Error Correction Method of Crude Oil Moisture Content Detection Based on BP Neural Network

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Abstract. Microwave phase-shifting sensor is one of the effective means to realize on-line detection of water content in high water-cut crude oil, but its detection accuracy is easily affected by salinity. Aiming at the mineralization components (NaCl and CaCl2) existing in water-bearing crude oil, the influence of different proportion and content of dual-component mineralization on the accuracy of microwave phase-shifting crude oil water content detection sensor was studied experimentally, and the influence rule of dual-component mineralization (NaCl and CaCl2) on the accuracy of crude oil water content detection was obtained. It is difficult to establish an accurate error compensation model because the relationship between the composition and content of salinity and the measured water content is affected by many factors. Therefore, a BP neural network model for error correction is established, which reduces the detection error of microwave phase-shifting crude oil moisture sensor from 13.912% to 1.821%, and improves the detection accuracy. BP neural network prediction model is superior to multiple linear regression prediction model.

1. Introduction
At present, most oilfields in our country are in the period of medium and high water cut exploitation, and the water cut of produced crude oil is generally high. Accurate on-line detection of the water cut data of crude oil is of great significance for optimizing the production technology of oil wells and improving the production of oilfields [1]. The traditional water content detection method has been difficult to meet the actual needs of the site [2]. Microwave phase-shifting method is one of the few effective methods for on-line accurate detection of water content in high water cut crude oil. This method has the advantages of high detection accuracy, wide measurement range, and the detection results are not easily affected by oil-water morphology [3]. The experimental results show that the two-component salinity (NaCl and CaCl2) has a certain influence on the detection accuracy of the microwave phase-shifting crude oil water content sensor, and with the increase of the two-component salinity (NaCl and CaCl2) content in the oil-water mixture, the detection value of water content shows an increasing trend. The water content of crude oil is easily disturbed by many factors (such as mineralization composition, content and temperature) in the detection process, and there is
great uncertainty among each factor, which cannot be expressed by a unified formula. Therefore, it is difficult to establish an accurate error compensation model.

BP neural network is a multi-layer feedforward network trained by error back propagation. It has great advantages in error correction. It is especially suitable for dealing with the complex internal mechanism, and can deal with the physical quantity of multi-factor interference at the same time. It can achieve simultaneous fitting of multi-group curves, and the results are closer to the reality[4]. When detecting the water content of crude oil, BP neural network algorithm is used to process the data, and then the component and content of salinity are compensated to improve the detection accuracy greatly. On the basis of the hardware of microwave phase-shifting moisture content sensor, BP neural network model is added to correct the error of online moisture content detection results. Finally, by comparing with the multivariate linear regression model, it is found that the absolute error of BP neural network model in predicting water cut of crude oil is smaller and more stable.

2. Principle of microwave water content sensor for crude oil

Stay 20 the dielectric constants of water and crude oil are about 80 and 2.5 respectively, and the difference between them is obvious. Pure water and crude oil do not conduct electricity, when water contains minerals, they have conductivity. The dielectric constants of oil-water mixtures with different proportions are different. The dielectric constants of oil-water mixtures can be expressed as follows [5]:

$$\sqrt{\varepsilon} = d\sqrt{\varepsilon_1} + (1-d)\sqrt{\varepsilon_2}$$

In formula: \( \varepsilon \) - dielectric constant of mixed medium;  
\( \varepsilon_1 \) - Permittivity of water;  
\( \varepsilon_2 \) - Dielectric constant of oil;  
\( d \) - Volume percentage of water (water content) in mixed media.

When oil-water mixing with different volume fractions, the conductivity and dielectric constant of the mixed medium are also different. The propagation properties of microwave in medium are determined by the conductivity and dielectric constant of media.[6]. When the volume percentage of water in oil-water mixture medium is different, the conductivity and dielectric constant of mixture medium are different, and the phase velocity of microwave propagating in medium with different conductivity and dielectric constant is also different. According to this principle, microwave probe emits microwave signals of certain amplitude and frequency, inserts probe into medium, and tries to measure the phase change of microwave signal through scales. The water content of crude oil can be obtained at a fixed rate.[7].

