

## FIELD EXPERIENCE WITH REAL TIME WATER-IN-OIL MONITORING

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### *Abstract*

*Water-in-oil or BSW monitoring in produced oil streams on offshore platforms in Campos Basin, Brazil, consists of a daily basis procedure to calculate the total liquid production balance. The measurement of the water cut becomes more critical through time when there is a natural depletion with a consequent decrease in the reservoir production, normally followed by an increase in water production, which can mask the oil fiscal metering. It is fundamental to consider the instability of the oil flow from the reservoir caused by gas or water slug, in the production columns, which can cause problems with sampling representivity and results from laboratory analysis carried out within pre-set periods. In the case of Petrobras, each analysis run represents the average value of six samples collected at the field locations and eventually the process of sampling can be problematic because of the process variations. Oils analysis is performed using centrifuging, decanting and by means of differential pressure measurement and none of these processes can be used in a continuous on-line basis. In order to guarantee a better representivity in the oil and water metering, a real time metering process is necessary. This can eliminate the constraints of the non-continuous metering processes and make the automation of the manifolds and oil gathering stations possible as well as the reduction of the total measurement uncertainties, among other advantages.*

*This paper intends to present the field experience and major advances in the real time water-in-oil monitoring technology which impacts directly on the final performance of the fiscal measurement processes and reduction of operations costs derived from the optimization of chemical product injection and analysis procedures.*

### 1 INTRODUCTION

Oil produced in a production facility is normally associated to salt water and sand. The fraction or percent of water is called *Basic Sediment and Water* or *BS&W* (or *water cut*) since the water volume is more representative than that of sand. Measurements of produced water and oil flow are critical for controlling the reservoir depletion and optimization of oil production and they depend on the determination of *BS&W*. There are other scenarios which are possible for application of an on-line *BS&W* flowmeter, among them one can mention:

- Oil to be transferred from a central production station to a refinery;
- After the treatment;
- After the production or test separator in the water and oil outlet lines;

The use of on-line *BS&W* monitors after the production or test separator allows to reduce its size and cost, since it is not necessary the three-phase separation process but double-phase one. Other aspects are evident, like:

- Possibility of automation of the measuring process in collecting units and its simplification, with consequent increase of reliability of the results;
- Reduction of cost associated to the analysis work done at the laboratory;
- Reduction of measuring uncertainty, with elimination of sampling process of the fluid produced on-line;
- Real time follow-up of modifications in the water production in the well;
- Instantaneous *BS&W* measuring.

It can be defined three groups of applications for *BS&W* or TOG (Oil and Greases Content) monitor in the oil industry. The first one, which refers to the oil quality, is applied in the 0 - 3% range of *BS&W* and it encompasses the processing, transportation, refining and detection of water in the oil produced (or oil contamination). The second one is applied in the 0 - 100% range of *BS&W* and it involves the produced water measurement. The last one is the quality of the produced water to be disposed (TOG), measured in terms of **ppm** (part per million) of oil.

Traditionally, the *BS&W* measurement is done in three ways: (a) in laboratory, (b) with sampling and reduced container with level gauge; c) differential pressure.

*BS&W* measurement in laboratory is done collecting a small sample of the fluid produced from a determined well directly in the production head or after the test separator. The methods include centrifuge separation or *Kal-Fischer* method. As the minute *BS&W* is different of the mean, it is critical to collect and to test several samples for obtaining a good representivity of the product. An aspect to be pointed out is the long run of answer of this method.

In the method of *BS&W* measurement by reduced container with level gauge, two shut-off valves are placed in a duct segment separated by a determined distance, which is the function of the phenomenon representivity. In operation, the two valves are simultaneously closed and a third one bypass is opened for giving continuity to the outflowing. The fluid retained between the two valves is drained to the container and, after decantation, it is observed the position of the oil and water separation interface in a scale rule, getting thus the *BS&W*.

