

**Design and Laboratory scale operation of a wave shaped flotation – assisted electrostatic coalescer**

**Technical and design report prepared for IChemE to obtain the Chartered Engineer status**

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**1- Introduction**

There are several areas of process engineering where considerable benefits accrue from being able to enhance the rate at which droplets of one liquid can be removed from another liquid in which they are substantially immiscible. Amongst the physical methods available for achieving such enhancement, electrostatic coalescence offers cost effective separation and minimal environmental impact for systems where the continuous phase is electrically insulating. Such circumstances arise in Solvent Extraction operations, emulsion liquid membranes processes, and in desalting and dehydration of crude oil emulsions. Of particular interest in all these applications is the possibility of using electric fields to treat systems in which the volume fraction of the electrically conducting phase is high and perhaps stabilised by the presence of surface active agents.

The electric field augments phase separation by promoting coalescence between the droplets. Increased rates of separation have been observed using AC, DC, and pulsed electric fields applied between electrodes which may be bare metal, insulation coated, or of composite construction (1). The mechanisms whereby electrostatic coalescence occurs (2) all involve the attraction of the opposite charges on the surface of proximate droplets, the net effect of which is to increase the incidence of collision followed by coalescence. The overall increase in droplet size which results from this process improves the general rate of sedimentation and therefore increases the rate of phase separation. Although the benefits of using electric fields to create larger droplets from many smaller droplets are self evident, there are still significant practical limitations on what can be accomplished with existing technology. For example, a major obstacle is the inhibiting effect that surface active agents, either naturally present or deliberately introduced, can have on the electrically augmented coalescence process. Another barrier may arise from the need to successfully treat such stable emulsions when the concentration of the conducting dispersed phase is relatively high, say 60% or thereabouts, since the likelihood of a conduction path forming between the electrodes, the attendant current leakage and loss of electric field can have a very deleterious effect on separator efficiency.

Research with liquid systems of this type has recently shown (3, 4) that electrically augmented coalescence occurs more rapidly when the stable emulsion to be treated is subject to simultaneous gas flotation. Reasons for this have been thoroughly revised elsewhere (2) but notably it is likely that the gas bubbles serve to remove excess surfactant from coalescing system. The gas – liquid interface providing accommodation for the surface active molecules that are released back into the organic phase when many small liquid droplets coalesce to form fewer larger droplets and these droplets

coalesce with the bulk interface. The use of gas sparging as an adjunct to electrical resolution is attractive from a practical point of view since it preserves the mechanical simplicity and low maintenance costs that are generally associated with electric treaters. Moreover, the technique offers scope for innovative separator design and it is in this context that a novel flotation-assisted electrostatic coalescer has been developed. The work reported here relates to batch tests that have been conducted with this prototype.

## **2- Design of the wave shaped flotation – assisted electrostatic coalescer**

The general features that must be incorporated in an electrostatic demulsifier include a high voltage electrode (with or without insulation), an earthed electrode, and a space sandwiched between them in variety of geometries to facilitate residence of emulsion in the equipment for the required duration (2, 5).

Furthermore, it has been postulated that electrically augmented demulsification occurs more rapidly when the emulsion is treated with simultaneous application of electric field and gas flotation (3, 4). These principles form the pillar of the design introduced in this report.

Another concept introduced in this design is the use of an inclined plate acting as the lower earthed electrode while serving other purposes. When an emulsion resides in an electrostatic demulsifier, the droplet – droplet coalescence (through its many mechanisms) that follows results in the formation of larger droplets of sufficient size that they fall rapidly due to the force of gravity. As this proceeds, a layer of bulk water phase forms at the bottom of the equipment, which needs to be discharged. When droplets fall on the inclined plate, a film of water gradually forms that streams down the slope to join a resident bulk phase below the inclined plate. In the present design the level of this phase is always kept constant by a T-shaped outlet set up in a manner so that any addition of water to the bulk phase is immediately removed from the cell. This also provides the droplets with a better droplet – interface coalescence (2) facility inside the demulsifier. The design can be further improved by introducing ridges in the plate to better guide the motion of the separated water.

As the emulsion moves in a coalescer subjected to an electric field, it loses its water content and droplets become smaller and further apart, so the electrical force required to promote coalescence amongst the remaining droplets must act over a greater range and therefore higher fields are desirable. This can be facilitated by positioning an inclined plate at the bottom of a horizontally mounted coalescer and introducing fresh emulsion from the point of greatest depths in the coalescer. As the emulsion moves towards the end of the cell depth of the emulsion reduces causing in the value of the electrical potential across the emulsion layer sufficient to promote coalescence amongst remaining smaller droplets. As the separated water moves down the inclined plate counter-current to the motion of the emulsion, an outlet can be introduced upstream of the demulsifier to facilitate its discharge. Gas flotation then can be introduced by laying perforated pipes on the inclined plate. The pipes also serve as ridges described earlier.

