Innovative adsorption and self-flotation hybrid operation for crude oil water emulsion processing


Abstract — A vibrational prototype self-floater actuated electromechanically is presented and evaluated. The patent is claimed by processes, (PI BR 10 2012 023580 3) and (PI BR 10 2013 024672 7) and trademark registration, No. 907094856. The technical principle is the disturbance of the fluid content for air bubbles generation (self-flotation) and collision promotion between oil droplets and adsorbent labyrinth. The technique has the advantage of avoiding usual addition of acid, emulsifier or coagulant because it is also polluting elements. It is by introducing promising adsorption technique applying hydrophilic recoverable adsorbent metal, high permeability (97%), current use and low cost. Relevant aspects in other unit operation techniques are addressed. Prototype, experimental apparatus and methodology are illustrated and described. Results are evaluated according to the efficiency of oil removing energy expenditure flow rate and the prospect of dispense using floaters. Further, besides requiring relatively little installation area under the test conditions, using low polluting energy and arises as an alternative to space problem of offshore platforms. Keeping to restriction of test condition, good results were obtained indicating good technique trend. Incipient research does not allow scale extrapolation although the prospect of industrial scale application is favorable in view of vibrational science and industrial technology for large-scale transportation being widely consolidated.

Index Terms — Adsorption, continuous flow system, mechanical vibration, natural flotation, separation of oil emulsion, crude oil production water, performance analysis.

I. INTRODUCTION

The production of crude oil for refining and obtaining derivatives is conducted under modalities technically referred to as on-shore and off-shore, ie, on the continent and in the sea. According to [45], 95% of pollutant power petroleum industry is the production water and in Brazil 80% of production is offshore [10]. It varied set of techniques of effluent treatment consisting of API oil separators, floaters, three-phase separators, membrane separators, cyclones, sand filters not to mention others, and can be seen in [10], [7] and [41].

The frame is environmentally aggravating and requires high flow rates to contain the dump industrial scale. Ten years ago Brazil has ever produced offshore only in the Campos Basin 584,000 m³/day of production water or 40,000 tonnes/year of equivalent oil [14] containing chemical substances flocculant, coagulant and demulsifier at concentrations of 1.0 mg/l to 300 mg/l of treated effluent [38]. Residue of chemical adjuncts such as aluminum sulfate and dozens of others is harmful to health as a whole [35].

The purpose of this work is promising, about sustainable and require any chemical additive process to improve performance. The adsorbent acts as metallic spiral treatment cell, high permeability with the advantage of allowing easy retrieval of the sorbent and oil impregnated by simple extraction with organic solvents [31] and [17]. The current and deliberate treatment policy, especially water, extensively uses load of chemicals whose destination is the environment. Despite the efficiency, should be viewed with perspective constraint because almost a century has passed and the water contamination problem by thin oil layer orbits engineers, technicians and researchers day-to-day [24] on pollution ascending scale.

II. THEORETICAL ASPECTS

The study of mechanical vibrations in fluid medium is not recent. Dates back to the early nineteenth century’s with the pioneering research on the capillarity phenomena of Simon de Laplace and Thomas Young. Twenty years later, Michel Faraday studied mechanics of surface wave [18]. It is not a work object describe phenomenology around the problem and its mathematical description. In fact there is scarcity literature on the subject as regards oil in water dispersion in the horizontal vibration and shock phenomena. About impact of oil drops, excellent overview of the art applicable to aviation oil is given by [36]. Notable writings of vibrational science of fluids and solids, in the stability area, mathematical description, inertial effect between fluid and particle, interactions between fluid and structure, vibrorheology of solid-liquid dispersion and its
implications, were produced by [5], [6] and [46]. Phenomena of capillarity-gravity in immiscible liquid interface and fluids critical stability in horizontal vibration were studied by [26]. Paradoxes in vibrational mechanics and unified mathematical theory of oscillations and wave propagation can be seen in [8] and [19] respectively.

The phenomenological basis for system design presented is the natural breaking of water, in a timely manner contemplated on a diligent work [4]. According to the author, between $10^{18}$ and $10^{20}$ air bubbles hatch from breaking waves, providing exquisite natural spectacle of transfer and mass exchange and energy in the atmosphere. As a result, there is the exchange of heat, dissolved gases, and essential biological material to the biogenesis. The bubbles size distribution in seconds that follow the breaking of a wave in the subsurface, and factors that determine the distribution spectrum was studied by [15]. Images, (1.a) and (1.b) illustrate.

