Method of eliminating the effect of a free gas on the measurement of water cut three-phase oil-water emulsion by the flow microwave water-cut meter

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Abstract. A method is proposed for eliminating the influence of free gas on the measurement of the water-cut of a three-phase oil-water emulsion (OWE) with an in-line microwave water-cut meter by introducing a specialized statistical processing of the current water-cut meter readings. The useful effect is to increase the accuracy of water cut measurements and to reduce the requirements for degassing the OWE at the stage of preliminary preparation. Additionally, it is possible to estimate quantitatively the extent of homogeneity violation of the working environment.

1 Introduction

The indispensable accompanying component of natural oil is the free gas, which is a mixture of hydrocarbon gases released from the oil well in the process of crude oil extraction, its transportation and processing [1]. After preliminary separation, the volume fraction of residual free gas (hereinafter – gas factor G), as a rule, does not exceed 5% of the volume (vol.%) of oil-water emulsion (OWE). Often the gas factor can reach 10% or more. The normative document MI 2575-2000 recommends to control the gas factor after the separation of free gas in the range 0.1 - 10 vol.% [2].

Microwave water-cut meters (hereinafter referred to as water-cut meters) are used to measure the OWE water-cut change in the characteristics of the resonator in the interaction of the resonator electromagnetic field (EMF) with the flow of the working fluid. A significant difference in the electrophysical properties of free petroleum gas and a produced water in the composition of the OWE [3], such as electrical conductivity \( \sigma \), permittivity \( \varepsilon \) and density \( \rho \), causes significant deviations of the average values of these parameters for a three-phase...
mixture with a hydrocarbon liquid in comparison with the situation when the free gas is absent. This circumstance leads to large systematic errors in measuring the proportion of water in the three-phase OWE composition with microwave water-cut meters, since the interaction of the EMI with the working fluid flow in the measurement zone depends on the above parameters of the mixture, in which a part of the aqueous phase of the OWE is replaced by gas.

Most often, as the primary information characteristic, the transmission losses $L$ of the resonator at the excitation frequency $f$ of EMF are used, forming the amplitude-frequency characteristic (AFC) of the resonator $L(f)$ in the working frequency range [4]. Next, the selected parameters of the frequency response are converted by the calculation algorithm of the water-cut meter to the value of the water-cut volume $W_v$ of OWE. The random distribution of free gas in the resonator measurement zone generates fluctuations of the averaged electrophysical parameters of the liquid, which leads to fluctuations of frequency response values and, accordingly, causes a random error in the water-cut meter readings during the measurement of the water fraction in three-phase OWE.

2 Mechanism of the free gas influence on the error of water cut measurement

2.1 Device for measuring the water-cut value of OWE

The proposed method of eliminating the influence of free gas on the in-line measurement of the proportion of water in the composition of a three-phase OWE is formulated on the example of a water-cut meter based on the EMF resonator described in [5].

2.2 Systematic shift and noise in the frequency response of the resonator

Place the figure as close as possible after the point where it is first referenced in the text. If there is a large number of figures and tables it might be necessary to place some before their text citation.

Figure 1 illustrates the appearance of a systematic shift in the level of losses and noise in the graph of the resonator frequency response for a mixture with $W_v = 65$ vol.% at $T = +30^\circ$C, mineralization of the aqueous component $S = 10$ g/l and $G = 20\%$ compared to the same AFC measured in the absence of free gas ($G = 0\%$).

The indicated values of salinity and temperature of the OWE are valid for all subsequent sets of discussed experimental data.

The method of AFC measurement is described in [6]. The AFC for each mixture was registered three times consecutively with a constant scanning step. The numbers on the abscissa axis correspond to the normalized relative detuning from resonance:

$$\delta_f = (f/F_r) \cdot 10^3/F_r,$$

where $F_r$ is the resonance frequency of the mixture at $G = 0\%$.

The coordinates of intersection points of AFC with calibration curve (CC) of the water-cut meter then are re-calculated in water-cut value $W_v$.

