IMPROVING CONVENTIONAL FLOTATION METHODS TO TREAT EOR POLYMER RICH PRODUCED WATER

ENVIRO-TECH SYSTEMS
"PROCESS WATER SPECIALISTS"

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1 Abstract

Flotation units, which operate with the assistance of gas in the flotation process, have been widely used for the treatment of produced water both onshore and offshore. Differing technologies are applied to Flotation units for a specific application. The advantages and disadvantages of each arrangement plus the requirements of the process determine the choice of gas floatation mechanism. These methods can be divided in two major categories: Induced Gas Floatation (IGF), Dissolved Gas Floatation (DGF). A close comparison of IGF and DGF is studied in this paper to identify the main criteria affecting the performance and functionality of floatation units and their accessories in different environments. Additionally, this paper will describe the effects and benefits of using both IGF and DGF at the same time. The authors will verify their hypothesis through three years of laboratory and field study.

2 Introduction

The protection of the environment has become an increasingly important consideration in the production of oil and natural gas; therefore, discharge of produced water containing residual oil and oil coated solids has come under intense scrutiny by regulatory agencies. Produced water is the largest portion of byproduct fluid that is produced in oil and gas production [1]. The total amount of water produced in the U.S. in 2007 was 21 MMMbbl/year with respect to 1.75 MMMbbl/year of oil and 24 MMMMscf/year of gas production [2]. The strict environmental regulations and the ever-increasing amount of water production is requiring oil and gas companies to extensively search for advanced processes to polish produce water, efficiently and economically.

A Flotation system is one of the common treatment methods that are currently widely used for oil, water and solid separation in the oil and gas industry. Gas Flotation is the addition of micro/macro gas bubbles to increase the tendency of oil droplets to float to the surface of the container where the specific skimming method is used to remove collected oil from the system. Over the past several years, new designs for the treatment of produced water by flotation have been developed. Mechanisms that produce gas bubbles can be categorized into two major methods: Induction, Dissolving. These new designs utilize features which improve the performance and reduce the operating problems associated with conventional designs.

3 Induced Gas Flotation

Induced Gas Flotation (IGF) is a water treatment process that clarifies wastewaters (or other waters) by the removal of suspended matter such as oil or solids. The removal is achieved by injecting gas bubbles into the water or wastewater in a flotation tank or basin. The small bubbles adhere to the suspended matter causing the suspended matter to float to the surface of the water where it may then be removed by a skimming device. The bubbles may be generated by an (1) eductors, (2) impeller or a (3) sparger.

In eductor style IGF (hydraulic unit), gas is introduced into a slipstream of effluent. This is used to carry the gas which is released into the active cells of the vessel. Because this fluid must be recycled back into the system (normally 50% of the design flow rate), this design effectively decreases the residence time of the fluid to be treated. [3]

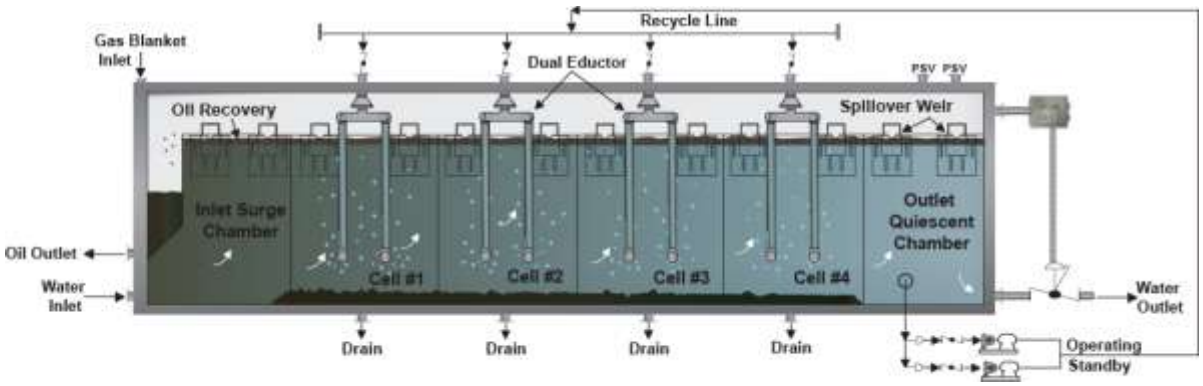


Figure 1.Induced Gas Floatation Vessel, Eductor Style (Cortesy of Enviro-Tech Systems. LLC.)

The second type of IGF, the Impeller (mechanical unit), utilizes an electric motors driven impeller to induce gas into the water phase. Dependent on the application, mechanical units tend to be more efficient than hydraulic units due to the introduction of gas from the top of the vessel directly into the aqueous phase. However, mechanical units are associated with maintenance difficulties and the emission of noxious vapors which leak around the seals and cover of the vessel.

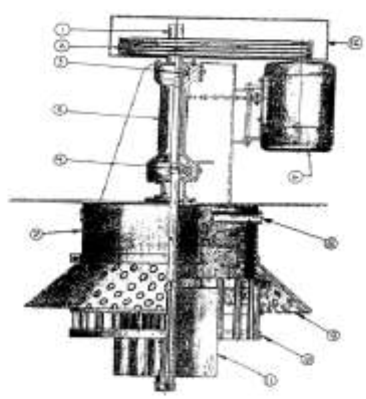


Figure 2. Mechanical Induced Gas Flotation (Wemco Design)

Lastly, the sparger tube method is used to generate small bubbles in a liquid. The pressurize gas passes through porous walls of sparger tube and create gas bubbles. The main setback of using sparger tubes is plugging/fouling of pores. This will create non-uniformity of bubble size distribution and high pressure drop across the tubes. Use of sparger tubes is limited with scale tendency of inorganic solutes.

Figure 3. Porous Sparger Tube Gas Floatation

4 Dissolved Gas Flotation

Dissolved Gas Flotation (DGF) systems are used for a variety of applications throughout the world. The process floats solids, oils and other contaminants to the surface of liquids. Once on the surface these contaminants are skimmed off and removed from the liquid. Oil and gas production facilities have used flotation systems to remove oil and solids from their produced and processed water (wastewater) for many years.[4] The keys to good separation are both gravity and the creation of millions of very small bubbles (herein called Micro-Bubbles). By attaching a small gas bubble to an oil droplet, the density of the droplet decreases, which increases the rate at which it will rise to the surface. Therefore, the smaller the gas bubbles created, the smaller the oil droplet floated to the surface. Efficient flotation systems need to create as many small bubbles as possible. The Micro-Bubbles can be generated by either (1) Saturator Vessel or (2) DGF pumps.