The use of air as an almost perfect dielectric for electrode insulation purposes is an innovative step. It is also appealing idea in terms of mechanical simplicity and economical convenience and is applied in the chosen design. The air insulation can be introduced by simply having a gap between the metal

high voltage electrode and the body of the demulsifier. The level of the emulsion in the equipment can then be controlled to keep the desired insulation thickness.

A design, which incorporates the above features, would have a side elevation similar to the one shown in Figure 1.

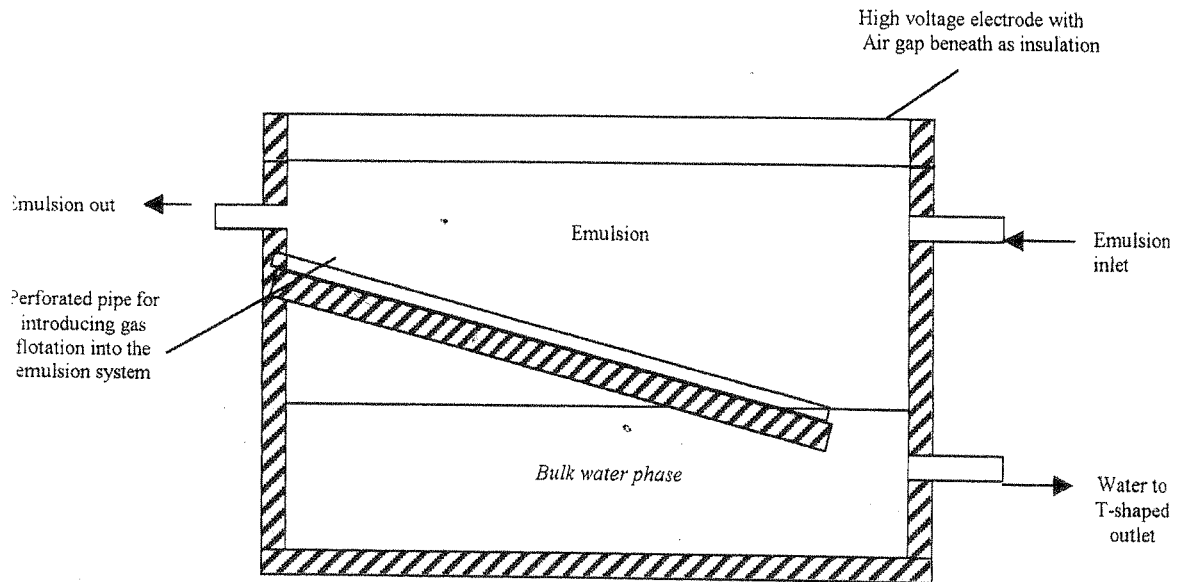


Figure 1- Side elevation of the design described above.

The next step in this conceptual design was to imagine an arrangement where a certain number of cells each similar to the one illustrated in Figure 1 were put into series one after the other. This would provide multiple emulsion treatment resulting in thorough resolution of the w/o emulsion system. Alternatively, the inclined treatment sections could be in a single demulsifier so that multiple treatment zones are created. Naturally, as the emulsion progresses through the demulsifier its water content and the size of droplets it contains decrease resulting on the need for more intense electric fields to be applied to the emulsion.

In case of the design shown in Figure 2, the simple design showed in Figure 1 has been modified to satisfy multiple treatment and field intensification requirements by incorporating a wave-shaped inclined plate.

Here again the flotation is provided by a series of perforated tubes connected at both ends to the gas supply.

The inclined wave-shaped plate has slots cut through at the bottom of the troughs in its profile to allow the water to pass through the plate. The body of the vessel underneath was divided into three sections by two weirs, which ensured that in operation the bulk interface formed three steps, each level with the bottom of the troughs in the wave-shaped plate. Any water separated in each zone

then would cause a change in the level of the water in the weir causing it to be transferred to the next section and eventually out of the cell by the provided means.

With these concepts in mind, the final shape of the wave-shaped flotation-assisted electrostatic coalescer design, as per Figure 2, is detailed below. A photographic illustration of the cell is also introduced in Figure 3.