*BS&W* measurement by differential pressure follows the same sampling routine of the preceding case, although the fluid retained is drained to a container in which, after a determined time, and measured the liquid column of it by means of the differential pressure. An alternative to this system is the measurement of the container weight for determining the *BS&W* by means of a charge cell or another principle.

A production facility always generates what is called produced water, which is typically a mixture of water from formation and water of injection. It can contain oil, salts, chemical compounds, solids and metals. Produced water is the primary product for discharging resulting from oil, gas and water separation from a production facility and normally its quality is monitored through daily analysis of TOG (Oil and Greases Content) measured in terms of **ppb** (parts per billion) ( $\mu\text{g/l}$ ) or **ppm** (parts per million) ( $\text{mg/l}$ ). The technologies of instruments for measuring TOG substantially differ of those used in *BS&W* flowmeter.

## 2 TESTS DONE

*BS&W* monitors are instruments in phase of implantation in PETROBRAS and then they are considered as new technology. They are so considered also for other operation companies which still do not know very well this kind of meter as to the field applications. An evidence of it are the Multi Client Project or *JIPs* (*Joint Industry Project*) conducted by agencies of high international credibility where PETROBRAS has participated along with other operation companies. In these projects several available monitors have been tested in the international market with different principles of working and submitted to different operational conditions.

In its Research Center – CENPES – a loop test was built for testing measures of this kind where concepts based in the microwave principle were submitted. It was done an evaluation of the behavior of these monitors as to the salinity variation of the water, temperature and API grade, using as reference the laboratory method of the Karl-Fischer kind.

By means of PROCAP 2000 (Program on Deep Waters Qualification) it was constructed the Test Site for Multi Phase Equipment of Atalaia (Aracaju, Sergipe) where it has been possible to test several instruments of varied technologies as is the case of those based in capacitance, inductive principles, Coriolis, radioactive attenuation and microwaves. The objectives of these tests done at the Test Site has been to evaluate the technologies as to the variability that naturally occur in a oil well or at a production facility. It has been mainly tested the instrument performance as to the salinity variability of water an API grade, using initially as reference the laboratory method of Karl-Fischer kind and comparison with known volumes and afterwards the instruments resident at the Site (capacitance and Coriolis). The Test Site has been used also as checking facility for several instruments of this kind in the facilities of the E&P segment.

At CENPES it was constructed a test loop (Figure 1) constituted by two 100 liter tanks (one for test and the other for discharging), 2 " lines and a centrifuge pump with discharge of 100 l/h operating at a pressure near the atmospheric. There is also a sampler (Figure 2) placed before the tested meter and that allows the sampling in several radial points in the internal tube. Such characteristic is very important, since it allows the checking of the synthetically produced emulsion stability.