In the first method, gas is dissolved into the recycle flow by adding air under pressure in a vessel called a saturator or gas dissolving vessel. Thus, the total amount of air delivered to the contact zone depends on the saturator pressure and the recycle flow. A typical saturator pressure is 500 kPa (72.5 psi). The recycle flow typically is 10% of the design flow rate. The recycle flow is injected through nozzles or special valves at the bottom entrance to the contact zone. Microbubbles are produced with sizes between 10 and 100 µm. These small gas bubbles give the water a milky appearance, thus the term white water is used to describe the bubble suspension in the DGF tank.

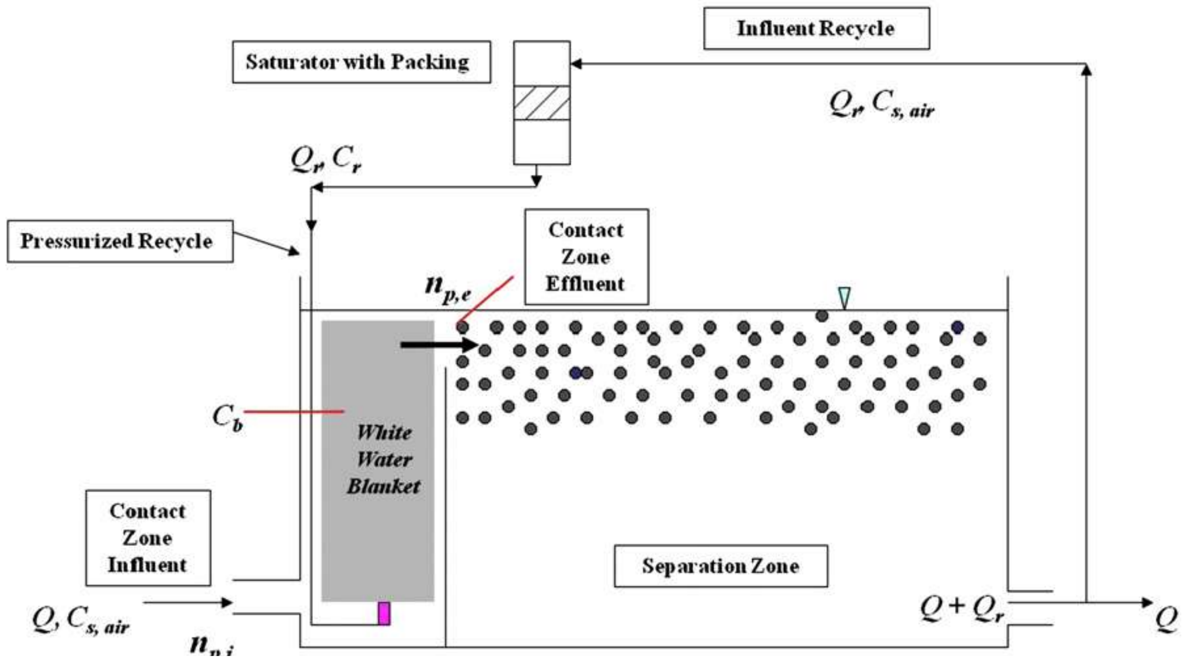


Figure 4. Dissolve Gas Floatation, external saturator [3]

In utilizing the second method, DGF pump, a single pump is used to mix gas and recirculate water. High shear and turbulence create small bubble with a large surface area at discharge of the pump; where the high pressure 550 – 690 KPa (80-100 psig) will partially dissolve gas to the water. The high pressure mixture of water-gas mixture then is referred to the atmospheric (or near atmospheric) tank. The sudden pressure drop and shear at pressure drop point will create numerous Micro-bubbles in the range of 30-50 µm. In this method, the recirculation rate can be reduced as low as 10% depending on the DGF pump design.

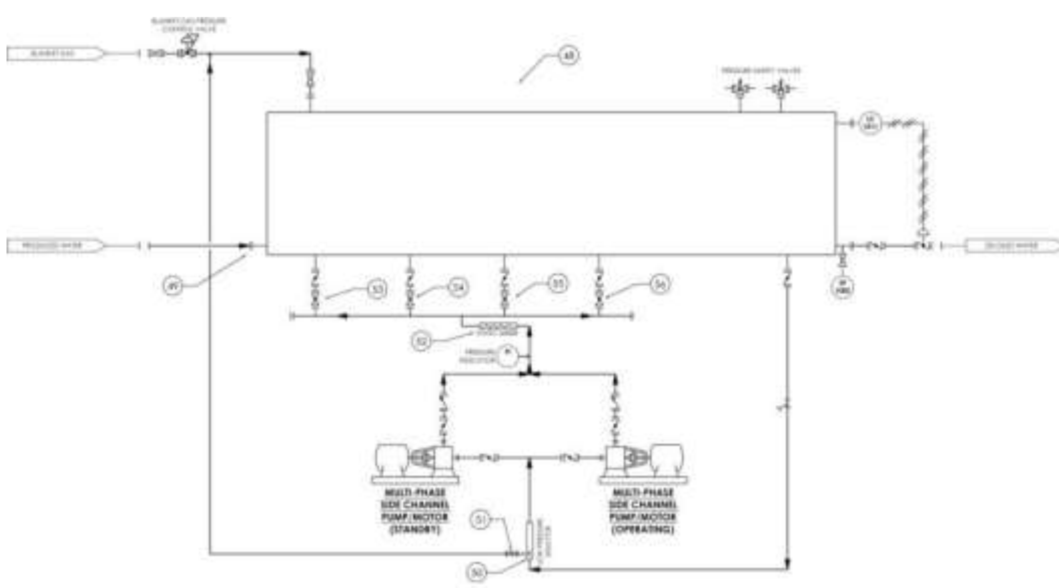


Figure 5. Dissolve Gas Floatation, Micro-Bubble Pump

5 Gas Flotation Flow Dynamics

For a better understanding of the effects methods of gas flotation have on the separation of contaminates the authors dedicate this section solely to the flow dynamics of gas flotation.