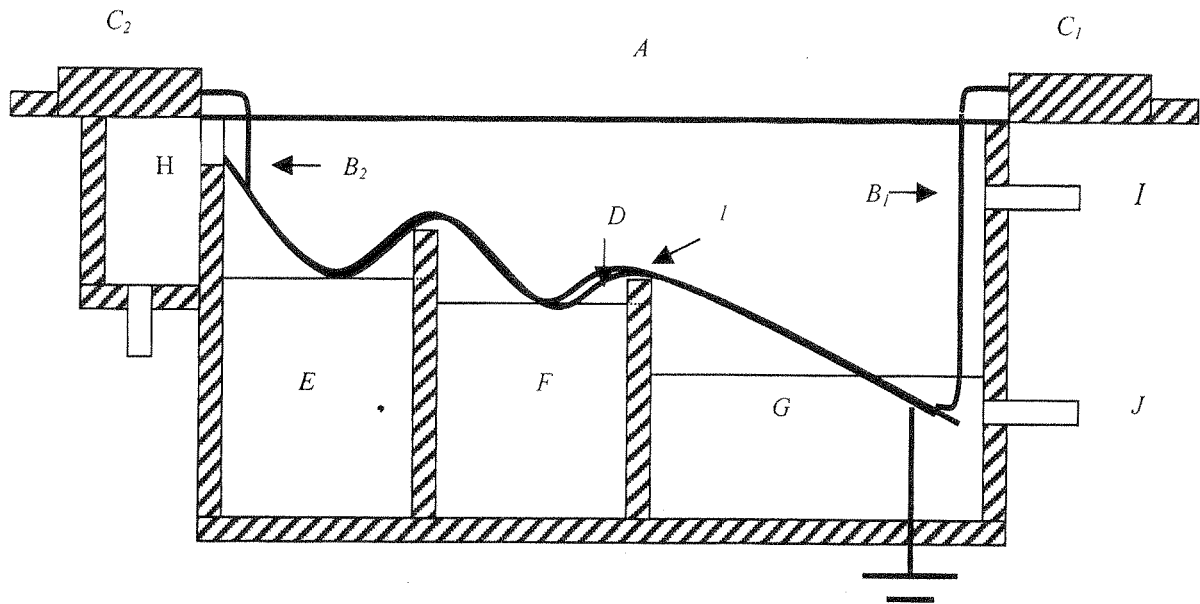


Figure 2. Schematic of the wave-shaped flotation-assisted electrostatic coalescer.

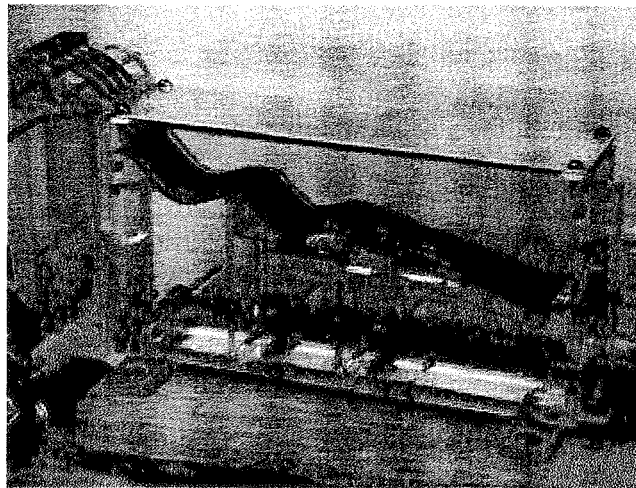


Figure 3. Photographic illustration of the -shaped flotation-assisted electrostatic coalescer.

The main body of the cell was made of Perspex with its dimension being 200 mm long, 100 mm high, and 40 mm wide with the volume available for treatment equal to 340 cm<sup>3</sup>. The elements of the design, denoted by the letters of the alphabet in Figure 2 are described below;

- A: High voltage electrode connected to the high potential source.

- B1, B2: Series of four separate perforated copper tubes following the same profile as the plate and connected to the gas supply via manifolds (C1 and C2) situated at the right and left hand side of the cell, respectively. The tubes were 2.5 mm outside diameter and were sealed to the plate beneath by silicon sealant, which proved to be resistant to the emulsion in the cell. In order to ensure an efficient air bubble flotation system, the tube arrangement was required to possess the following features:
  - Uniform delivery of air through out the cell for thorough treatment of the emulsion at all stages in the cell.
  - Mild motion of the air bubbles to avoid turbulence in the cell which would disrupt the coalescence process and/or rupture coalesced droplets.