Figure 1 - Test loop at CENPES

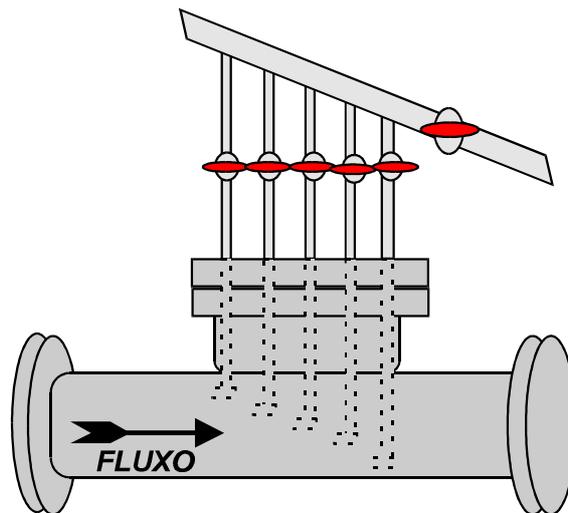
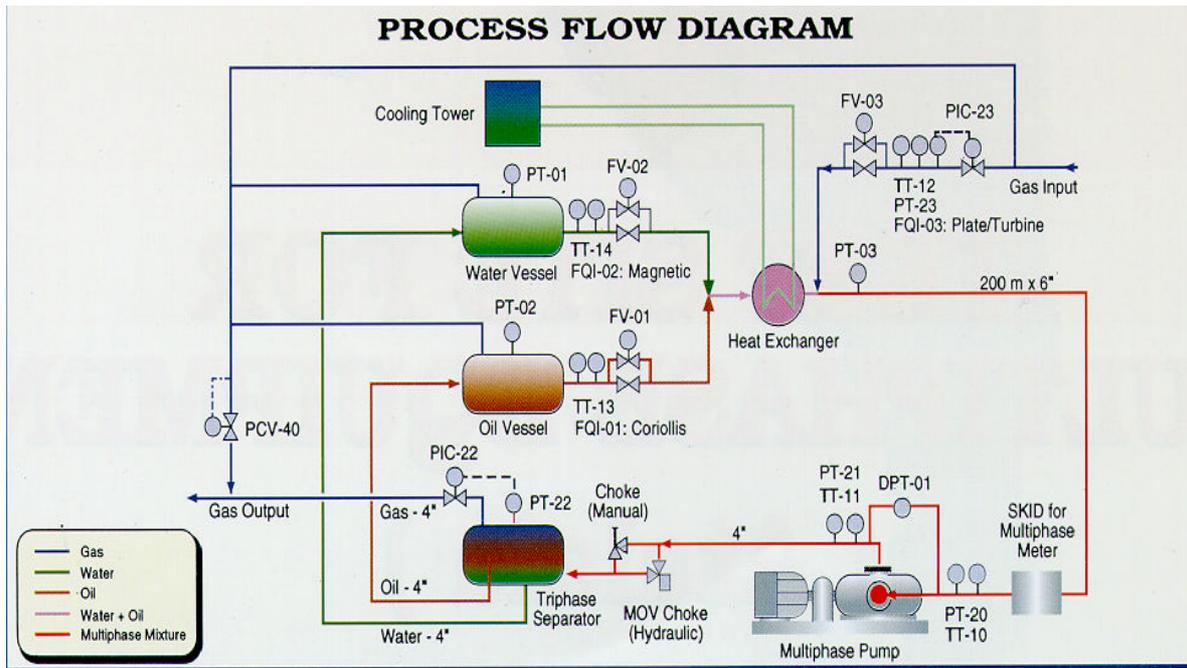


Figure 2 - Details of the adopted sampler

At the Test Site of Atalaia it was constructed a test loop (Figure 3) constituted by a 150 liter tank of 3" and a centrifuge pump with discharge of 10 m<sup>3</sup>/h. There is also a sampler similar to that of Figure 2 placed before the tested meter for allowing the representative sampling of the outflowing. Such characteristic is very important, since it allows the checking of the synthetically produced emulsion stability. A new test loop was constructed using the resident equipment at the Test Site, such as the oil accumulator container, 100 m<sup>3</sup>/h centrifuge pump and specific instrumentation of the capacitance kind, Coriolis type, temperature and pressure transducers and data acquisition system. This new loop can allow the realization of tests in operational conditions nearer to the reality of a oil well at pressures of up to 15 bar.



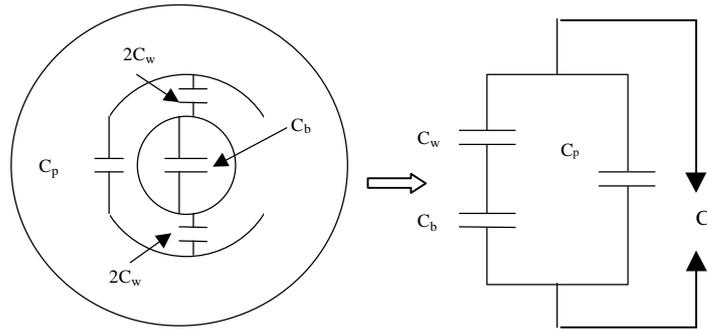
**Figure 3 - Test loop at the Test Site of Atalaia**

