjunction with the Higee Absorber, there is a slight increase in the degree of the absorption of air due to reduced back-mixing within the packing.

6.3 Hydrodynamic Studies

11) From the simulation graphs it is obvious that a multi-nozzle system dramatically performs in a better way than the single nozzle system due to the fact that the bubbles disperse over a wider spectrum.

12) The vectors of the velocity stream in the one nozzle system appeared larger than in the multi nozzle system where the bubble path seemed not to disturb the homogeneity of the system.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE WORK

1) By using more advanced bubble size and bubble movement techniques we will be able to more accurately observe the main factors which are fundamental to understand the hydrodynamics of the flotation process. These include:

a) Measurement of the number density of the generated bubbles which will enable the validity of the derived correlation to be confirmed.

b) The motion of the bubbles in the flotation tank can be correlated against the FLUENT models and thus a better understanding of the regimes by which bubbles move in tanks can be obtained and eventually better tank design achieved.

Knowing the velocity of formed bubbles will allow designs which reduce turbulence in systems where fragile flocs appear.

2) More results should be obtained using the Higee absorber. Throughout our research the Higee rotary saturator seems to operate better than the conventional system as far as the better level of saturation which can be achieved. In order to utilize this

high degree of saturation a better technique of removing the fluid from the system should be developed which would result in full utilization of the above system by allowing the bubbles to be generated at 1 atmosphere which is the pressure of the liquid at the outlet end.

3) With the aid of the simulation model there is a vast field of exploration available examining different designs of flotation tanks and nozzle structure. Different gases can also be introduced and there is a great scope for investigating the effects of their properties. Finally, bubbles at different sizes could be introduced and examined in order to evaluate the optimum flotation performance.

CHAPTER 8

REFERENCES

1) ADVANCED STUDY INSTITUTE

"The scientific Basis of Flotation"

Proc., N.A.T.O., Cambridge U.K., 5-16 July, (1982).

2) APLAN F.F.

"Flotation", Ch. in "Encycl. of Chem. Tech.", Kirk-Othmer, (eds.), vol. 9, J. Wiley and sons, U.S.A. (1966)

"Flotation", Ch. in "Handbook of Separation Techniques for Chemical Engineers", P.A. Schweitzer, (ed.), Mc-Graw Hill, N.York, (1979).

3) ASTARITA G. & SAVAGE D.

"Gas treating with chemical solvents"

John Wiley and Sons, New York, (1983)

4) AZBEL D.

"Two phase flow in chemical engineering"

Cambridge University Press ,pp161, (1981)

5) BALASUNDARAM V. & PORTER J.E.

Department of Chemical and Process Engineering,

The University of Newcastle Upon Tyne, England, 1990, (Private communication).

6) BELL C.

Ph.D. Thesis

University of Newcastle Upon Tyne, (1975)

7) BENZINGR.J. & MYERS J.E.

"Low frequency bubble formation at horizontal circular orifices"

Ind. Eng. Chem. 48, 2087, (1955)

8) BIESINGER M.G. & VINING T.S.

"Industrial Experience with Dissolved Air Flotation"

Ind. Waste Conf. (1974)

9) BISWAS A.

"The role of Carbon Dioxide in flotation of carbonate minerals"

Indian Journal Tech. 15, 6, 187, (1967).

10) BRATBY J.

"Aspects of sludge thickening by Dissolved Air Flotation"

Water Pollution, 421, (1978)

11) BRATBY J. & MARAIS G.V.R.

"Saturator Performance in Dissolved Air Flotation"

Water Res., 9, 929, (1975)

12) BUREAU OF MINES

"Mineral Facts and problems"

  Bulletin 667, U.S.A., (1975)

13) BURFITT M.

"The performance of full-scale Sludge flotation plant"

Water Pollution Control, 474, (1975)

14) BUSEV A.I. & IVANOV V.M.

"Analytical Chemistry of Rear Elements"

  Mir. Publ., Moscow, (1981)

15) CALDERBANK P.H.