5.1 Flotation Concept

In the macroscopic perspective, by introducing the gas bubbles in the water-oil mixture, the oil droplets float to the surface as a result of three principles:

a) Intensifying of vertical velocity of lighter components,
b) Breakage of large vortex (eddies) in continuous media and convert them to smaller vortices with high rotational velocity,
c) Attachment of gas bubbles to the contaminates.

Gas bubbles are the lightest fluid in every IGF unit. Therefore, they have the most powerful buoyancy force. As the gas bubbles travel upward they carry with them surrounding water. In other words, gas bubbles exchange their upward momentum with the surrounding media through the drag momentum exchange as they rise.

In a homogeneous flow, where only one phase exists, the eddies can grow and create a large swirl flow. While in a heterogeneous flow, where multiple phases exist, smaller eddies will form. In both scenarios, the total turbulence energy is the same (Conservation of Energy) but, the eddies carry a smaller amount of water which leads to higher vorticity. Introducing gas bubbles into the system changes the media to a heterogeneous flow field. In other words, gas bubbles break the large eddies into smaller ones with higher vorticity, which have higher efficiency in the separation and coalescence of oil droplets.

As the number of gas bubbles increase in the system, the probability of collision between oil droplets and gas bubbles increase. The outcome of each collision between gas bubbles and oil droplets can be bouncing or attaching (adhering). In the case of attachment of gas bubbles on the surface of oil droplets, the buoyancy of the outcome parcel will increase, which causes the rapid rise of the oil droplets. A significant size difference between gas bubbles and oil droplets may cause unbalanced force at the gas bubble/oil droplet interface; potentially causing the disjointing of bubbles and oil droplets. Disjoining probability will increase as the travel distance to the surface and gas bubble/oil droplet size difference increases.

In summary, the floatation process occurs in three steps,

1. Collision: It is mainly a function of the number of bubbles, the distribution of gas bubbles and contaminated water flow pattern. Increases in the number of uniformly distributed gas bubbles increase the efficiency of gas flotation
2. Attachment: The ratio of the gas bubble to oil droplet size and relative velocity between two particles determine the fate of each collision to be attachment (adhering) or bouncing. In general, the smaller gas bubble which travels with lower speed has the highest chance of attachment (adhering).
3. Rising: The coalesced parcel of gas bubble and oil droplet rises to the water surface with a speed which is a direct function of gas bubble diameter. However, while traveling to the surface large gas bubbles disjoin from the oil droplet. The chance of disjoining is directly a function of gas

bubble size and rising distance. Therefore, there is a critical bubble size for operating conditions that will effectively attach to the oil droplets and float them to the surface without disjointing.

6 Induced Gas Floatation (IGF), Eductor Design

Based on industry preference, the authors utilized the Eductor design IGF for the foundation of their study. Additionally, due to the simplicity of design and minimal operational issues, this selection will remove all other uncertainties in regards to poor operation philosophy. Furthermore, this section describes the detail process, operation and design of an Eductor style IGF system, ENVIRO-CELL™

The ENVIRO-CELL consists of six (6) cells including two (2) quiescent cells and four (4) active cells. The process is initiated when oily wastewater enters the ENVIRO-CELL at the inlet. The inlet cell provides a surge capacity, dampening the incoming flow, allowing the flotation process to properly function. It also provides a buffer for free oil removal and skimming, lowering the oil content of the process before entering the first active cell.

Following the initial quiescent cell is four (4) active cells. Utilizing eductors to enhance the Venturi effect, the second stage of the flotation process accounts for stage separation with each active cell capable of approximately 60% removal of oil with a composite efficiency range of 90-97%.

The final stage of the process provides a clearwell or quiescent area for the removal of small oil droplets. The recirculation system uses the Venturi Principle to create minute bubbles, which is the basis of the flotation process. These small bubbles eject at the outlet of each eductor, rise and attach to free oil droplets providing accelerated buoyancy for their lift. The simplified oil removal process directs the separated oily froth to the adjustable oil weir for removal. The processed water passes through the complete flotation process and exits the vessel for further treatment or discharge.

Two (2) ANSI centrifugal recirculation pumps are designed to operate with one (1) operating and one (1) standby, for clean water injection of Eductors. The recycle flow is fixed by the pump sizing and the Eductor sizing. Clean water from the final cell of the IGF is recycled through the ENVIRO-CELL Eductors to provide maximum gasification to create the bubbles that provide the lift for oil removal. The pumps should operate for continuous running.

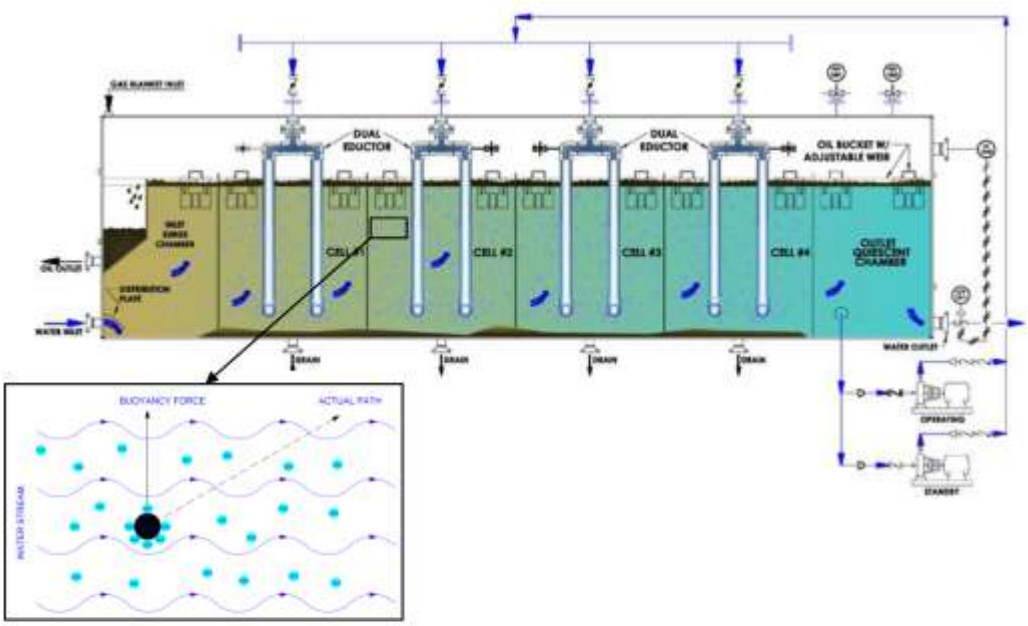


Figure 6. ENVIRO-CELL Principle of Operation

In the normal process where produced water with salinity of 25-55 PPT and natural gas induced to the water, the gas bubbles generated are in the range of 100-200 µm. These Macro-bubbles (Figure 7- #9) will travel through each cell and collide with different oil droplets. When oil droplets and gas bubbles collide, the outcome can be attachment (adhering) or bouncing. The probability of attachment is related to the offset of the oil droplet center, and the trajectory of air/gas bubbles. The critical offset can be evaluated by means of conservation of energy law. When the interfacial energy change of an oil droplet and gas bubble is equal or greater than the rotational energy of the oil droplet, caused by tangential momentum exchange, gas bubbles will stick to the oil droplets. [6]