### 3 DESCRIPTION OF THE TECHNOLOGIES

#### 3.1 CAPACITANCE

The operation principle of the capacitance *BS&W* monitor is based on two electrodes installed in the internal walls inside the measuring section in opposite phases, with the aim of measuring the dielectric constant of the oil/water mixture. From the previous knowledge of the oil and produced water dielectric constant, it is possible to determine the water cut present in the mixture, since it is critical for recalibration of the instrument in case of variation of the oil type used. Normally the instrument is not intrusive. The capacitor plates can vary in shape according to the manufacturer (helical, etc.).

Figure 4 shows the electric model [1] of a typical capacitive sensor. The model is constituted by different capacitors. There is the capacitance between the electrode and the internal wall ( $2C_w$ ) of the duct, the capacitance ( $C_p$ ) among the electrodes by means of the liner, the effective capacitance ( $C_b$ ) of the mixture and the capacitance ( $C_s$ ) resulting from all other capacitances.

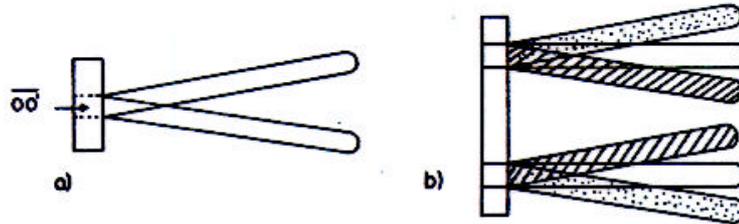


**Figure 4 - Electrical model of the capacitance sensor**

It is important to point out the capacitive kind sensor only operates in continuous oil outflowing regime, since in the case of continuous water regime the oil/water regime provokes short-circuit in the capacitor. Reduction of the internal diameter of the measuring section due to paraffin or other material deposit can alter the performance of the meter, due to the alteration in the dielectric constant of the environment. Another aspect is the segregation of the phases in outflowing that, due to the water concentration in some parts of the internal wall of the section can result in short-circuit situations of the capacitive sensors. In these cases, the performance of the meter can be done with the installation of a high efficiency mixer upstream of it.

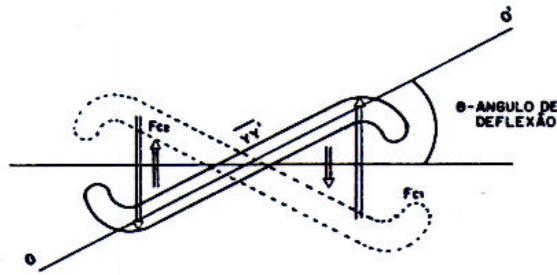
### 3.2 CORIOLIS

The operation principle of the *Coriolis* kind meter is based on two sensor tubes generally in shape of an U which in conditions of zero flux and submitted to magnetic strengths induced by the instrument by itself, acquire an oscillating movement around axe OO' (Figure 5).



**Figure 5 – Oscillating movement of the tube of the Coriolis meter with zero flux**

When the fluid passes through the tubes, the combination of angular and linear velocity will generate the Coriolis acceleration. The strength generated produces a torsion (Figure 6) in the tube that is proportional to the mass discharge in outflowing.