"Gas liquid contacting on plates"

Trans. Inst. Chem. Eng. 34, 79, (1956)

16) CASSEL A.E. & KAUFMAN K.M.

"The effects of size on microflotation"

Water research, 9, 1017, (1975)

17) CLARK A.N. & WILSON D.J.

"Foam Flotation-Theory and Applications"

M. Dekker, N.York, (1983)

18) COLLINS G.L. & JAMESON G.J.

Chem. Eng. sci., 31,985, (1976)

19) CONWAY A. & NELSON R.

"High-solubility gas Flotation"

Journal of WPFC, 53, 1199, (1981)

20) DANCKWERTS P.V. & SHARMA M.

"The absorption of Carbon Dioxide into solutions of Alkalis and Amines"

The Chemical Engineers, (1966)

21) DAVIDSON L. & AMICK E.H.

"Formation of gas bubbles at horizontal orifices"

A.l.ch.E. Journal, 2, No 3, 337, (1956)

22) DAVIDSON J.F. & SCHULER B.O.G.

"Bubble formation at an orifice in a viscous liquid"

Trans. Inst. Chem. Eng. 38, 144, (1960)

23) DAVIDSON J.F. & SCHULER B.O.G.

"Bubble formation at an orifice in an inviscid liquid"

Trans. Inst. Chem. Eng. 38, 335, (1960)

24) DICK R.I.

"Sludge Treatment"

"Physicochemical Processes for Water Quality Control"

Weber W.J., (ed.), ch. 12 559, Wiley Interscience, Toronto, (1972).

25) EVERSOL W.G. & WAGNER G.H. & STACKHOUSE E.

"Rapid formation of gas bubbles in liquids"

Industrial Eng. Chem. 33, No 11, 1459, (1941)

26) FLINT L.R. & HOWARTH W.J.

Chem. Eng. Sci., 26, 1155, (1971)

27) FUERSTENAU D.W. (ed.)

"Froth Flotation", 50th Anniv., A.I.M.E., N. York, (1962)

28) FUKUI Y. & YUU S.

"Measurement of the charge on small gas bubbles"

AIChE Journal 28, 866,(1982)

29) GADDIS E.S. & VOGELPOHL A.

"Bubble formation in quiescent liquids under constant flow conditions"

Chem. Eng. Sci., 41, 97, (1986)

30) GEHR R. & HENRY J.G.

a) "Laboratory Techniques for Evaluating Batch Flotation of Activated Sludge"

Proc. 11th Canadian Symp., Water Pollution Research in Canada (1976).

b) "Measuring and predicting flotation performance"

Journal of WPCF, pp 203, February (1978)

31) HUGHES R.R. & HANDLOS A.A.

"The formation of bubbles at simple orifices"

Chem. Eng. Progr. 51, 557, (1955)

32) JACKSON R.

"The formation and coalescence of bubbles and drops in liquids"

The Chem. Eng., 107, May (1964)

33) KARGER B.L

"Nomenclature Recommendations for Adsorptive bubble separation method"

Sep.Sci., 2, 401, (1967)

34) KATTI S. & LANGFITT B.

"Development of a simulator for commercial absorption based on mass transfer rate approach"

65th Annual Convection Gas Processors Association, San Antonio, Texas,

35) KHURANA A.K. & KUMAR R.

"Studies in bubble formation III"

Chem. Eng. Sci. 24, 1711, (1969)

36) KIRK R.E. & OTHMER D.F.

Encyclopedia of Chemical Technology, 6, 597, (1951)

37) KITCHENER J.A.

Seminar, "Technologically Important Aspects of Interface Science", Imperial College of Sci. and Techn., London, June 27-July 1, (1983).

38) KLASSEN V.I. & MOKROUSOV

"An introduction to theory of Flotation"

Butterworths, London, (1963)

39) KUMAR. R. & KULOOR N.R

"Bubble formation in viscous liquids under constant flow conditions"

The Canadian Journal of Chem. Eng. 48, 383, (1970)

40) KUMAR R. & KULOOR R.