The principle block diagram of the microwave crude oil moisture sensor is shown in Fig. 1. The oscillator is used for energy conversion. It can convert DC power into AC power with a certain frequency, and then input it to the directional coupler. Directional coupler is a general microwave component, which is mainly used for the separation of microwave signals, converting the AC power input by oscillator with a certain frequency into two circuits. One microwave signal passes through the amplifier to the IQ regulator, and after the filter amplifier, a set of specific frequency and phase microwave signals are obtained. The other microwave signal passes into the microwave probe. Through crude oil with different water content, the frequency and phase of the microwave signal will change due to the difference of
the conductivity and dielectric constant of the oil-water mixture. Through the amplifier and the IQ demodulator, the frequency and phase of the microwave signal will change. The last two signals are sent to the microprocessor in the ADC converter. The two signals of different phases are compared with the microprocessor, and the change of phase is converted into the change of moisture content. Finally, the detection of moisture content is displayed.

![Microwave moisture content sensor schematic](image)

**Fig. 1** Microwave moisture content sensor schematic

3. Experimental study on the influence of two-component salinity (NaCl and CaCl2) on detection accuracy

3.1. Effect mechanism of salinity on detection accuracy of microwave phase-shift crude oil moisture sensor

The total amount of various salts in salinity water is an important index for determining the chemical composition of water. It is generally expressed by the total amount of various salts in 1L water[8]. The detection accuracy of microwave phase-shifting crude oil moisture sensor is easily affected by salinity, and with the increase of salinity, the detection error increases[9]. NaCl, CaCl2, MgCl2 and Na2SO4 are the main inorganic salts and minerals dissolved in water-bearing crude oil[10]. The influence of NaCl and CaCl2 on the measured value of microwave phase-shifting sensor for detecting water content in crude oil is studied, and its influence law is obtained. This experiment mainly studies the mineralization degree of two components.

3.2. Analysis of Test Data Result

This test is aimed at two-component salinity. (NaCl and CaCl2 were calibrated during the experiment). Eight water content points (water content of oil-water mixture in the range of 0% to 100%) were calibrated as follows: (w1 = 60%, w2 = 65%, w3 = 70%, w4 = 75%, w5 = 80%, w6 = 85%, w7 = 90%, w8 = 95%) . The salinity of 21 groups (from 0% to 1%, increased by 0.05% in each group, a total of 21 groups) and five components of mixed solution (1:9, 3:7, 5:5, 7:3, 9:1 with pure sodium chloride and calcium chloride respectively). So a total of 840 sets of data were obtained. Figure 2 shows the trend chart of water content change with two-component salinity (NaCl and CaCl2). It can be seen from the graph that with the increase of two-component salinity (NaCl and CaCl2), the detection value of water content also shows an increasing trend.
Fig. 2 Variation Trend of water content with salinity

From the above test results, it can be seen that the two-component salinity in oil-water mixture (The content of NaCl and CaCl₂ has a great influence on the accuracy of microwave phase-shifting crude oil moisture sensor. With the increase of the content of NaCl and CaCl₂ in oil-water mixture, the detection value of water content increases gradually. K indicates the main trend slope (k > 0), and the detection value of water content will deviate greatly from the actual value, so the measurement results will be further calibrated. It is necessary.

4. Correction Model of Crude Oil Moisture Error Based on BP Neural Network

4.1. Establishment of sample database

The established BP neural network model contains four variables in each set of sample data: water content detection value, mineralization component and content, and water content value of calibration point. According to the requirement of neural network for preprocessing data, the data are divided into learning samples (720 groups) and detection samples (120 groups). Part of the data are listed and classified: Table 1 learning samples, Table 2 testing samples:
Table 1. Microwave phase shift method moisture content detection sensor measures neural network learning sample data pair (Part)

| Serial number | 1° | 2° | 3° | 4° | 5° | ... | 716° | 717° | 718° | 719° | 720° |
|---------------|----|----|----|----|----|-----|------|------|------|------|------|
| $\delta_1'$  | 53.7° | 58.2° | 61.2° | 68.0° | 51.0° | ... | 95.1° | 93.9° | 100° | 95.6° | 98.1° |
| $\eta'$      | 9.00° | 9.00° | 2.33° | 2.33° | 1.00° | ... | 0.11° | 0.11° | 0.11° | 0.11° | 0.11° |
| $M'$         | 0.00° | 0.00° | 0.00° | 0.05° | 0.15° | ... | 0.90° | 0.95° | 0.95° | 1.00° | 1.00° |
| $\delta_2'$  | 65.0° | 70.0° | 75.0° | 80.0° | 60.0° | ... | 90.0° | 85.0° | 95.0° | 85.0° | 90.0° |

Table: $\delta_1'$ - Water content (%), $\eta'$ - ratio of sodium chloride to calcium chloride, $M'$ - total salinity (g/l) of two components (NaCl and CaCl$_2$), $\delta_2'$ - water content (%) of calibration point.