![Images](image_url)

Fig. 1. Images of breaking surface waves: a) Disruption and breaking wave, and burst of air bubbles and aerosol formation (Extracted from: [11]), b) Image of a subsurface wave after breaking and bubbles and microbubbles formation. (Extracted from: [15]).

Related effects use of vertical oscillation energy applied to reactors and aerated columns in separation and mass transfer process have been extensively studied by [28], [47], [1] and [4]. Reported increases of up to 400 % in the mass transfer coefficient associated excitation energy and reducing the air bubbles size by vibrational effect. Frequency range of 5 Hz to 30 Hz and amplitude of 1.66 mm to 3.0 mm were used. Vertical vibration of gas-liquid systems can contribute to retention of air bubbles (hold-up) favoring and promoting increased adsorption on the contact surface at the air-liquid interface by reducing the bubbles size. In 1963, Baird [1] and [2] derived an expression to determine the retention of an air bubble in terms of the distance from the liquid level subjected to vertical vibration. Trolinger [45] investigated the helical motion of a particle on the rise compared to the fluid motion in microgravity under horizontal sinusoidal vibration and so concluded that three additional terms of the Stokes drag force is needed to predict the movement therefore retention. There are many and diverse research on cavities containing fluids in vertical vibration. On the other hand, inconvenient of large-scale industrial application is the cost and energy intake necessary to vibrate large masses.

The system under consideration operates in a horizontal vibration of low frequency (14 Hz to 50 Hz) and amplitudes in the range of 0.55 mm to 2.4 mm. The goal is forming, destabilizing surface waves and undertake kinetic contribution to triggering shock dispersed oil particles against adsorbent material. Thus vibration is of wide industrial application in conveying machines industries whose volumes and rates reach, 130 tons/hour, at frequencies range of 5-20 Hz and amplitudes from 1 to 15 mm [43]. According Blekhman [6] and Ur’ev [46] on dispersions vibrated horizontally smaller solid particles moving in phase forward in the oscillating fluid, reaching amplitudes slightly larger than disturbance amplitude. This can produce the necessary shock to absorption and displacement Stokes’s nonslip layer [20] and cause sessile grip. The developing study by these researchers is valid to dispersion where the solid-liquid interfacial tension is practically, null. Petroleum wastewater is a liquid-liquid dispersion whose interfacial tension orbits 24 μN/m to 35 μN/m range and droplets behave such pseudo-solid [3]. This condition does not invalidate at first, extend the principle to other dispersions especially water oil production whose tensor activity of natural surfactants present, increases the mobility of dispersed particles [21], [30] and [29].

In sum current principles of unit operation has limited effectiveness and often requires extensive use of chemical additives no less pollutants to increase performance [14] and [41]. The global legislation to preserve the overall ecosystem is day-to-day more restrictive. Usual treatment techniques at high flow rates such as cyclone and flotation require additives for good performance. Cyclones although have advantages to produce high flow usually lose efficiency of oil/water separation when the diameter of the oil droplets is less than 50 micron [38].

Electrochemical techniques such as electro-coagulation and electrochemical Fenton process, whose literature reports good treatment results [16] and [22], require acidifying naturally brackish medium with high acidifying load. Technical separation membranes or aluminum silicate adsorbents are well suited to low flow rates. Considering the effluent bulk of the oil industry, the high specific surface of adsorbents, micro and macro-porous (10 to 1,000 m$^2$/g) [42], while they offer great areas to adsorption, permeability is lost. The sorbent metal used in this system, such as part of the technology and process kinetics, has efficiency associated with fluid-structure shock, and self-flotation due fluidic disturbance to form and breaking surface waves. The consequence of this is the generation of microbubbles gaseous barrier intercepted by metallic labyrinth, whose function is to retain oil droplets and hurl them against the adsorbent with 97% of permeability and no more than 0.015 m$^2$/g of specific surface which calculation is shown in the next section on experimental methodology.