"The formation of bubbles and drops"

Advanced in chemical Engineering, 8, 256, (1972)

41) LANAUZE R.D. & HARRIS I.J.

"A note on gas bubble formation"

Chem Eng. Sci. 29, 1663, (1974)

42) LEIBSON I. & HOLCOMB E.G. & CACOSO A.G.

"Rate of flow and mechanics of bubbles formation from single submerged orifices"

A.I.ch.E. Journal, 2, No 3, 296, (1956)

43) LEMLICH R.

"Adsorpive Bubble Separation Techniques"

Academic Press, New York (1972)

44) LEVENSPIEL O.

"Chemical Reaction Engineering"

Wiley Int. Ed. (1972)

45) LEWIS D.A. & DAVIDSON J.F.

"Bubble sizes produced by shear and turbulence in a bubble column"

Chem. Eng. Sci. 38, 161, (1983)

46) MARAIS G.v.R.

"Dissolved Air Flotation-an evaluation of inter-relationships between Process variables and their optimisation for design"

Water S.A. 1, 57, (1975)

47) MARMUR A. & RUBIN E.

"A theoretical model for bubble formation at an orifice submerged in av inviscid liquid"

Chem. Eng. Sci. 31, 453, (1976)

48) MARTIN M.J.J.

"Dissolved Air Flotation- An Alternative Method to Solids/Liquid Separation.", Water Trt. Jour. Refocus, (1974)

49) MATIS K.A.

a) Ph.D. Thesis, University of Newcastle Upon Tyne, (1977)

b) Chem. Chron., 44, 54, May 1979

c) Chem. Chron., 46, 27, March 1981

50) McCAN D.J. & PRINCE R.G.H.

"Regimes of bubbling at submerged orifice"

Chem. Eng. Sci. 26, 1505, (1971)

51) NEMEROW N.L.

"Industrial Water Pollution"

Addisn-Wesley, U.S.A., (1971)

52) PINFOLD T.A

Sep.sci. 5, 379, (1970)

53) PLAKSIN I.N.

"Interaction of minerals with gases and reagents in the flotation"

Trans. AIME 214, 319, (1959)

54) RAMAKRISHNAN S. & KUMAR. R. & KULOOR N.R.

"Studies in bubble formation I under constant flow conditions"

Chem. Eng. Sci. 24, 731, (1969)

55) RAMIREZ R.ERNEST

"Comparative physicochemical study of industrial wastewater treatment by electrolytic, dispersed air and dissolved air flotation technologies"

Proceedings of the 31st Industrial Water Conference, Purdue University (1976)

56) REAY D. & RATCLIFF G.A

a) Can. J. of Chem. Eng., 51, 2,178, (1973)

b) Can. J. of Chem. Eng., 53, 481, (1975)

57) RUFF K.

Chem. Ing.Technik., 48, 759, (1976)

58) SARDAR S. & WEILAND R.H.

"A non equilibrium stage approach for the design and simulation of gas treating units"

Annual Meeting, A.I.Ch.E. San Fransisco, (1984)

59) SEBBA F.

"Ion flotation"

 Elsevier Publications, N. York, (1962)

60) SHANNON W.T. & BUSSON D.H.

"Dissolved Air Flotation in Hot Water"

Water Research 14, 759, (1980)

61) SHERWOOD T.K. & DIGFORD R.L.

"Mass transfer"

McGraw-Hill, New York, (1975)

62) SUTHERLAND K.L & WARK I.W.

"Principles of flotation"

Austr. Inst. Min. & Metal. (1955)

63) TAKAHASHI T. & MIYAHARA

"Fundamental studies of bubble formation in Dissolved Air Pressure Flotation"

Journal of Chem. Eng. of Japan, 12, 275, (1979)

64) UNNO H. & INOE I.

"Size reduction of bubbles by orifice mixer"

Chem. Eng. Sci. 35, 1571, (1980)

65) VAN KREVELEN D.W. & HOFTIJZER P.J.

"Studies of gas bubbles formation. Calculation of interfacial area in bubble contactors"

Chem Eng. Progr. 46, No 1, 29, (1950)

66) VESILIND P.A.