In the absence of free gas, three realizations of AFC are practically merge (blue curve in Figure 1), which allows determine $W_v$ quite exactly. Impact of free gas leads to jumps at AFC graph, which is illustrated in Figure 1, where three realizations of AFC are given at $G = 20\%$.
(red curves). Instead of a single solution, there is an extended area of intersection of AFC and CC. As a result, the accuracy of water-cut meter readings is lost, and the random scatter of readings increases with the increase of a gas factor.

From the foregoing, it is necessary to suppress the noise component of AFC before calculations of the \( W_v \) value. The classic technique here is the accumulation of data and their subsequent statistical averaging. As an example of using this approach in Figure 1 black line shows the AFC averaged over three passes. As one can be seen from figure, the averaging procedure of \( L(f) \) does not lead to the effective noise suppression.

### 3 Noise suppression in the AFC response

Radical noise suppression is proposed to be performed by smoothing the function \( L(f) \), previously averaged in the general case over several implementations on the base of the calculation of locally weighted average values of the Gaussian random variable (in our case these are transmission resonator losses) [7]. This method is most effective when data are taken at points separated by intervals having approximately equal width. This condition is fulfilled by fixing the scanning step \( L(f) \) in the working frequency range. The analytical expression underlying the smoothing procedure \( L \) is given in (2):

\[
L_{sf} = \sum_{j=0}^{N} \frac{1}{\sqrt{2\pi \cdot 0.37}} \cdot e^{-\frac{(f_i-f_j)^2}{2(0.37)^2}} \cdot L_j \\
= \sum_{j=0}^{N} \frac{1}{\sqrt{2\pi \cdot 0.37}} \cdot e^{-\frac{(f_i-f_j)^2}{2(0.37)^2}} \cdot L_j
\]

Here \( f_i \) and \( f_j \) are, correspondingly, \( i \)-th and \( j \)-th discrete AFC frequencies; \( L_j \) are averaged resonator transmission losses at frequency \( f_j \); \( b \) is the parameter (coefficient) of smoothing; \( N \) is the number of frequency counts in AFC; \( L_{sf} \) are the smoothed transmission losses of resonator at frequency \( f_i \).
The degree of noise suppression during smoothing is determined by the smoothing parameter “b”. Its value is usually set several times larger than the selected interval between data points on the frequency axis and is determined by how large the window is desirable to use when smoothing. Parameter b, on the one hand, is limited from below by the necessity to ensure effective noise suppression at the maximum level of the gas factor, and, on the other hand, is limited from above by the necessity to track slow changes in transmission losses caused by changes in the water value of the measured medium.

As the analysis of the obtained data showed, the appropriate value for this parameter $b = 4$ for the mixtures in Figure 1. Figure 2 demonstrates the efficiency of the noise suppression in resonator transmission losses with help of the discussed averaging and smoothing procedures for the mixture $W_r = 65\%$, conditioned by the action of free gas with $G = 5$ and 20%. Preliminary averaging of the $L(f)$ function was done by three AFC implementations, smoothing parameter $b = 4$. The coordinates of the AFC intersection point with the calibration curve are determined with the help of noise-free resonator transmission losses, and then the water-cut meter numerical algorithm align to them sought value $W_r$.

![Fig. 2. Fragments of three AFC resonator transmissions in the region of intersection with calibration curve for the mixture with $W_r = 65\%$, $S = 10 \text{ g/l}$, $T = +30^\circ\text{C}$ for each from three levels of the gas factor $G$: 0, 5 and 20% (a) before and (b) after averaging and smoothing.](image)

4 Selection of the smoothing coefficient

Figure 3 explains the choice of parameter $b$. It presents AFC fragments in the region of their intersection with CC after averaging and smoothing procedures for three values of $b$: 1, 4 and 16 at $G = 20\%$. The transformed AFC is denoted as $L_p(f)$.