A logic flowchart for experimental assembly is shown in fig. (2).
III. EXPERIMENTAL APPARATUS AND METHODOLOGY

To test the system and performance evaluation, 1.3 liters per test of effluent water emulsion with low oil content (1.5 to 2.5 mg/ℓ), were used such as diluent. The pH was monitored every assay obtaining the average value (pH = 9.18). This procedure yielded qualitatively proximal emulsions like real emulsions maintaining natural alkalinity by the concentration of salts and surfactants responsible emulsion stability. Emulsion was getting by mixture on 14 Hz containing high viscosity oil (5,000 cp) and salt water. Viscosity was obtained on average measured with viscosimeter (Brookfield Mod LVDV -II) on rotations to 830 rpm range mixer provided with impeller blades with flat cutting. The average OGC (Oil Grease Content) of the synthetic effluent was entering the treatment vessel per test was 121 mg/ℓ average, which were slaughtered, 16 mg/ℓ considered vessel impregnation, measured by impregnation gravimetric test successive. The final OGC obtaining effluent test was 105 mg/ℓ taken as the average reference value. By similar method was measured emulsion tank impregnation, impellers, homogenizer tank for gravity feed and flow control valve. Total average was 330 mg/ℓ. Based on these values oil was seeded in test water production to obtain average concentrations between 400 mg/ℓ and 500 mg/ℓ. According to [38] effluents from crude oil production water with this concentration have generally 75 % free oil and 24 % oil emulsion. The free oil probably impregnate very easily, justifies prepare emulsion with the highest concentration. Figure (3) shows the micrographs of emulsion for monitoring the average droplet size, made with electronic microscope (Olympus BX-51TRF). Analyzes of droplet size and statistical distribution of an emulsion can be seen in [34] and [41].

As a part of the adsorbent cell metal spiral sponge (3M Scotch Brite) household, made of stainless steel (ASTM-316) with average internal diameter of the helicoid radius of 4 mm was used. Figure (4) shows detailed picture of the adsorbent. Figure (5) shows the adsorbent microscopy to determine the average surface area. Based on the specific gravity of steel (ρ = 7.85 kg/ℓ) two spiral portions each one with sponge of 5.5g average weight were used. Microscopic inferring of thickness and width of the metal band was 15 micron and 513 microns, respectively, which corresponds to specific surface area of 0.015 m²/g, ie, far below minerals adsorbents.
The sewage flow to vat was performed so that the level of sewage never fell below certain order to ensure maximum variation above 4% in flow rate by falling head height value. The flow measurement was directly performed with use of timer and beaker capable of 500 mℓ with control performed by needle valve. The treated effluent is automatically transferred to amber container to be taken pH measure and final OGC as shown in (6). Figure (7) and (6) show respectively homogenizer gravity feeder and inertial physical prototype. The bench is equipped with vibration dampers (vibra-stop) 500N countercharge at the bottom and attached directly to the sidewall with steel bar bezel. Figure (8) shows the analog-digital monitoring system, and fig. (9) crude (right) effluent sample and treated (left) effluents.

Image of the treatment cell on vibration were obtained with the aid of industrial-strobe (Frata-150 from Brazil), digital microscope (MicroZoomCap®) and image capturing software.

Digital monitoring to obtain the dynamic behavior of the system was carried out using digital oscilloscope (Agilent 1002A DSO), source (MPL Minipa 1303M), piezoelectric accelerometer (Analogic ADXL 202 JQC) with board amplifier (Gain = 15) and displacement sensor (LVDT DG5.0 Solartron). Relation between displacement amplitude and excitation frequency was analyzed to determine natural frequency and elastic stiffness. On the other hand induced air flotation was obtained with assistance of automotive mini-compressor (Pmax = 5 atm) with flow rate 0.184 m³/h per calibrated rotameter (OMEL LAMDA from Brazil). The working pressure was 1.4 atm.