When enough of the gas bubbles attach to the oil droplets (Figure 7 - #10) this results in the reduction of the density of parcel (Figure 7- #11) and increases the rising velocity of oil droplets. However, if the buoyancy of the gas bubbles are more than the IFT between oil and gas, the bond between gas and oil droplets will break, which cause the oil droplet to return back to the solution. Therefore, IGF efficiency is limited by the minimum oil droplet size wherein the smallest gas bubbles can separate.

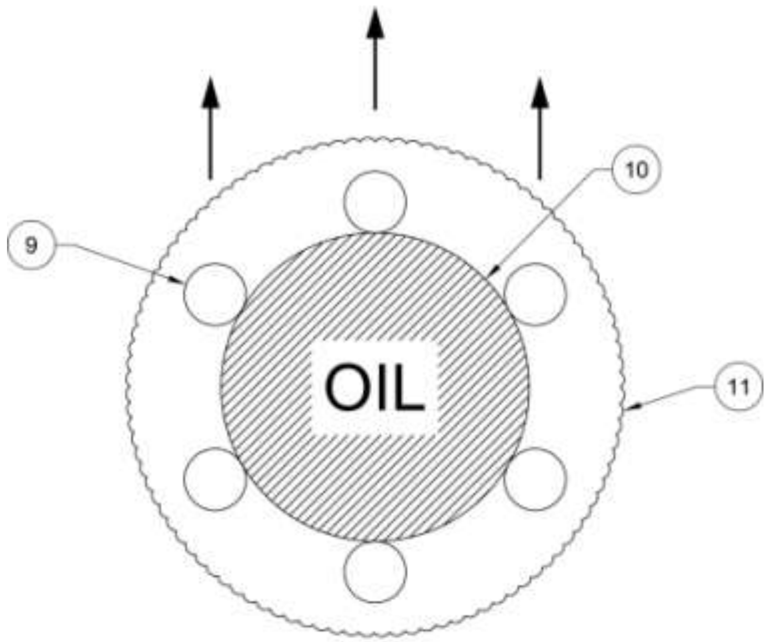


Figure 7. Attachment of Macro-Bubbles generated by IGF, eductor method, on separation of oil droplets

7 Dissolved Gas Floatation (DGF), Micro-Bubble Pump,

Micro-Bubble Pumps (DGF) are the most common DGF method in the oil and gas industry. Therefore, a secondary technology focus of the research will concentrate on the DGF pumps. This section describes the process and the philosophy behind dissolved gas floatation.

As is shown in figure , a DGF pump is installed on an atmospheric vessel to enhance the separation efficiency by the addition micro bubbles into the system. As the processed water enters the vessel from the inlet nozzle, it interacts with microscopic gas bubbles, which will attach to them and increase the pace of rise of oil droplets to the surface as is described in Section 5: Gas Flotation Flow Dynamics.

Processed water from the end of the vessel will be recycled through the DGF pumps. In the DGF cycle the recycled water will be passed through low pressure eductors, which create enough suction to entrain up to 30% gas in the incoming water through the needle valve from the gas blanket wherein the operator can control the gas percentage in the stream. The gas and water mixture will go through a series of centrifugal stages in the Multiphase-Side Channel pump. The pressurization of gasified water along with high shear forces in the pump will dissolve significant portion of gas in water. By passing the gasified water through a high shear static mixer the bubbles will break down to smaller size. As a final stage the small bubbles and dissolved gas in water will pass through a series of globe valves with a modified globe to create further shear. The significant pressure drop (80-100 psig) across the globe valve will create uniform microscopic bubbles (10-50 μm), which help the flotation of bubbles to the surface wherein they will be skimmed off by use of a mechanical or hydraulic skimmer system. Due to the minuscule size of the Micro-bubble, the produced population of bubbles will be significantly greater than Micro-Bubbles at specific volume of gas. This will increase the probability of collision between bubbles and oil droplets.

Additionally, Micro-Bubbles have a significantly higher tendency to attach to oil droplets than Macro-Bubbles because of their minute size. Despite the high collision and attachment probability of Micro-Bubbles, they cannot increase the overall density of parcel to raise the oil droplet to the surface within a typical retention time of 5 minutes. In other words, the retention time required to effective remove the contaminates only using Micro-Bubbles is higher than typical only using IGF. However, the overall efficiency of the gas floatation is significantly more.

8 Induced/Dissolved Gas Floatation (IDGF)

The aforementioned process description and shortcoming of each floatation methods motivate the authors to investigate the combination of both methods. This section describes the process, and design of Induced/Dissolved Gas Floatation (IDGF).