"Treatment and Disposal of Wastewater Sludges"

An. Arbor Sciences, (Publishers), (1974)

67) VRABLIK E.R.

"Fundamental Principles of Dissolved Air Flotation of Industrial Wastes"

Proceedings of the 14th Purdue Industrial Waste Conference, 743-779, (1959)

68) WARD C.A. & BALAKRISHNAN F.

Trans. ASME, J.Basic Eng. 695, (1970)

69) WRAITH A.E.

"Two stages bubble growth at a submerged plate orifice."

Chem. Eng. Sci. 26,1659, (1971)

70) ZABEL F.THOMAS & MELBOURNE J.D.

FLOTATION

.   .

.

APPENDIX I

RESULTS OF BUBBLES SIZE MEASUREMENT FOR DIFFERENT PRESSURE AND LIQUID FLOWRATES

Operating conditions: Conventional saturator, Tap water

The following Tables give the number of bubbles which have count for three different liquid flowrates

TABLE 1.1

LIQUID FLOWRATE 5 cc/sec

	PRESSURE (psi)					
	10	20	30	40	50	60
	No OF PHOTOGRAPH					
	1	2	3	4	5	6
BUBBLE DIAMETER (μm)	NUMBER OF BUBBLES					
30	1	1	1	2	3	1
40	3	2	1	1	2	6
50	2	2	2	2	4	10
60	3	1	1	1	10	11
70	2	1	2	1	11	20
80	7	2	2	15	16	10
90	6	2	10	13	18	9
100	7	1	24	17	15	4
110	5	5	21	14	5	5
120	4	14	13	15	2	4
130	3	25	8	4	3	4
140	2	20	1	1	2	4
150	11	14	2	5	1	3
160	10	3	4	2	1	2
170	12	3	2	3	3	1
180	9	2	3	2	2	3
190	8	1	2	1	1	2
200	5	1	1	1	1	1

TABLE 1.2

LIQUID FLOWRATE 10 cc/sec

	PRESSURE (psi)					
	10	20	30	40	50	60
	No OF PHOTOGRAPH					
	7	8	9	10	11	12
BUBBLE DIAMETER (μm)	NUMBER OF BUBBLES					
30	2	1	2	1	2	6
40	1	3	3	2	4	7
50	3	1	5	4	6	10
60	4	2	4	6	11	15
70	3	3	1	9	13	17
80	5	4	18	12	12	11
90	4	11	17	17	17	8
100	3	13	12	15	9	6
110	15	12	20	8	8	6
120	12	15	4	9	2	2
130	21	11	2	11	1	3
140	19	7	1	2	4	1
150	5	9	2	1	3	1
160	3	1	1	1	2	2
170	2	2	3	0	1	1
180	1	3	1	1	1	2
190	4	1	2	0	2	1
200	3	1	2	0	2	1

TABLE 1.3

LIQUID FLOWRATE 18 cc/sec

	PRESSURE (psi)					
	10	20	30	40	50	60
	No OF PHOTOGRAPH					
	13	14	15	16	17	18
BUBBLE DIAMETER (μm)	NUMBER OF BUBBLES					
30	4	3	2	7	6	5
40	4	2	5	8	9	9
50	3	5	22	18	19	17
60	4	4	10	20	19	18
70	2	18	10	14	15	10
80	17	14	8	4	3	11
90	15	12	6	4	5	5
100	13	9	5	5	1	6
110	7	7	10	5	2	5
120	6	2	3	1	4	2
130	4	5	4	2	2	3
140	5	3	2	1	2	1
150	5	6	2	1	1	2
160	4	4	1	3	1	2
170	2	2	2	3	1	1
180	1	2	2	2	4	1
190	2	1	3	1	5	0
200	2	1	3	1	1	0

APPENDIX 2

RESULTS OF CALCULATED AND OBSERVED AVERAGE BUBBLE DIAMETER FOR DIFFERENT PRESSURES

Operating conditions Tap water, Conventional saturator

The following Tables give the calculated and the observed value of the average bubble diameter for different liquid flowrates.