Operating parameters of dynamic system as natural frequency of low structural damping and displacement in three frequency bands were obtained with assistance of digital sensors, previously cited, and after treatment was done by the algorithm, Fast Fourier Transform with the aid of a Matlab® software. The average natural frequency of the system is 14.3 Hz. Due to the irregular mass distribution, above 30 Hz system moves rotationally. The amplitude of the rotational motion was measured with LVDT, tangentially at inclination (-45°) on the circle shown in fig. (12), a reproduction of the top view system.
As the swing radius is 75 mm, the column was moved to the formed medium circle periphery to obtain translational motion with amplitude of 2.4 mm approximately to frequency range of 33 Hz, and 0.55 mm for 47 Hz. Although measurements with accelerometers meters are more precise, it was decided for the simplicity of measurement do it with LVDT. Recovery of displacement signals from acceleration signals is not simple procedure due to acceleration change on time. Good results with numerical procedure can be seen in [23]. To minimize wave destructive interference by sub-harmonics side of the vat and drift flow towards the harmonic disturbance, longitudinal ribs were installed inside. The system is driven by motor (DC) 150 W power with rotary unbalance of 93.42g at 20 mm of eccentricity. Figures (13), (14), (15) and (16) show signals obtained with LVDT and accelerometer assistance for determining parameters values such as natural frequency and translational displacement.

The following figures show movement diagnosis of the vibrating table. The system is self-excited at frequencies above 25 Hz. Values for the natural frequency varied in the range of 12.52 Hz measured with acceleration sensor (Fig. 16) and 13.77 Hz, with a displacement sensor with application of the Fast Fourier Transform to the displacement signal (Fig. 22). The structural damping is obtained by the logarithmic decrement method [37]. It can be analytically calculated by principles of deformable body mechanics [33] or through the system static deflection with correction for template finite stiffness developed by [13]. Considered values of 2.4 mm and 2.39 mm as translational oscillation amplitude at the circular path tangency point, are approximations. It considers curvature radius of the trajectory very large compared to displacement of 2.4 mm. The best analytical treatment should consider Legendre-Lissajous trajectories described in [9]. Figures (17), (18), (19) and (20) show change of rectilinear to rotational motion. Regarding the system elastic instability (buckling) [33] was not taken into account due the weight of the system on springs be approximately 47 N, therefore well below the critical buckling load of the springs (Security risk coefficient 3.5 approx.).
Fig. 17. Acceleration signal in time at 14 Hz. Accelerometer was positioned with the axis toward excitation force.

Fig. 18. Acceleration signal in time at 47 Hz. Accelerometer was positioned with the axis toward excitation force.

Fig. 19. Acceleration signal in time at 33 Hz. Accelerometer was positioned with the axis at -45° direction excitation force.

Fig. 20. Acceleration signal in time at 47 Hz. Accelerometer was positioned with the axis at -45° direction excitation force.

Fig. 21. Amplitude logarithmic decrement obtained by hammer impact test (0.395kg) abandoned at 257 mm height above system table.

Fig. 22. Displacement signal frequency spectrum measured with LVDT to the test hammer impact.

IV. PRESENTATION OF RESULTS

The system designed and studied showed satisfactory results in the test conditions. As stated, is not pretention in this initial phase do extrapolation of the scale concepts regarding to the industry operational volume. Nor do we intend to discuss geometric parameters of tank treatment construction. Figures (23), (24) and (25) show results of the induced air flotation process. The energy consumption slightly increases with excitation frequency, however higher frequencies seem to increase permeability. According to [25] study on applying vibration to flow in porous media, vibration increases the effective flow of fluid by capillary by clearance and interfacial rupture. It shows results through the fig. (24), and seem to confirm the issue.

Fig. 23. Power consumption in operation with induced flotation in three frequency bands as such function the retention time.
Fig. 24. Influence of the effective flow rate compared to the nominal flow rate in open flux (no adsorbent) operating on induced flotation.

Shown are results indicating on fig. (25) of tendency to remove dispersed oil with increasing excitation frequency in the analysis limit. The higher value is subject of future work. The union points of the dispersion did not properly indicate functional trend; is solely for the purpose of perception analysis. It can be seen, by the general trend, which the flow rate seems to dominate the issue. The increase of flow velocity means increased process yield. In this case, speed is primarily kinetic energy, and can foster clash of droplets of dispersed oil with adsorbent to promote separation. According to \([26]\) vibration frequency and amplitude, individually, seem to influence less than product \((X_0 \cdot 2\pi f)\) considered \((X_0 \text{ – amplitude})\).