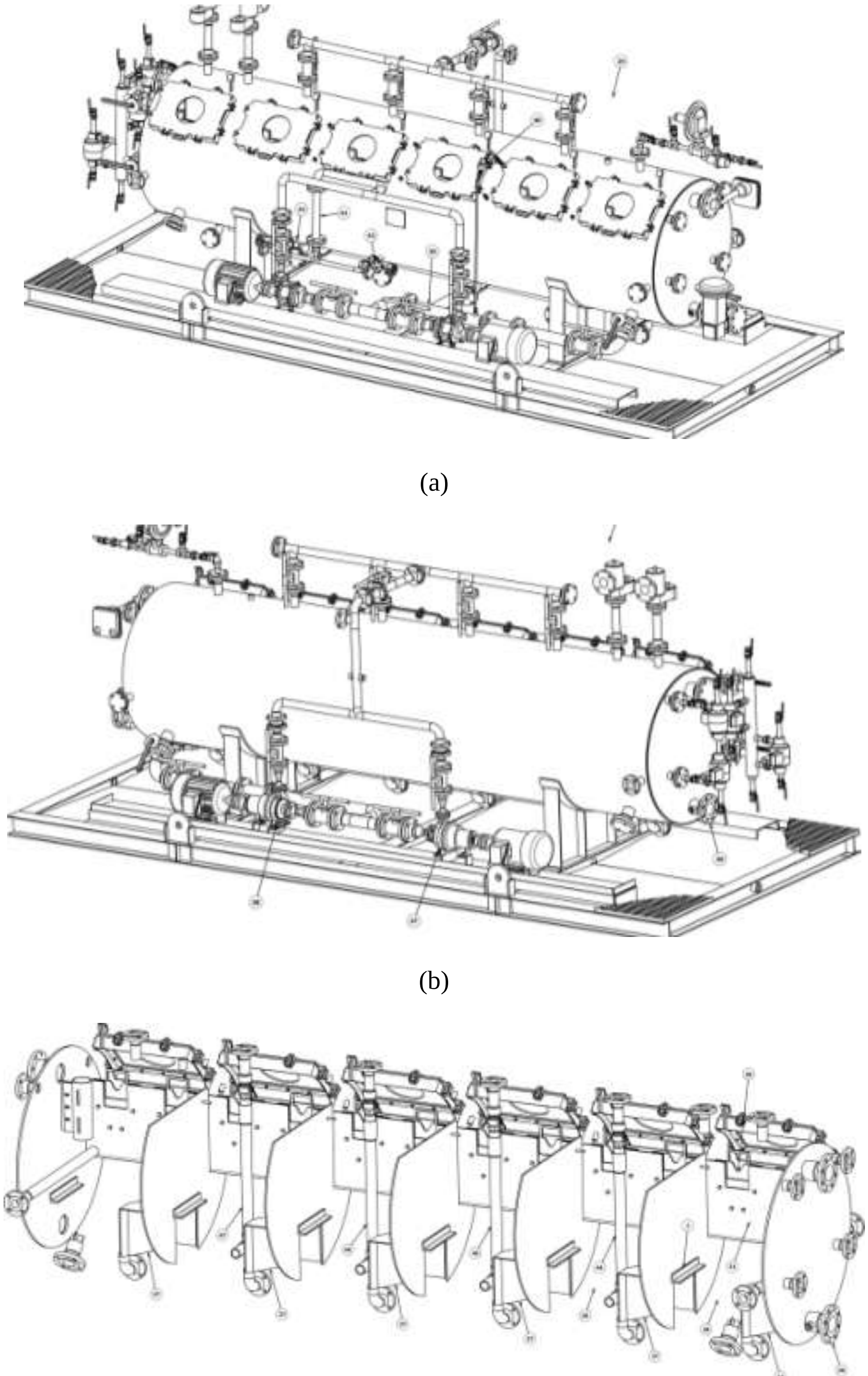
As is shown in figures 8, the micro-bubble floatation will be utilized as a compliment to the current traditional IGF unit wherein Macro-Induced bubbles will be created through venturi type eductors.

The contaminated water enters the vessel via an inlet nozzle, wherein the first Micro-bubble injector introduces the bubbles to the incoming oil droplets. The separated oil will spill over the weirs to the oil bucket. As the processed water enters the first IGF+DGF cell, the micro-bubbles injected from the tangential entry point with the macro-bubbles introduced through the eductors.

This modification can be employed to gasify the early stages of the separation with micro-bubbles and combination of Micro and Macro bubbles in proceeding cells will highly increase the total efficiency of the system.

Figure 9 shows the interaction between gas bubbles and oil droplets in which microscopic gas bubbles will attach to the oil droplets and lower the parcel density as the macroscopic bubbles employ the high Interfacial Tension (IFT) between microscopic and macroscopic bubbles as they attach to the parcel of oil droplets and micro-bubbles and rapidly bring them to the surface. In other words, early stage introduction of micro-bubble will create intermediate layer around the oil droplet and macro-bubbles will lift the oil droplets by attaching to this layer.

This modification will eliminate the limitation of both IGF and DGF methods by removing the smallest oil droplets using micro-bubble and increasing the rise velocity through the attachment of macro-bubbles.



(a)

(b)

(c)

Figure 8. IGF/DGF combination with DGF in first two cell and IGF in cells 2-5 (a) DGF side (b) IGF side (c) Internals

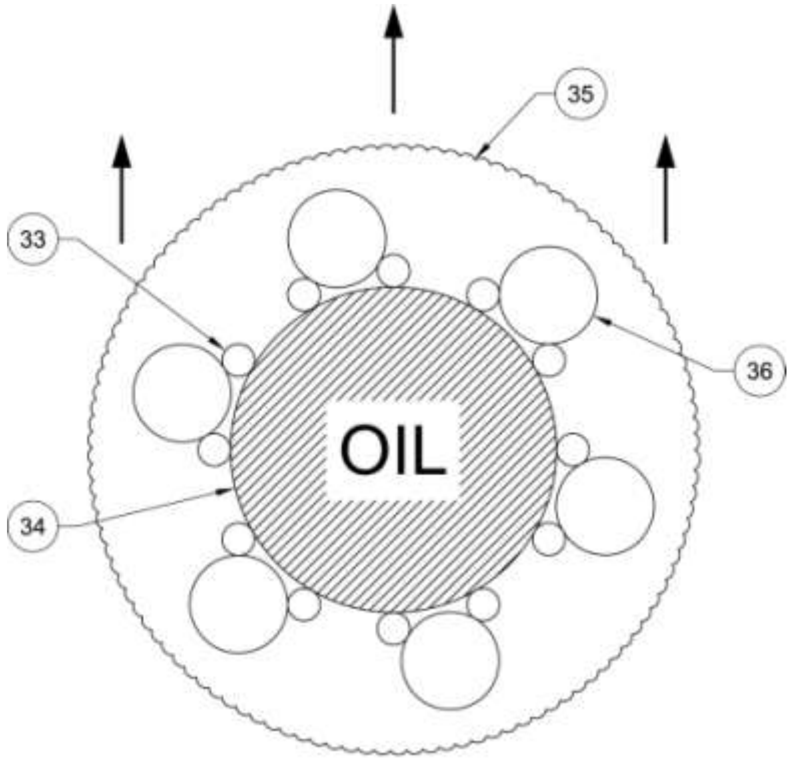


Figure 9. Attachment of Micro-Bubbles intermediate film, and lifting macro-bubble to oil droplets

9 Field Test Results

Now extensively laboratory tested, the authors decided to elevate their theory by organizing the field test in the polymer rich field, Oman (Field X). The test was conducted using ENVIRO-CELL^{TM} EC-33,000 BPD (EC-3) IGF unit with retrofitted Micro-Bubble pump in the first two (2) cells of the IGF vessel. The package was equipped with two (2) Oil In Water (OIW) analyzers (Advance Sensors EX-100) to measure inlet and outlet oil concentration and determine the efficiency of the system in different scenarios.