TABLE 2.1

LIQUID FLOWRATE 5 cc/sec

PRESSURE (psi)	CALCULATED (μm)	EXPERIMENTAL (μm)
10	148.4	135.0
20	134.9	129.0
30	120.8	112.7
40	116.3	107.3
50	104.4	91.7
60	106.9	90.1

TABLE 2.2

LIQUID FLOWRATE 10 cc/sec

PRESSURE (psi)	CALCULATED (μm)	EXPERIMENTAL (μm)
10	135.1	116.1
20	123.1	114.5
30	111.7	99.2
40	102.5	96.4
50	106.7	91.9
60	97.32	80.7

TABLE 2.3

LIQUID FLOWRATE 18 cc/sec

PRESSURE (psi)	CALCULATED (μm)	EXPERIMENTAL (μm)
10	115.9	102.2
20	111.7	97.3
30	109.6	88.8
40	98.1	77.5
50	105.6	80.6
60	89.0	77.5

APPENDIX 3

OBTAINED RESULTS USING THE HIGEE ROTATING DISK UNDER DIFFERENT CONDITIONS

In the following tables are listed the results which were obtained using the Higee rotating disk under different gas flowrates, liquid flowrates, pressures and packings.

TABLE 3.1

A)Effect of the rotation speed

Operating conditions

Packing:	None
Axial length:	5cm
Gas flowrate:	1000 cc/sec
Liquid flowrate:	91 cc/sec

Rotation speed (rpm)	500	600	700	800	900	1000
Pressure (psi)	6.5	10.9	14.5	19.6	29.7	35.5
Inlet Temp. ($^\circ$C)	17.4	17.4	17.6	17.8	17.8	17.8
Outlet Temp. ($^\circ$C)	18.5	18.6	18.4	19.0	19.4	19.5
Inlet O_2 Conc. (ppm)	8.96	8.96	8.87	8.87	8.87	8.8
Outlet O_2 Conc. (ppm)	17.1	17.2	17.2	17.0	16.8	80.1
Outlet air flow(cc/sec)	6.17	6.21	6.18	6.13	6.05	6.04
Outlet Air Conc. (mg/lt)	81.7	82.2	81.9	81.1	80.1	80.0

TABLE 3.2

B) Effect of Gas Flowrate at Low Rotation Speed

Operating conditions

Packing:	None
Axial length:	5cm
Rotation Speed:	500 rpm
Liquid flowrate:	91 cc/sec
Pressure:	6.5 psi

Gas Flowrate cc/sec	1000	1500	2000
Inlet Temp. ($^\circ$C)	18.2	18.2	18.2
Outlet Temp. ($^\circ$C)	19.2	19.2	19.3
Inlet O_2 Conc. (ppm)	7.78	8.78	8.78
Outlet O_2 Conc. (ppm)	15.03	17.23	17.32
Outlet air flow(cc/sec)	6.12	6.19	6.23
Outlet Air Conc. (mg/lt)	71.61	82.05	82.48

TABLE 3.3

C) Effect of Gas flowrate at High Rotation Speed

Operating conditions

Packing:	None
Axial length:	5cm
Rotation Speed:	1000 rpm
Liquid flowrate:	91 cc/sec
Pressure:	35.5 psi

Gas Flowrate cc/sec	1000	1500	2000
Inlet Temp. ($^{\circ}$C)	18.4	18.4	18.4
Outlet Temp. ($^{\circ}$C)	18.8	19.7	19.8
Inlet O_2 Conc. (ppm)	8.74	8.74	8.74
Outlet O_2 Conc. (ppm)	16.46	16.6	16.68
Otlet air flow (cc/sec)	5.92	5.94	5.99
Outlet Air Conc. (mg/lt)	78.4	76.07	79.42

TABLE 3.4

D) Effect of Rotation Speed

Operating conditions

Packing:	Thick DECLON
Axial length:	5cm
Liquid flowrate:	147 cc/sec
Gas flowrate:	1000 cc/sec