To obtain the best combination of air inlets and hole sizes, many configurations were tested. A series of trial and error experiments with different perforation sizes and gas inlet arrangements were carried out (2). To simplify the tests the emulsion in the cell was replaced with an amount of water, which would provide the same head as the emulsion. This was calculated on the basis that for  $H_1$  height (with the height taken at utmost depth of the layer) of the emulsion with the density of  $\rho_1$ , the required height of water that has the same head,  $H_2$ , can be estimated from the following equation where  $\rho_2$  is the density of the water:

$$H_1\rho_1g = H_2\rho_2g \quad (1)$$

Where  $H\rho g$  is the pressure head of the layer with height  $H$ , density of  $\rho$  and  $g$  is the acceleration due to the force of gravity.

Using the above method it was found that best flotation was achieved when the tubes were isolated in point 1 of Figures 2 and 4 with each section bubbled independently. The perforation sizes were uniformly drilled at 0.03 mm and separated by a distance of 5 mm from one another on the wave-shaped inclined plate, D. For the purpose of the flotation experiments, the cell was only bubbled in the deepest section of the three to avoid turbulence while operating.

C1, C2: Manifolds connecting the copper tubes to the gas supply.

D: Wave-shaped inclined plate which also acted as the earthed electrode. It was made of brass and sealed to the body of the cell by silicon sealant. The plate was 40 mm wide and left and right edges of the plate were situated at 40 mm and 80 mm from the bottom of the cell, respectively. Figure 4 illustrates the electrode in plan view.

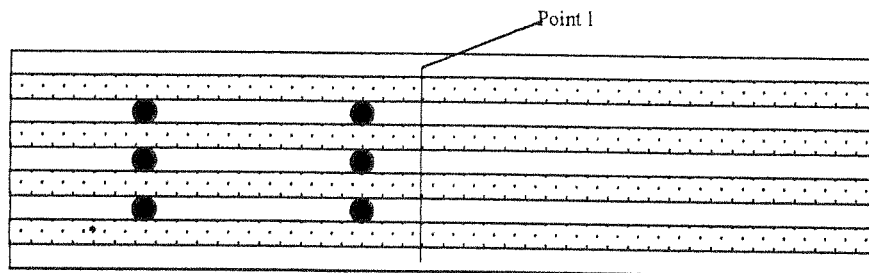


Figure 4. Plan view of the wave-shaped inclined plate/electrode.

The plate has slots cut through at each trough to facilitate contact between the water separated in the emulsion and the body of the cell beneath.

E, F, G: These were three sections separated by two weirs. They were filled with water to the bottom of the trough. The separated water from the emulsion at each section of the cell passed through the slots provided and joined the bulk water beneath. This changed the level of the water in each section and the added water poured over the edge of each weir to the next section and was finally removed from the demulsifier as illustrated in Figure 5.