The water was produced from Enhanced Oil Recovery process in Oman (Field X), using primarily water flooding and secondarily, polymer flooding. After primary treatment of water and injection of chemicals, the process water entered the EC-3 with retrofitted micro-bubble. The treated water from gas floatation enters tertiary treatments to further reduce the concentration of contaminates. Table 1 shows the main water characteristics.

Figure 10. Field Installation of IGF + DGF Water Treatment Package

Table 1. Operatin conditions of produced water treatment package, gas floatation

DESCRIPTION	UNITS	TDS = 4510 mg/lt (0.45214 % w/w) at 32 oC, Oil and Suspended Solids Free									
Temperature	oC	15.56	20.00	25.00	30.00	35.00	40.00	45.00	50.00	55.00	60.00
Molecular Weight	kg/kgmole	18.07	18.07	18.07	18.07	18.07	18.07	18.07	18.07	18.07	18.07
Mass Density	kg/m3	1003.41	1003.33	1003.25	1003.18	1003.11	1003.05	1003.00	1002.96	1002.93	1002.90
Specific Heat Capacity	kJ/kg.oC	4.13	4.14	4.14	4.14	4.14	4.15	4.15	4.15	4.16	4.16
Dynamic Viscosity (Note 1)	mNs/m2 or cP	1.44	1.34	1.23	1.13	1.04	0.95	0.88	0.81	0.74	0.69
Kinematic Viscosity	cSt	1.43	1.33	1.22	1.13	1.03	0.95	0.88	0.81	0.74	0.69
Thermal Conductivity	W/m.oC	0.60	0.61	0.61	0.62	0.63	0.63	0.64	0.64	0.65	0.65
Surface Tension	Dynes/cm	73.65	72.68	71.63	70.64	69.69	68.79	67.92	67.10	66.30	65.54
DESCRIPTION	**UNITS**	**TDS = 6000 mg/lt (0.60273 % w/w) at 40 oC, Oil and Suspended Solids Free**									
Temperature	oC	15.56	20.00	25.00	30.00	35.00	40.00	45.00	50.00	55.00	60.00
Molecular Weight	kg/kgmole	18.09	18.09	18.09	18.09	18.09	18.09	18.09	18.09	18.09	18.09
Mass Density	kg/m3	1004.49	1004.40	1004.31	1004.22	1004.15	1004.08	1004.03	1003.98	1003.95	1003.92
Specific Heat Capacity	kJ/kg.oC	4.13	4.13	4.13	4.14	4.14	4.14	4.14	4.15	4.15	4.15
Dynamic Viscosity (Note 1)	mNs/m2 or cP	1.46	1.35	1.25	1.15	1.05	0.97	0.89	0.82	0.76	0.70
Kinematic Viscosity	cSt	1.45	1.35	1.24	1.14	1.05	0.96	0.89	0.82	0.75	0.69
Thermal Conductivity	W/m.oC	0.60	0.61	0.61	0.62	0.63	0.63	0.64	0.64	0.65	0.65
Surface Tension	Dynes/cm	73.71	72.74	71.70	70.70	69.76	68.85	67.98	67.16	66.36	65.60

Note 1. This is only viscosity of water, concentration of polymenr highly effect the viscosity of mixture

The field test was conducted in two (2) different scenarios: IGF only and combination IGF/DGF. Primarily the IGF only configuration was tested in polymer concentration. The main purpose of this test was to establish the basis for the test results, efficiency, operating condition and chemical injection rate. Table 2 shows the inlet and outlet oil concentration to and from gas floatation package at different polymer concentration.

Secondarily, the combination of IGF and DGF was tested by introducing Micro-Bubbles in first two cells and addition of Macro bubbles in the remaining cells. The test was to prove the theory of IGF/DGF combination package great efficiency. Figure 11 and table 3 demonstrate the inlet and outlet oil concentration to and from gas floatation package at different polymer concentration when both DGF and IGF pumps were in operation.

Table 2. Summary of the results from IGF only test at different polymer concentration and flow rate

Produced Water	Polymer	IGF Inlet Oil Concentration (PPM)	IGF Outlet Oil Concentration (PPM)	Efficiency
Flow Rate	Concentration			
(m3/hr)	(ppm)	(ppm)	(ppm)	%
7	700	7.1	5.5	22.5%
7	1000	14.5	6.3	56.6%
7	1000	16.5	8.4	49.1%
7	1000	23.5	15.6	33.6%
7	1000	23.3	16.4	29.6%
14	600	26.3	11	58.2%
14	600	32.8	15.8	51.8%
14	600	39.4	17.4	55.8%
14	600	36.2	22.2	38.7%
14	1000	14.5	6.3	56.6%
14	1000	29.2	12.2	58.2%
14	1000	23.5	15.6	33.6%
14	1000	23.3	16.4	29.6%
14	1000	16.5	8.4	49.1%

Table 3. The results of IGF + DGF at different flow rate and polymer concentration

Produced Water Flow Rate (m3/hr)	Polymer Concentration (ppm)	IGF Inlet Oil Concentration (PPM) (ppm)	IGF Outlet Oil Concentration (PPM) (ppm)	Efficiency %
7	200	37.3	8.9	76%
7	200	41.6	12.6	70%
7	400	40.5	12.2	70%
7	400	67.8	22.5	67%
7	400	60	27.2	55%
7	500	57.8	33.1	43%
7	500	52.9	36.2	32%
7	800	78.1	37.3	52%
7	800	77.3	40.7	47%
7	800	21.1	11.1	47%
7	800	25.9	12.6	51%
7	1000	18.9	10.3	46%
7	1000	28.4	15.9	44%
7	1000	79.8	55.1	31%
14	100	53.8	5.5	90%
14	200	73.4	27.5	63%
14	300	63.9	16.3	74%
14	300	56.7	24.5	57%
14	400	53.3	33.3	38%
14	400	48.2	30.9	36%
14	400	172	86.4	50%
14	600	128.9	78.4	39%
14	800	41.4	32.2	22%
14	800	52.6	38	28%
14	800	132	56.6	57%
14	1000	126.2	71.3	44%