Fig. 25. Diminution of contents of oil and grease as a function of flow rate for three ranges of frequency and displacement amplitudes. Ranges are determined by Matlab\(^5\) based on the minor and major measurement.

Figures (26), (27), (28) and (29) show results of natural flotation (Vibrauto-flot) process. The power consumed viewing the fig. (26), is substantially lower because to obtain pressurized air to perform flotation, increases the power consumption. With the rotative unbalance of the engine, the operation is realized virtually on empty with relatively low energy consumption.

The expressive of effective flow increase shown in the fig. (27) is due to a 50\% reduction in weight of adsorbent to avoid blockage of air entering the treatment cell by rising effluent due to blockade caused by air bubbles and relatively high interfacial tension air/water \((72 \mu \text{N/m})\) against \((24 \mu \text{N/m})\) water/oil. Even with a 50\% increase in the porosity of the adsorbent cell (nominal space occupied by the adsorbent at the top of the vat, viewed in fig. (10) and fig. (11), the yield of oil removal does not seem to have been influenced, and this proves the good perspective of this innovative technique of liquid/liquid separation to oil/water emulsion. Figure (28) and (29) can confirm the premise. In figure (29) on 47 Hz, yields were low and may indicate limit or lost of efficiency caused by desorption at higher frequencies. Figure (30) shows image magnified of the adsorbent impregnated with characteristic droplets sessile of relatively strong impacts between oil drop and adsorbent surface.

Fig. 26. Comparison of power consumption between processes (Vibraflot and Vibrauto-flot).

Fig. 27. Rise of effective flow in the natural flotation (Vibrauto-flot) against process excitation frequency.

Fig. 28. Residence time as a function of frequency (Vibrauto-flot and Vibra-flot).

Fig. 29. Decrease content of oil and grease and specific flow behavior as a function of frequency (Vibrauto-flot).
V. SUMMARY

Project and analysis of a novel technique to separating oil and water emulsion of crude oil industry was presented and results were evaluated and discussed. The idea, in its preliminary course, presents good prospect of industrial application for its simplicity and efficiency attested in bench scale. Future works will investigate the expanding for biggest volumes and required geometric dimensions of the system. The concern with crude oil industry especially its industrial waste is the main worry. The technique also provides solution towards decrease of deliberate use of chemicals adjuncts in treatment of oily waters that is not less pollutant. The search for sustainable techniques for treatment is urgent. Regional waste in common use can and should be subject to reuse according to its own peculiarities. In respect to organic wastes [39] reports adsorptive properties of wood flakes and sawdust by the presence of tannin compounds, and adds that only in Belem, in Brazil, over 500,000 tonnes of sawdust are produced at a cost of USD $ 2/m3. Other natural fibers abounding in Brazil such as sial and coconut fiber are adsorbents by high relative surface [27]. The studied process is only valid for the conditions in which it was tested, and is intended solely for emulsion of oil and water. The use of vibratory energy is important and is little pollutant. Physics of vibratory motion is an established science, and little explored in this regard especially on applied treating of surface waves. According to Professor dr. Illya Blekhman born in St. Petersburg [6] vibratory action thus as can aggregate, can to disaggregate, consolidates and destroys, damages the measurement and serves as a measure, it is hazardous to health and serves as therapy, bothers and relaxes, orduains and clutters, increases or reduces gravity and increases capillarity; short vibration is abnormal. The Swiss alchemist, Teophrastus Bombastus, aka "the Paracelsus" said that what separates poison of remedy is the correct dose, and this is the measure of vibration.

ACKNOWLEDGMENTS

In appreciation at:

- Design Group and Sustainable Development - GDDS / UFCG-Brazil.
- Graduate Program in Science and Petroleum Engineering - PPGCEP / NUPPRAR / UFRN - Brazil.
- Multi-disciplinary Laboratory Materials and Structures Active - LAMMEA / UFCG – Brazil.
- Vibration and Instrumentation Laboratory - LVI / UFCG – Brazil.
- Laboratory Simulation and Automation Engineering - LaSEA / UFPB – Brazil.

REFERENCES

[21] FUJASOVA-ZEDNIKOVA, M.; Vobecká, L.; Vejrazka, J.; Ruzicka, M. C.; Drahoš, J. Effect of liquid properties and solid material on bubble-