Rotation speed (rpm)	500	600	700	800	900	1000
Pressure (psi)	6.5	10.9	14.5	19.6	29.7	35.5
Inlet Temp. ($^{\circ}$C)	16.2	16.2	16.2	16.4	16.4	16.4
Outlet Temp. ($^{\circ}$C)	16.9	17.4	17.6	17.8	17.8	18.1
Inlet O_2 Conc. (ppm)	8.9	8.9	8.9	8.86	8.26	8.26
Outlet O_2 Conc. (ppm)	16.38	16.07	16.20	15.94	15.29	15.19
Outlet air flow (cc/sec)	5.89	5.78	5.82	5.73	5.50	5.46
Outlet Air Conc. (mg/lt)	78.02	76.53	77.13	75.9	72.81	72.35

TABLE 3.5

E) Effect of liquid flowrate at high rotation Speed

Operating conditions

Packing:	Thick DECLON	
Axial length:	5cm	
Rotation Speed:	1000 rpm	
Gas flowrate:	1000 cc/sec	
Pressure:	35.5 psi	

Liquid flow (cc/sec)	147	370	574	2110
Inlet Temp. (^{0}C)	16.4	16.0	16.4	18.0
Outlet Temp. (^{0}C)	18.1	16.9	17.1	18.2
Inlet O_2 Conc. (ppm)	8.26	8.99	8.73	8.51
Outlet O_2 Conc. (ppm)	15.19	16.68	15.96	13.97
Outlet air flow (cc/sec)	63.67	88.4	117.9	131.0
Outlet Air Conc. (mg/lt)	72.35	79.46	75.76	66.52

TABLE 3.6

F) Effect of gas flowrate at very high rotation Speed

Operating conditions

Packing:	Thick DECLON	
Axial length:	5cm	
Rotation Speed:	1457 rpm	
Liquid flowrate:	574 cc/sec	
Pressure:	78.31 psi	

Gas flow (cc/sec)	1000	2000
Inlet Temp. (^{0}C)	16.4	16.6
Outlet Temp. (^{0}C)	17.1	17.1
Inlet O_2 Conc. (ppm)	8.73	8.73
Outlet O_2 Conc. (ppm)	15.91	15.73
Outlet air flow (cc/sec)	36.01	35.7
Outlet Air Conc. (mg/lt)	75.76	74.94

TABLE 3.7

G) Effect of Liquid flowrate at very high rotation Speed

Operating conditions

Packing:	Thin DECLON	
Axial length:	2.5cm	
Rotation Speed:	1457 rpm	
Gas flowrate:	1500 cc/sec	
Pressure:	78.31 psi	

Liquid flow (cc/sec)	528	1055	1583	2110	3210
Inlet Temp. ($^\circ$C)	16.0	15.6	16.5	16.1	16.4
Outlet Temp. ($^\circ$C)	16.5	15.9	16.6	16.3	16.2
Inlet O_2 Conc. (ppm)	8.03	8.11	8.18	7.89	8.17
Outlet O_2 Conc. (ppm)	14.4	14.79	15.0	13.67	14.22
Outlet air flow (cc/sec)	28.74	61.96	93.92	114.0	180.4
Outlet Air Conc. (mg/lt)	65.58	70.45	71.47	65.10	67.71

TABLE 3.8

H) Effect of Liquid flowrate at high rotation Speed

Operating conditions

Packing:	Thin DECLON	
Axial length:	2.5cm	
Rotation Speed:	1000 rpm	
Gas flowrate:	1500 cc/sec	
Pressure:	37.5 psi	

Liquid flow (cc/sec)	1055	1584	2110	2408
Inlet Temp. ($^\circ$C)	13.9	14.6	14.8	14.8
Outlet Temp. ($^\circ$C)	14.4	14.2	14.7	14.9
Inlet O_2 Conc. (ppm)	8.43	8.19	8.10	7.85
Outlet O_2 Conc. (ppm)	15.27	14.15	14.14	13.77
Outlet air flow (cc/sec)	63.67	88.40	117.9	131.0
Outlet Air Conc. (mg/lt)	72.706	67.23	67.34	65.57