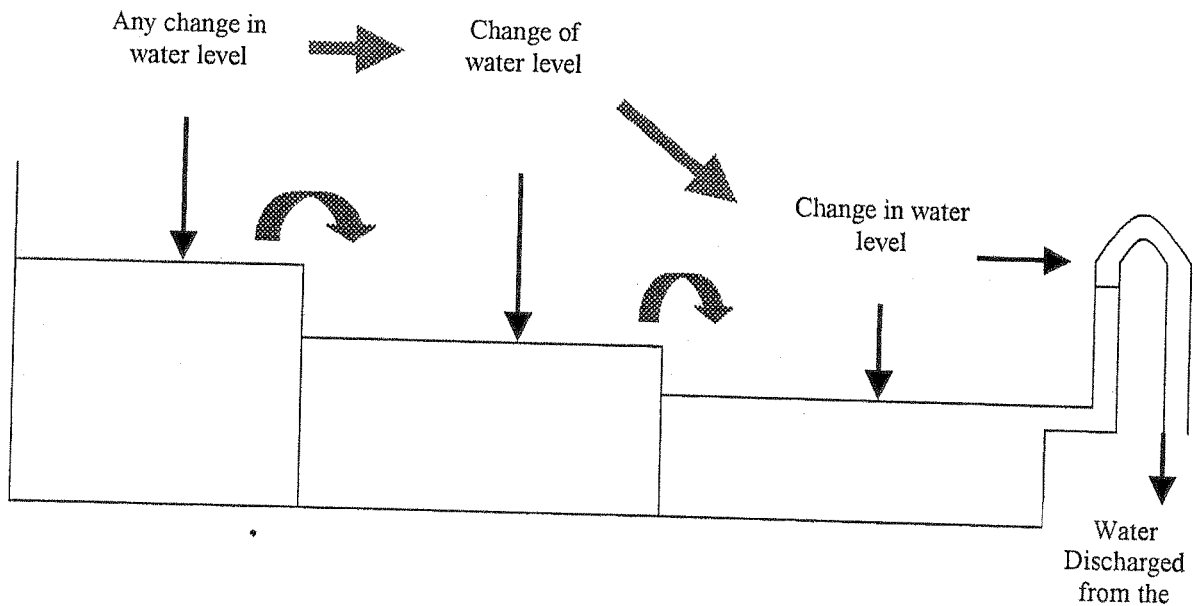


Figure 5. Water discharge system in the coalescer.

H: Sink and tap provided in which the treated emulsion accumulated before discharging to further complete discharge from the cell through these outlets provided at the bottom of the tap.

I: emulsion inlet into the cell.

J: Separated water outlet leading to a T-Shaped level holder.

### 3- Operation of the waved-shaped flotation-assisted electrostatic coalescence

High voltage was supplied to the apparatus from a trek 20/20C high voltage amplifier which was used in conjunction with a low function generator. The high voltage waveform was monitored by employing 1/2000 voltage divider coupled to an oscilloscope.

The test emulsion was prepared under ambient conditions by mixing distilled water (40 vol%) into the organic phase (mineral oil-heavy white/odourless kerosene in the ratio of 4:1, 58 vol%) in the presence of anhydrous Lanolin (2 vol%) in proportions shown. This formulation for the water-in-oil emulsion was developed after extensive investigation in a previous study (6). Mixing was

accomplished using a Silverson L4RT homogeniser with the impeller speed gradually increased to  $10200\text{ s}^{-1}$  while the aqueous phase was slowly added to the agitated organic phase. The mixing time for a 500 ml batch was 10 minutes and the resultant emulsion was stable for at least 2.5 hours.

Phase separation performance was quantified by a light transmission method. For this purpose the separator was illuminated from behind the section where the emulsion depth was greatest and digital video images were recorded through the front face of the separator. The lighting, the size, and the location of the area being recorded were maintained constant throughout the study. For the work reported here, the video camera was used with a 16 mm focal lens. The camera was connected to a Kodak Motion Corder Analyzer (Model 1000 B) which has a 1086 frame memory, a resolution of 640 by 480 pixels and a trigger facility. The sequence of images stored on the Motion was transferred to OPTIMAS, an image analysis package which can be used to analyse images based on the different shades of gray of each pixel. The frame storage capability of the Motion Corder meant that it was not possible to record images continuously for the whole of a batch experiment. Instead the progress of each batch was observed at intervals using a sequence of 10 short video samples each made of 10 frames which were then analysed for their mean greyness. For each sample this information and the time of its recording (including the initial pre-treatment zero time value) was exported to an MSExcel sheet for further analysis.

The procedures for each experiment was that a 196 ml batch of freshly made emulsion was placed in the separator which already contained distilled water up to the maximum level in each section. Once digital images of the untreated emulsion had been recorded, an air flow of  $133\text{ ml s}^{-1}$  was introduced to the emulsion and at the same time the designated electric field was applied. Images of the emulsion were then recorded and saved as the demulsification process proceeded. Each batch was evaluated for 665 seconds divided for image sampling purposes into the following intervals 15s, 90s, 200s, 320s, 382s, 443s, 507s, 600s, and 665s. The field and the flotation were switched off at the end of 600s recording. The state of the emulsion after treatment was recorded at the 665s image sample. If required a physical sample of the emulsion was removed at this time for observation under a microscope. The applied electrostatic fields were of two alternating types as shown in Figure 6, with most of the experiment being conducted with Type B field.

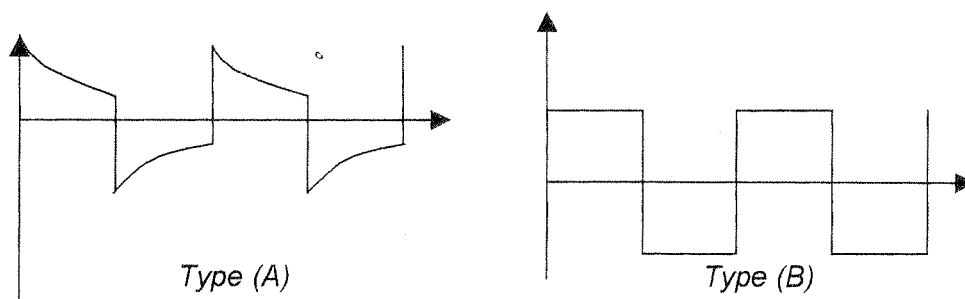


Figure 6. Type A and Type B Electrostatic waveforms.