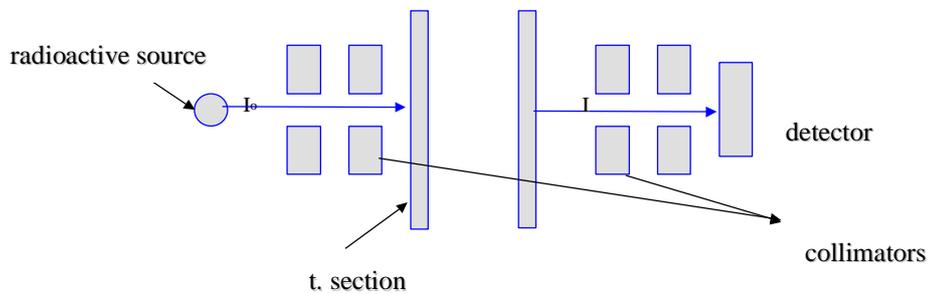
**Figure 6 - Deformation of the tube deriving from torsion due to the Coriolis forces (with flux)**

The Coriolis force module generated is small but is amplified by the instrument and it is function of the mass that flows in the tube and of the resulting acceleration. As it is at the same time a mass flowmeter and density meter, the Coriolis meter is also used for measuring *BS&W* from the previous knowledge of the oil and produced water densities used, and for it it is critical the re-calibration of the instrument in case of variation in the oil type used. The *BS&W* calculation is done using the following formula (where  $\rho$  is the density and the subscripts *m*, *o* and *w* stand for measured, oil and water respectively):

$$BS\&W (\%) = 100 \cdot [(\rho_m - \rho_o) / (\rho_w - \rho_o)] \quad (1)$$

### 3.3 GAMMA RAY ATTENUATION (*GAMMA ATTENUATION*)

Figure 7 show an arrangement of a gamma-densitometer [2] for measuring parameters and properties in multiphase flow that consists of a radioactive source, collimators, detector and test section. The collimators objective is to reduce a narrow and unidirectional radiation beam.



**Figure 7 - Simplified arrangement of a gamma-densitometer showing the radioactive source, collimators, the test section and the detector**

Gamma rays beam when passes the double- and multiphase mixture will be attenuated by the internal wall of the tube, mixture and opposite wall of the tube. In the *BS&W* determination it is convenient to measure the radiation intensity for the tube full of water (*BS&W* = 1) and full of oil (*BS&W* = 0) for eliminating the effect of the attenuation suffered by radiation in the tube wall, with the following expression:

$$BS\&W = \text{Ln}(I/I_a) / \text{Ln}(I_o/I_a) \quad (2)$$

where:

$I$  – measured intensity;

$I_n$  – Intensity of the emerging radiation with tube full of oil;

$I_a$  – Intensity of the emerging radiation with tube full of water.

### 3.4 INDUCTIVE

The inductive kind monitor measures the electrical conductivity of the oil-water mixture when water is the continuous phase. It is constituted of two toroid type devices involving a non conductive liner. The first toroid generates a magnetic field that induces an electrical field in the double phase and, as the environment is conductive, an electrical current will be generated in the fluid. This electrical current in the oil-water mixture consequently induces a tension in the second toroid according to the Lenz law. By means of a system of automatic control of the very monitor, the electrical current in the fluid is kept constant and equal to the current equivalent to 100% of *BS&W*, by means of the actuation of the excitation tension in the main toroid from the reading of the tension induced in the second toroid.

The electrical conductivity of the oil-water mixture is determined by measuring the voltage between two electrodes placed between the two toroids and the electric current, that is:

$$\sigma_m = (I_{\text{constant}}/\Delta V)/(L/S) \quad (3)$$

where:

$\sigma_m$  – electrical conductivity of the environment;

$I_{\text{constant}}$  – constant electrical current in the outflowing;

$\Delta V$  – voltage;

$S$  – area of pipe section;

$L$  = distance between electrodes;

The measured *BS&W* is function of the electrical conductivities of the mixture and water, that is:

$$BS\&W = f(\sigma_m, \sigma_n) \quad (4)$$

The electrical conductivity of the environment must have a minimum value for the inductive meter to be applicable. When the oil is the continuous phase, this meter is not applicable because electrically oil is an insulator. When oil is dispersed in water and not emulsionized, the measured *BS&W* will represent the free or continuous water. In the case of oil dispersed in water, but emulsionized, the meter will measure only the free water and not the total *BS&W*, since the meter will not detect the emulsionized water in oil (due to the fact of emulsion does not contribute for the electrical current as described above).