Figure 3 shows that at $b = 1$ the graph of $L_p(f)$ (black curve) contains the significant remaining noise. As a result, there are three points of intersection of $L_p(f)$ with CC, which determines the random scatter of the water-cut meter readings. At $b = 4$ (blue curve), the noise is almost completely suppressed, which ensures the uniqueness of the humidity counting. A further increase of $b$ value up to 16 (red curve) demonstrates characteristic tendency for this mathematical method to replace a real noisy AFC by its mean value on the basis of counts.
when $b \to \infty$. Accordingly, the use of the curve $Lp(f)$ at $b = 16$ to measure the intersection point coordinates with CC leads to a systematic error.

![Graph showing transmission losses vs. relative frequency](image)

Fig. 3. A fragment of the averaged and smoothed AFC response in the area of intersection with the calibration curve for the mixture $W_v = 65$ vol.%, $S = 10$ g/l, $T_{cm} = +30^\circ$C, $G = 20\%$ at $b = 1, 4$ and 16.

Our experiments have shown that in the water-cut range 40 - 100 vol.\% the optimal values of parameter $b$ lie in the range 3 - 4. But this conclusion is obtained on a specific experimental device. Therefore, one can not exclude that abovementioned recommendation may be corrected in other possible situations.

## 5 Estimate of the noise intensity

The noise component of the primary ACF response $N(f)$ at the intersection range of ACF with the calibration curve is defined as the difference:

$$N(f) = L(f) - Lp(f)$$

(3)

The small mean value of $N(f)$ indicates that $b$ is correct. Next, the mean square deviation (MSD) $\sigma N$ of the resonator transmission losses interacting with the three-phase OWE, characterizing the noise intensity, can be calculated as:

$$\sigma N = \sqrt{\frac{1}{K} \sum_{k=0}^{K} N(f_k) - \left( \frac{1}{K} \sum_{k=0}^{K} N(f_k) \right)^2}$$

(4)

Where $N(f_k)$ is the noise at the frequency of the next count $f_k$; $k$ is the count number; $K$ is the number of AFC counts used in the analysis. In Figure 4 the results of calculation of noise intensity $\sigma N(G)$ and water-cut meter measurements $W_v(G)$ are presented for mixtures with water-cut $W_v = 50, 70$ and $90$ vol.\%, at each of which the gas factor $G$ took the values $0, 5,$
10 and 20%. The temperature of the mixture and the mineralization of water component were maintained unchanged: +30°C and 10 g/l, respectively. For the calculation of $W_v$, the AFC averaged over three implementations and then smoothed by the formula (2) at $b = 4$ is used.

![Image](attachment:image.png)

Fig. 4. Noise intensity $\sigma N(G)$ AFC (a) and calculated volumetric water-cut $W_v(G)$ (b) on the base of averaged AFC, smoothed with parameter $b = 4$, for mixtures $W_v = 50, 65 \text{ и } 90 \text{ об.к.}, S = 10 \text{ g/l}, T = +30^oC$ in the diapason $G = 0 - 20\%$.

As can be seen from Figure 4, curve families $\sigma N(G)$ and $W_v(G)$ are regular, monotone and one-to-one functions in the range of gas factor $G = 0 - 20\%$. As $G$ increases, the noise intensity increases too for all mixtures. At the same time, the calculated water-cut value is reduced. The latter circumstance is due to the replacement of a part of OWE water component with its large attenuation and dielectric permeability by a free gas, having parameters close to indicators of a dry oil, i.e. much less. The values of water-cut given as parameters above the curves in Figure 4 a, b correspond to the oil in the absence of a free gas.