#### 4- Results and discussion

It is apparent from the data shown in Figure 7 that as the time of treatment proceeds mean greyness values increase, establishing a similar trend for each of the applied voltages. The mean greyness value indicates the extent of coalescence and therefore phase separation in the emulsion. Confirmation of this may be seen from the photomicrographs given in Figure 8 which depict the state of the system moments after the treatment end point. Also, it should be noted that in the absence of the dispersed phase the light transmitted through the separator registered a mean greyness value of 176.5. Figure 9 is also a dynamic illustration of the flotation-assisted electrostatic coalescence as obtained by the OPTIMAS package at four points of the treatment including the start and end points of the treatment. The contrast in mean greyness between the start and end points observed in these pictures show the obvious success of equipment in providing decisive phase resolution of the w/o emulsion system.

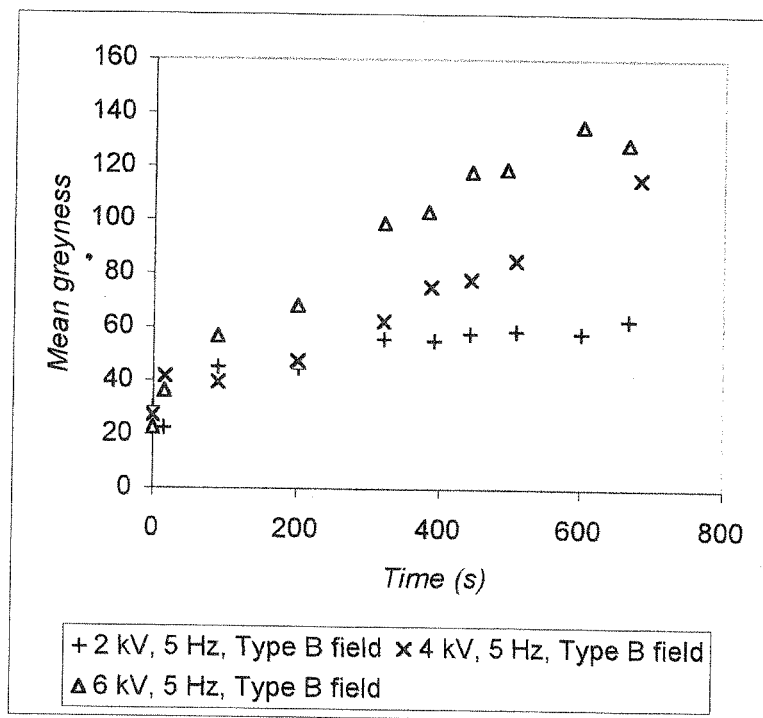


Figure 7. Rate of change of mean greyness value as a function of applied voltage magnitude.