TABLE 3.9

I) Effect of Liquid flowrate at high rotation Speed

Operating conditions

Packing:	Thin DECLON
Axial length:	2.5cm
Rotation Speed:	1000 rpm
Gas flowrate:	500 cc/sec
Pressure:	37.5 psi

Liquid flow (cc/sec)	1055	2110	2480
Inlet Temp. $(^\circ C)$	11.4	12.5	13.4
Outlet Temp. $(^\circ C)$	11.0	12.6	13.1
Inlet O_2 Conc. (ppm)	10.09	9.92	9.52
Outlet O_2 Conc. (ppm)	16.02	14.26	13.26
Outlet air flow (cc/sec)	66.8	118.9	129.9
Outlet Air Conc. (mg/lt)	76.28	67.9	63.14

TABLE 3.10

J) Effect of Gas flowrate at high rotation Speed

Operating conditions

Packing:	Thin DECLON
Axial length:	2.5cm
Rotation Speed:	1000 rpm
Liquid flowrate:	1055 cc/sec
Pressure:	37.5 psi

Gas flow (cc/sec)	500	1000	1500	2000	3000
Inlet Temp. $(^\circ C)$	11.4	14.4	15.0	15.2	15.1
Outlet Temp. $(^\circ C)$	11.0	14.7	15.3	15.4	15.3
Inlet O_2 Conc. (ppm)	10.09	9.14	9.03	8.57	8.58
Outlet O_2 Conc. (ppm)	17.64	15.64	16.75	15.6	15.64
Outlet Air Conc. (mg/lt)	84.0	74.47	79.79	74.27	74.4

TABLE 3.11

K)Effect of Liquid Flowrate at high rotation Speed

Operating conditions

Packing:	Thin Declon
Axial length:	2.5cm
Gas flowrate:	1500 cc/sec
Rotation Speed :	1000 rpm
Pressure:	37.5 psi

Liquid flow cc/sec	528	1055	1583
Inlet Temp. (^{o}C)	14.8	15.8	14.3
Outlet Temp. (^{o}C)	16.2	16.1	14.4
Inlet O_2 Conc. (ppm)	8.36	8.28	8.30
Outlet O_2 Conc. (ppm)	15.72	14.33	13.86
Outlet air flow (cc/sec)	63.67	88.4	117.9
Outlet Air Conc. (mg/lt)	74.81	68.24	66.10

APPENDIX 4

RESULTS OF AIR FLOWRATE MEASUREMENTS USING THE CONVENTIONAL SATURATION FOR DIFFERENT PRESSURES AND LIQUID FLOWRATES

PRESSURE
(psi)

	10	20	30	40	50	60

GENERATED AIR FLOWRATE
cc/sec

LIQUID FLOWRATE
cc/sec

LIQUID FLOWRATE cc/sec	10	20	30	40	50	60
5.0	0.04	0.11	0.15	0.20	0.23	0.32
6.0	0.05	0.15	0.20	0.25	0.31	0.41
8.3	0.08	0.20	0.29	0.39	0.44	0.55
10.0	0.09	0.21	0.30	0.45	0.52	0.70
11.6	0.10	0.25	0.40	0.50	0.61	0.80
18.0	0.15	0.39	0.60	0.80	1.00	1.19

APPENDIX 5

CALCULATION OF THE AMOUNT OF GENERATED AIR USING THE HIGEE ABSORBER

For each run of the Higee rotating Disk a value was obtained for the Oxygen concentration in the sample in ppm(mg/lt).

To compare that with the conventional saturator this result should be converted to cc/sec. This was achieved by the following way.

Each value was multiplyed by 10^{-6} to convert the units.

Then the obtained result was multiplyed by the related liquid flowrate for this particular run.

Finally the result was divided by the corresponding density of water for this particular temperature and the density of water was obtained from analogous Tables.

The result was expressed in cc/sec.