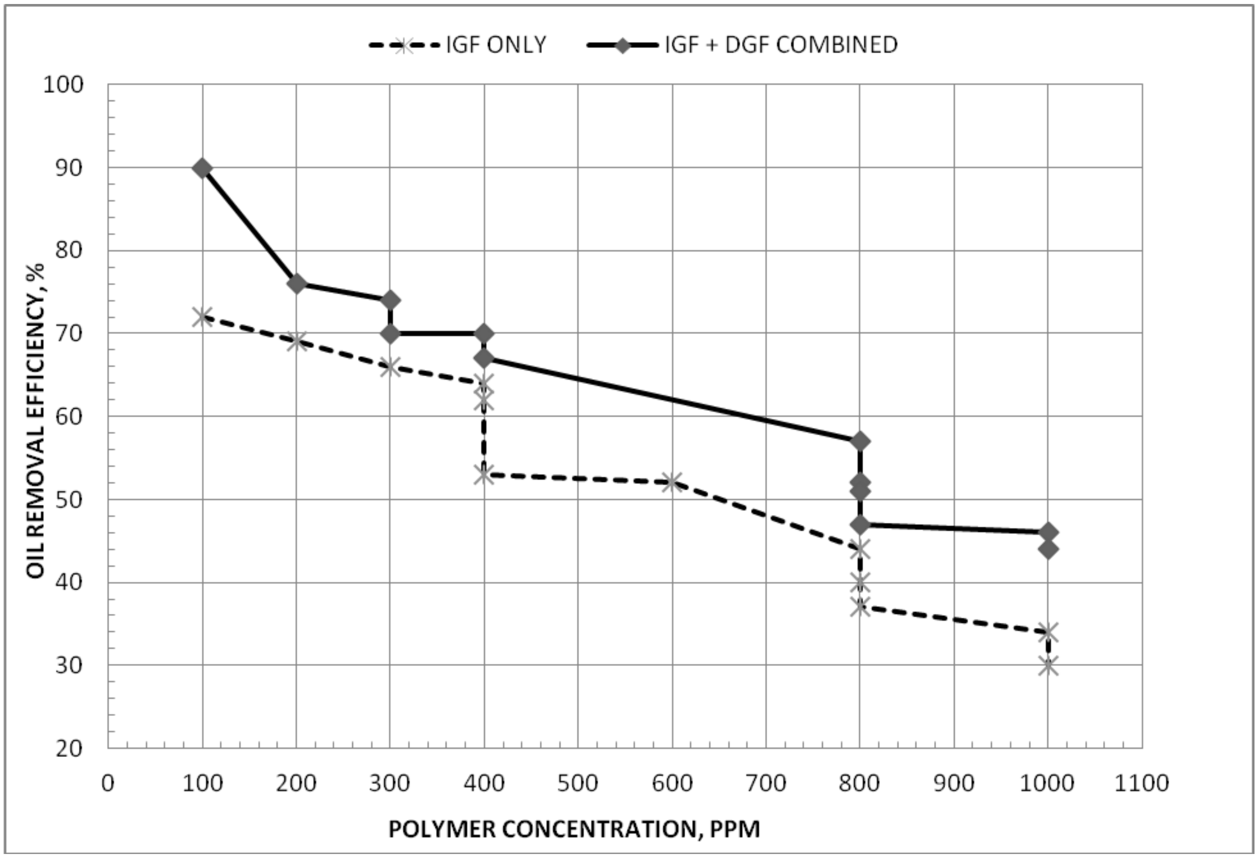


Figure 11. Efficiency of IGF versus combination of IGF and DGF

Figure 12 shows the percentage improvement of outlet water quality by combination of DGF and IGF. The average of 25% was seen as a result of this modification.