### 3.5 MICROWAVE BY ENERGY ABSORPTION

*BS&W* monitor based on microwave by energy absorption uses a measurement section with an electromagnetic oscillator, a transmission antenna and another receptor. In this case, the water fraction is determined by the measurement of electrical properties of the mixture that outflows by the measurement section. Normally, the instrument is intrusive and it can be used with option of removal probe. Parallely, the dielectric constant of the oil/water mixture is measured and compared with data from the internal table of the instrument according to temperature, API grade and salinity. In case of variation of the oil type used, uncertainties are not degraded in a significant way. The frequency ranges vary according to the manufacturer, from 2 through 10 GHz.

### 3.6 MICROWAVE WITH RESONANCE CAVITY

This monitor uses its measurement section as an open resonance cavity, where inside an electromagnetic field is tuned at a characteristic frequency that is function of the cavity dimensions and of the dielectric constant of the environment (or of the fluid inside the cavity) what makes it an instrument for measuring density. The instrument has an electromagnetic oscillator and two antennas or plates. Normally, the instrument is intrusive, since it has still two metallic grids, one at each passageway of the duct (upstream and downstream), in a way to characterize the resonance cavity.

### 3.7 MICROWAVE BY PHASE DIFFERENCE

*BS&W* monitor based on microwave by phase difference uses a measurement section with an electromagnetic oscillator module, a transmission antenna and another receptor. The measurement section consists of a short-circuited coaxial transmission line at one of the ends and made up by a conducting bar with a small diameter where the oil-water mixture acts like dielectric environment. The propagation speed of an electromagnetic wave will vary according to the environment, consequently in an oil-water mixture, where the dielectric constant of oil is about 2.2 and that of water is about 80, the wave length will vary in function of *BS&W*.

The oscillator module contains two separate oscillators, one of them operating in the oil-continuous region and the other in the water-continuous region. When oil is the continuous phase, the reference frequency is of approximately 100 MHz and for each variation of 1% the *BS&W* will correspond to a variation of 200 kHz in the oscillator frequency. In the case of continuous water, the reference frequency is of approximately 150 MHz and it has a sensibility of 50 through 150 kHz for 1% of variation in the *BS&W*, depending on the water salinity.

As the measurement section is a short-circuited coaxial cable at one end, the electromagnetic wave transmitted suffers total reflection in the opposite short-circuited end and it goes back to the transmitter. When oil is the continuous phase, the energy loss of the electromagnetic wave reflected is low, and in the case of water-continuous regime the energy loss is high. The identification of which phase is the continuous one is done by the measurement of the lost energy of the electromagnetic wave reflected in the short-circuited end. There is a cut line for switching the oscillator from oil-continuous to water-continuous situation or vice versa and this cut line is the measure of the energy level of the electromagnetic wave.

## 4 SCENARIOS FOR APPLICATION OF THE *BS&W* MONITORS

Table 1 presents the recommended technologies from the results of tests done by PETROBRAS. In the first column left it is chosen the expected range or using the monitor. Observe the differences among ranges of *BS&W* and TOG (Oil and Greases Content) monitors, as well as the technologies.