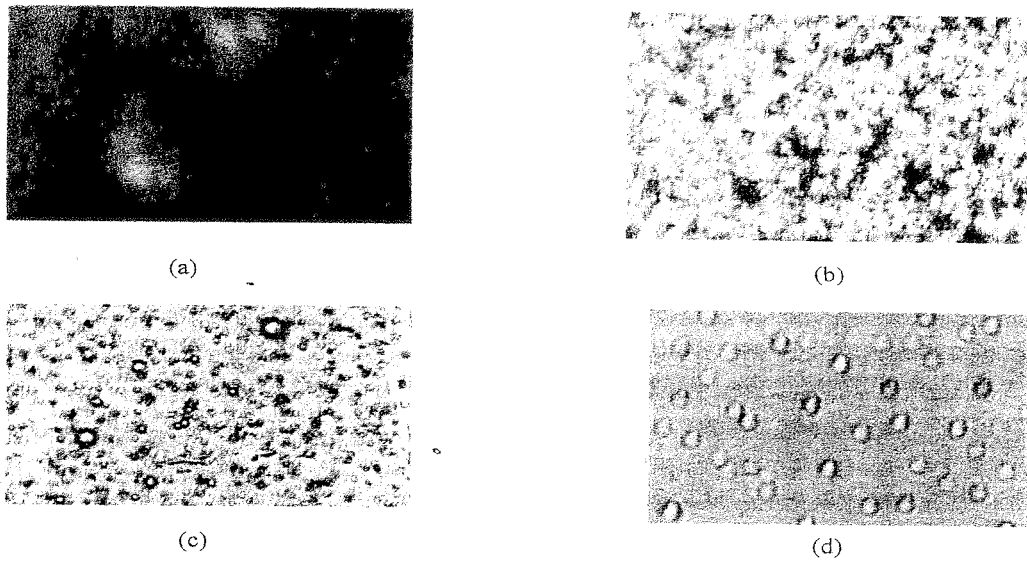


Figure 8. Micrographic images of a) untreated emulsion; b) 2 kV, 5 Hz, Type B field; c) 4 kV, 5 Hz, Type B field; d) 6 kV, 5 Hz, Type B field.

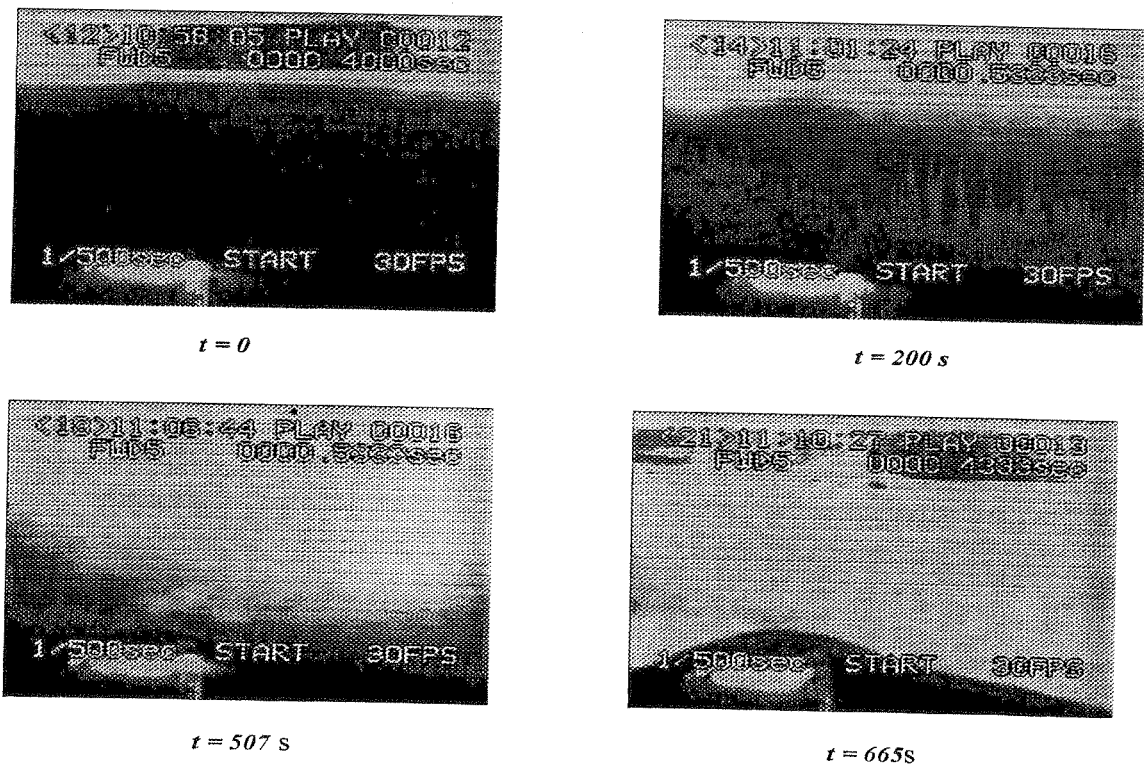


Figure 9. Dynamic representation of flotation-assisted electrostatic coalescence as obtained with OPTIMAS.

Further evidence of the beneficial effect on coalescence of increasing the applied voltage magnitude is given in Figure 10 which shows the mean greyness values obtained at 665 seconds (treatment end point) for three different frequencies. For a given frequency, voltage comparisons are valid since

each batch has received enegisation by the same number of cycles. It is clear that for the range of frequencies used the best phase separation occurs at 50 Hz except at the highest applied voltage. Here it is possible that the sudden fall in performance may be explained by the combined effects of voltage magnitude and rate of change being such as to cause Rayleigh instability and hence droplets break up. As far as the general trend with frequency is concerned, it is known from electrical analysis of a broadly equivalent circuit (7) that the dynamic response of the circuit influences the magnitudes of the electric field appearing in the emulsion. In particular, because the equivalent resistance of the emulsion is negligible compared to the air gap, the voltage drop across the emulsion is relatively small compared to the applied voltage source for an appreciable time in each cycle. At low frequencies, resistive currents dominate for most of the cycle except immediately after a change in the direction of the applied voltage at which time the displacement currents are important. At moderate and higher frequencies the displacement current components remain important throughout the cycle and therefore the magnitude of the voltages applied between the electrodes and across the emulsion itself is comparable.