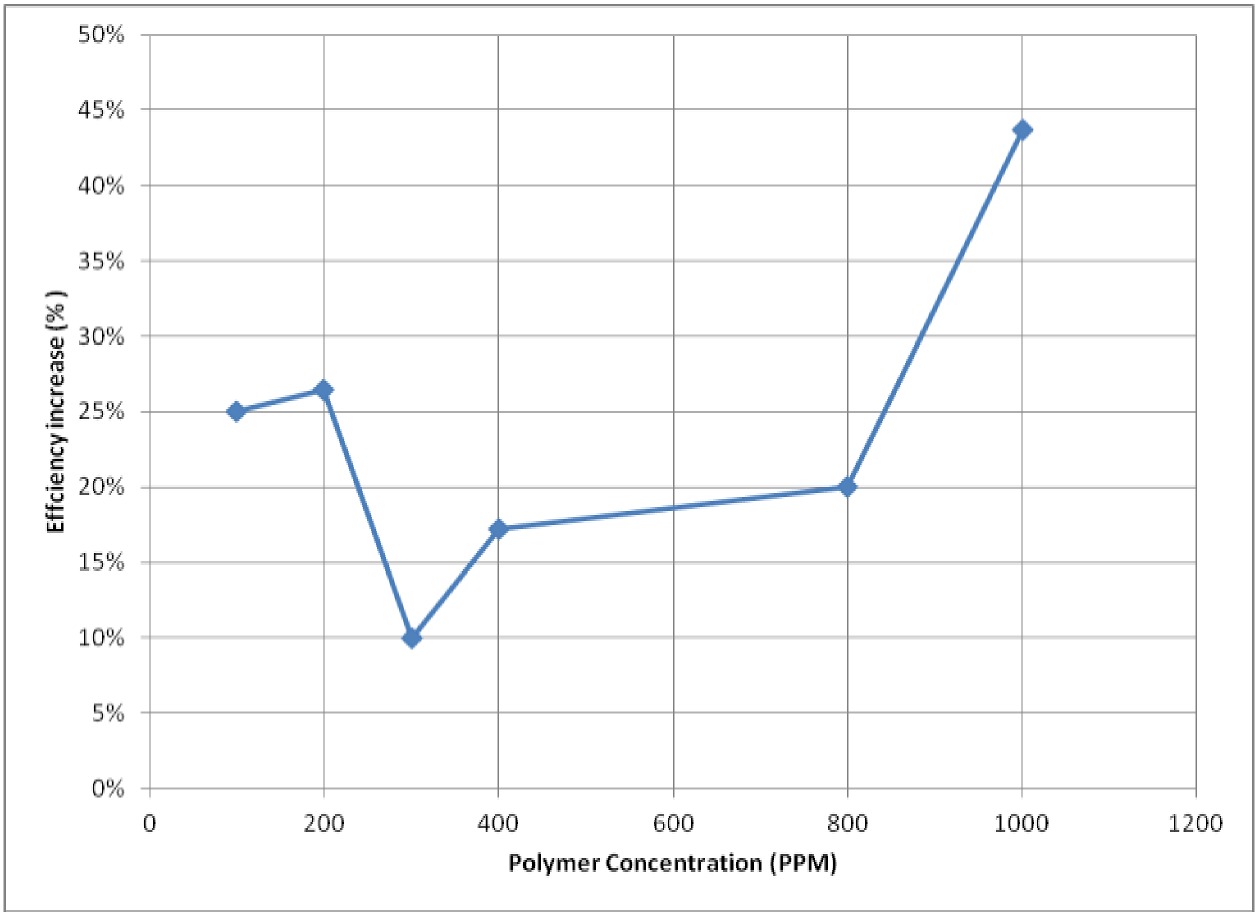


Figure 12. Improvement in total efficiency of gas flotation due to addition of DGF to IGF

Figure 13 depict magnified picture of Micro bubbles using On-line high speed digital camera with a magnification lens, then utilizing image processing and object recognition to determine the size and number of micro-bubbles in line.

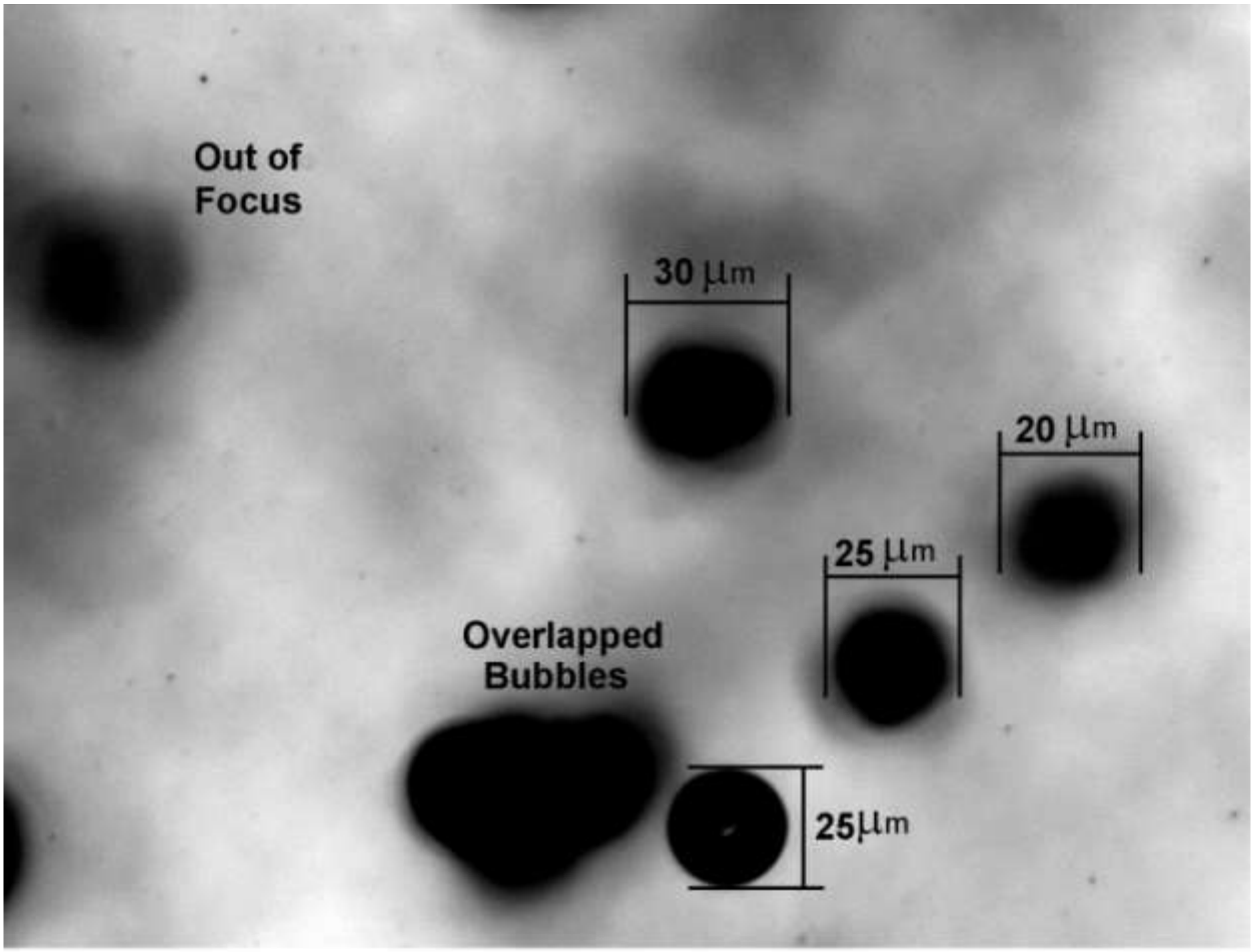


Figure 13. Microscopic Picture of micro-bubbles [8]

10 Conclusion

Through extensive theoretical study done by the authors, they identified major setbacks with using traditional gas floatation methods. In summary, induced gas floatation efficiency is limited by the size of oil droplet that can be separated using Macro-Bubbles. On the other hand, dissolve gas floatation will create microscopic bubbles that are not strong enough to rise the oil droplets in retention time provided in a typical gas floatation system. By combining two technologies, micro-bubble as the first step of separation will create an intermediate film of bubbles around the oil droplet and macro bubble as secondary step of separation will attach to the intermediate film and increase the speed of rise. This theory was proved through conclusive data gathered through three years of experiment.

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