**Table 1 – Recommended Technologies from the Selected Range**

<b>Measurement Range</b>	<b>Actual Gas Volume Fraction</b>	<b>Recommended Technology</b>	<b>Notes</b>
0 – 3 % <i>BS&amp;W</i>	< 5 %	<ul style="list-style-type: none"> <li>• CAPACITANCE</li> <li>• MICRO-WAVE</li> </ul>	
	≥ 5 %	<ul style="list-style-type: none"> <li>• NOT APPLICABLE</li> </ul>	A multiphase meter is recommended
3 – 10 % <i>BS&amp;W</i>	< 5 %	<ul style="list-style-type: none"> <li>• CAPACITANCE</li> <li>• CORIOLIS</li> <li>• MICRO-WAVE</li> </ul>	
	≥ 5 %	<ul style="list-style-type: none"> <li>• NOT APPLICABLE</li> </ul>	A multiphase meter is recommended
3 – 60 % <i>BS&amp;W</i> (OIL-CONTINUOUS)	< 5 %	<ul style="list-style-type: none"> <li>• CAPACITANCE</li> <li>• CORIOLIS</li> <li>• MICRO-WAVE (Full Range)</li> </ul>	
	≥ 5 %	<ul style="list-style-type: none"> <li>• NOT APPLICABLE</li> </ul>	A multiphase meter is recommended
60 – 100 % <i>BS&amp;W</i> (WATER-CONTINUOUS)	< 5 %	<ul style="list-style-type: none"> <li>• CORIOLIS</li> <li>• INDUCTIVE</li> <li>• MICRO-WAVE (Full Range)</li> </ul>	1 – 40 % oil-in-water
	≥ 5 %	<ul style="list-style-type: none"> <li>• NOT APPLICABLE</li> </ul>	A multiphase meter is recommended
0 – 100 ppm Oil and Greases Content (TOG)	< 5 %	<ul style="list-style-type: none"> <li>• IR Scattering</li> <li>• IR/Laser Scattering</li> <li>• IR Spectrophotometry</li> <li>• UV Fluorescence</li> </ul>	Typical of produced water systems
	≥ 5 %	<ul style="list-style-type: none"> <li>• NOT APPLICABLE</li> </ul>	Gas must be removed in the sample pre-conditioning

OBS: A) IR: Infrared; UV: Ultraviolet

## 5 CRITERIA FOR SELECTION

Several parameters are necessary for the selection criteria of a determined *BS&W* meter. The adequate choice of a *BS&W* meter is function of the application scenario, operational conditions, variability of the process, such as oil and/or water-continuous regime, arrangement of phases, variations of the properties and of the requested uncertainties. One type of meter is not the solution for all operational conditions. The knowledge of the application scenario's variability is critical for defining the characteristics of the meter to be selected.

Due to the fact that the fluids produced at the well have different physical and chemical properties, along with the process of water or vapor injection in the formation, oil outflowing presents different variability that differently impact *BS&W* monitor in function of its conceptions and physical principles of functioning.

Once the relative permeability of oil decreases in function of the increase of the water production of the reservoir, the trend is the gradual increase of *BS&W*. Produced water may have different origins, among them the formation water or the injected water in the formation that make salinity and consequently the density of the produced water to vary with time.

In the water-continuous region, variation in water salinity will break the robustness of measuring of the microwave type, for instance, due to the great attenuation and phase displacement of the

electromagnetic waves in the conductive environment. In the case of Coriolis monitor and for radioactive attenuation there is no influence in this case. In the oil-continuous region, variation in the water salinity will not break the robustness of monitors of the microwave and capacitance types.

The presence of a third phase, as free gas, introduces systematic errors in determining *BS&W* in two ways. For measuring *BS&W* in an oil, water and gas outflowing it is necessary to combine two instrument with different physical principles for compensating the volume occupied by free gas. As *BS&W* monitors have only one sensor, the systematic error increases in function of the increasing in the free gas fraction in the outflowing. The second way is the actual response of the instrument with the presence of free gas. If free gas is dispersed as micro bubbles, normally the monitor measures the property with inadequate uncertainty, but acceptable, depending on the case. If free gas is segregated, normally the instrument response loses its sense.

If the process pressure is low and near that of atmosphere, density monitors (Coriolis and radioactive attenuation) are more tolerant to the gas presence, since it is dispersed in the liquid, than those based on dielectric constant (capacitance or micro waves).

Tables 2 and 3 present the normally present variability in oil and water outflowing for *BS&W* monitors.