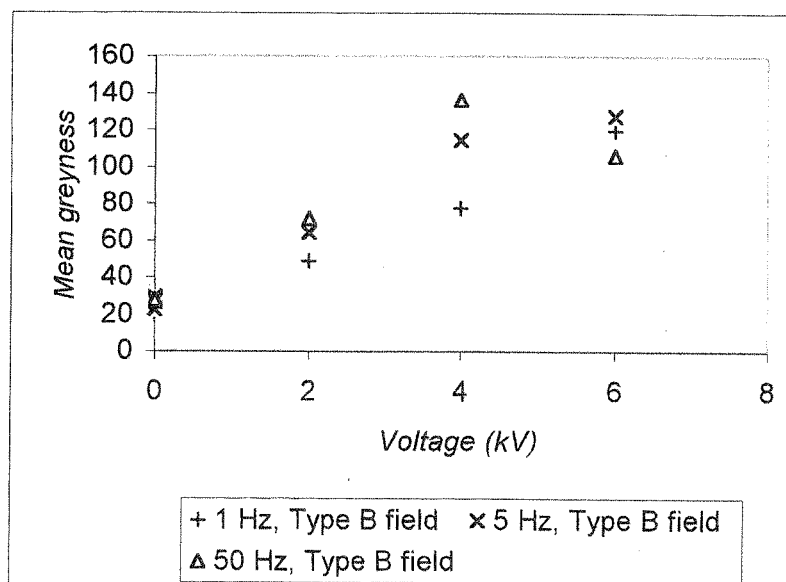


Figure 10. Mean greyness at 665 s after the application of different voltages as a function of frequency.

In the context of this work where the same potential difference is applied across the electrodes for frequencies of 1 Hz, 5 Hz, and 50 Hz, it is therefore to be expected that the field in the emulsion would increase accordingly. The higher field strength then experienced by the droplets being the reason for the observed improvement in phase separation with increasing frequency.

Further evidence of the importance to be attached to the dynamic response of the coalescer may be seen in Figure 11 where the performance of the flotation-assisted electrostatic coalescer is improved by changing the waveform of the source voltage. Somewhat surprisingly, the type A waveform outperforms the Type B waveform, perhaps indicating that the temporal field profile experienced by the droplets in the emulsion is also a factor in achieving good coalescence.

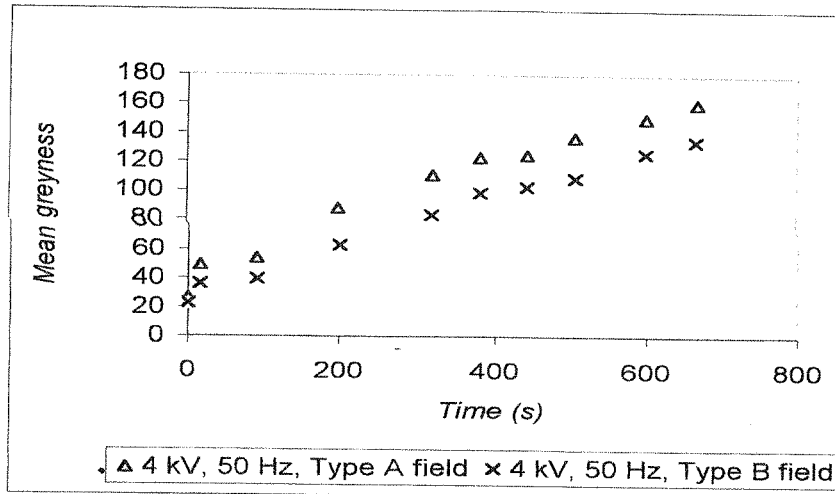


Figure 11. Mean greyness as a function of the applied waveform.

## 5- Conclusions

The prototype design of a novel flotation-assisted electrostatic coalescer has been conducted; its philosophy has been discussed along with relative drawings and illustrations. It has been also demonstrated that this equipment provides efficient resolution of a stable water-in-oil emulsion. Phase separation, monitored by a non-invasive method employing digital video images analysis, is shown to be a function of source voltage waveform, magnitudes, and frequency.

## 6- References

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