6 Correction of the measured water-cut value

The relationship between the level of the gas factor and the noise intensity determined during the processing of the primary data (see Figure 4a) makes it possible to calculate the value of $G$ and then, turning to Figure 4b, to correct the current readings of the water-cut meter $W_v$, raising them to the value $W_{v0}$ corresponding to degassed oil. The necessary ratios are given below. The parameters of calculated formulas are selected during the calibration of the working device. Let us introduce a composite (complex) function $W_v(\sigma N(G))$, where the noise intensity $\sigma N(G)$ acts as the argument, and $G$ plays the role of an implicit parameter. In Figure 5 this function corresponds to mixtures in Figure 4. One can note that the curves in Figure 5 are closer to linear dependencies in comparison with similar functions in Figure 4, and their length characterizes the measure of the free gas impact on the calculated water-cut value in a condition of constant water-up of the mixture. The larger the water-cut value, the stronger the influence of free gas to the calculated value of $W_v$ and the longer $W_v(\sigma N)$ curve. The isolines of the gas factor of the shape $\sigma N (W_v)$, shown in Figure 5 by dashed lines, have
approximately linear relationship relating the increase of noise intensity with increase of the prescribed mixture water-cut at $G = \text{const}$. The set of curves $\sigma N(G)$ and $W_v(G)$ in Figure 4 forms an implicit 3D parametric surface $Pw(x,y,z) = 0$, consisting of points with coordinates $x = \sigma N(G)$, $y = W_v(G)$, $z = W_{vd}(G)$, where the gas factor $G$ acts as a parameter for the coordinate functions $x$, $y$ and $z$. Coordinate function $z = W_{vd}(G)$ in the range $G = 0$ - 20% is supplied in accordance with the humidity value $W_{vd}$ which was established for the test mixture during AFC measure in the absence of oil gas ($G = 0\%$). Surface $Pw(x,y,z)$ (Figure 6) is the unambiguous function in the plane $(x = \sigma N(G)$, $y = W_v(G)$) and can therefore be represented explicitly:

$$W_{vd}(G) = Fw(\sigma N(G), W_v(G))$$  \hspace{1cm} (5)

where $Fw$ is the functional transformation of measured values of the noise intensity $\sigma N$ and the water-cut value $W_v$ to the corrected humidity value $W_{vd}$, which restores the true volume value of water component in the mixture if the gas factor lies within 0 - 20%.

**Fig. 5.** Dependence of calculated volumetric water-cut $W_v$ on the noise intensity of resonator transmission losses due to the influence of free gas in the mixture with $W_{vd} = 50$, 65 and 90 vol.%, $S = 10$ g/l, $T = +30^\circ\text{C}$ at values $G = 0$, 5, 10 and 20%.

**Fig. 6.** Surface $Pw(x,y,z)$, where $x = \sigma N(G)$, $y = W_v(G)$, $z = W_{vd}(G)$.
The noise intensity \( \sigma_{N(G)} \) and calculated water-cuts \( W_v(G) \) for mixtures shown in Figure 4 were put through the correction function \( F_w \). The results are shown in Figure 7. They demonstrate high efficiency of the required water-cut value recovery in the working range of the gas factor.

A useful side effect of the described method of suppressing the influence of free gas on the readings of a water-cut meter is the ability to quantify the disturbance in the homogeneity of the working fluid flow. In the absence of free gas (a prerequisite condition), local fluctuations in the OWE water-cut values manifest themselves in the AFC of the water-cut meter in the same way as the noise created by the mixture of free gas. Therefore, the above-mentioned mathematical apparatus allows directly relating the observed noise intensity of the transmission losses with the level of "inhomogeneity". The resulting estimate is linked to a specific working device. This is her fault. However, as far as authors know, today there is no quantitative measure of flow homogeneity.

![Fig. 7. Indications of water-cut meter without correction (dotted line) and with the correction (solid line) for mixtures \( W_{0i} = 50, 65 \) and 90 vol.%, \( S = 10 \) g/l, \( T = +30^\circC \) in the diapason \( G = 0...20\% \)](image)

### 7 Conclusion

The proposed method of eliminating the impact of free gas on the water-cut measurement of a three-phase oil-water emulsion by a water-cut meter deserves a wide applications, since it allows not only to increase the accuracy of water cut measurement of a three-phase OWE, but also to reduce the requirements of its degassing at the stage of preliminary preparation. An additional useful point is the opening possibility of a quantitative assessment of the violation degree of the homogeneity of the working environment. The new scientific results obtained as a result of our studies are in good agreement with the data of various scientific studies that have been obtained by other scientists [8-19].

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