**Table 2 – Variability for Capacitance, Inductive and Coriolis Monitors**

<b>VARIATION SOURCE</b>	<b>CAPACITANCE</b>	<b>INDUCTIVE</b>	<b>CORIOLIS</b>
Sensitivity to free gas	High	Low	Low up to 5% of gas
Sensitivity to oil-water separation	Does not work	None [4]	None [5] [6]
Application window	Oil-Continuous regime	Water-Continuous regime	0 - 100%
Intrusivity to pipe	Yes	Yes	Yes
Intrusivity to process	No	No	Yes
Moving parts	No	No	No
Simplicity	Yes	Yes	Yes
Recommended phase arrangement (oi/water)	Dispersed water as bubbles in oil	Anyone, under water-continuous regime [4]	Anyone
Cost	High	High	Intermediate
Recommended installation position	Vertical	Vertical	Horizontal
Radioactive source	No	No	No
Environment impact	No	No	No
Pressure drop	No	No	Low/intermediate (depends on the sensor shape)
Sensitivity to salinity variation: Oil-continuous: Water-continuous:	No [3] Not applicable	Not applicable Yes [4]	No No
Sensitivity to oil density variation	No [3]	No [4]	Low (depends on variation range)
Sensitivity to viscosity variation	No [3]	No [4]	No [5]
Sensitivity to vibration	No	No	Some
Calibration	Easy	Easy	Easy
Installation effects	No	No	No

**Table 3- Variability for Microwave and Radioactive Attenuation Monitors**

<b>VARIATION SOURCE</b>	<b>MICRO-WAVE (EBERGY ABSORPTION)</b>	<b>MICRO-WAVE (RESONANCE CAVITY)</b>	<b>MICRO-WAVE (PHASE DIFFERENCE)</b>	<b>RADIOACTIVE ATTENUATION</b>
Sensitivity to free gas	Intermediate/High	Intermediate/High	Intermediate/High	Low up to 5% of gas
Sensitivity to oil-water separation	High	Low	High	High
Application window	0 - 100%	0 - 100%	0 - 100%	0 - 100%
Intrusivity to pipe	Possibility of installing at a pipe bend	Yes	Yes	No
Intrusivity to process	Yes	Yes	Yes	No
Moving parts	No	No	No	No
Easiness of installation	Yes, Possibility of installing at a pipe bend	Need to interrupt the pipe run	Need to interrupt the pipe run	clamp-on
Simplicity	Yes	Yes	Yes	Yes
Recommended phase arrangement (oi/water)	Homogeneous flow	Homogeneous flow	Homogeneous flow	Homogeneous flow
Cost	Intermediate	Intermediate	Intermediate	Intermediate/ low
Recommended installation position	Vertical	Vertical	Vertical	Vertical
Radioactive source	No	No	No	Yes
Environment impact	No	No	No	Yes
Pressure drop	Low	Low	Low	None
Sensitivity to salinity variation: Oil-continuous: Water-continuous:	No [7] Yes	No [8] Yes	No [9] Yes [10]	No [6], [11] No [6], [11]
Sensitivity to oil density variation	No [7]	No [8]	?	Depends on the variation
Sensitivity to viscosity variation	No [7]	No [8]	No [10]	No
Sensitivity to vibration	No	No	No	No
Calibration	Easiness depends on the model	Intermediate easiness	Easy	Easy
Installation effects	None but the specified minimum velocity must be guaranteed	No	No	No

## 6 CONCLUSIONS

The use of on-line *BS&W* monitor in production facilities allows the optimization of the process with evident advantages.

Its application in the oil industry is irreversible and it will demand from users a better operational knowledge of the functioning of this kind of equipment. The management of its utilization as to the periodic calibration and maintenance will also demand special attention, since it is an instrument categorized as process analyzer, whose characteristic demands a more dedicated accompanying than that of the common instrumentation.

Manufacturers shall make its products more friendly in terms of easiness of calibration, implementation plenum of digital technology, resources for on-line salinity measurement in real time, improvement of interfaces with the operator and reduction of prices.

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