Table 2. Microwave phase shift method Moisture content detection sensor Measured neural network detection Sample data pair

| Serial number | 1° | 2° | 3° | 4° | 5° | ... | 116° | 117° | 118° | 119° | 120° |
|---------------|----|----|----|----|----|-----|------|------|------|------|------|
| $\delta_1'$  | 51.4° | 71.3° | 72.8° | 81.7° | 64.2° | ... | 60.5° | 63.7° | 64.5° | 96.5° | 100° |
| $\eta'$      | 9.00° | 9.00° | 2.33° | 2.33° | 1.00° | ... | 0.11° | 0.11° | 0.11° | 0.11° | 0.11° |
| $M'$         | 0.00° | 0.00° | 0.00° | 0.05° | 0.15° | ... | 0.75° | 0.80° | 0.85° | 0.95° | 1.00° |
| $\delta_2'$  | 60.0° | 85.0° | 90.0° | 95.0° | 75.0° | ... | 60.0° | 65.0° | 65.0° | 90.0° | 95.0° |

Table: $\delta_1'$ - Water content (%), $\eta'$ - ratio of sodium chloride to calcium chloride, $M'$ - total salinity (g/l) of two components (NaCl and CaCl$_2$), $\delta_2'$ - water content (%) of calibration point.

Normalization of sample data: Different dimension data may affect the effect of modeling. In order to improve the effect of modeling, the experimental data are normalized first, and the normalized data are between 0 and 1, which makes the effect of data fusion more ideal. The data normalization formula is as follows:

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$  \hspace{1cm} (2)

Formula: $X$ is the original data before normalization, $X'$ is the normalized data, $X_{\min}$ and $X_{\max}$ are the minimum and maximum values before normalization.

4.2. Establishment of BP Neural Network Model

The excessive layers of BP neural network will increase unnecessary running time and slow down its convergence speed. Therefore, three layers of BP neural network are selected to correct the influence of two-component salinity (NaCl and CaCl$_2$) on the detection accuracy.
of microwave phase-shifting crude oil moisture sensor. The measured value of water content, salinity component and content are input into BP neural network to get the fitted water content value. Finally, the error is compared with the water content value of the standard point. Its structure is shown in Fig. 3.

![Figure 3](image)

**Fig. 3** Neural Network Model for Predicting Water Cut of Crude Oil

The determination of the number of hidden layers and the number of hidden layer nodes: BP neural network can be achieved as long as there is a hidden layer in most experiments. So the number of hidden layers is 1. The number of hidden layer neurons has a great influence on the accuracy and accuracy of BP neural network model. According to empirical formula:[11]

\[
h = \sqrt{0.43m + 0.12n^2 + 2.54m + 0.77n + 0.35 + 0.51}
\]

(3)

Formula: M is the number of nodes in the input layer. N is the number of nodes in the output layer. H is the number of hidden layer nodes.

Finally, the number of neurons in the hidden layer is 4, and the number of neurons in the output layer is 1, that is, the water content of the calibration point.

4.3. **BPNeural Network Training**

The input layer is the normalized values of the sample data, and the input formula of the kth input neuron in the hidden layer is as follows:

\[
F_k = \sum_{j=1}^{n} \omega_{jk} - \theta_k
\]

(4)

In the formula: \(F_k\) - The input of the kth neuron in the hidden layer;

\(\omega_{jk}\) - The connection weights between the first neuron in the input layer and the K neuron in the hidden layer;

\(\theta_k\) - Threshold of the kth neuron;

n - Number of neurons in the input layer.

The output of the hidden layer is \(k = 1, 2, 3, 4...\) and Q and Q are the number of neurons in the hidden layer.

The expression of the excitation function U is as follows:
\[ U(s) = \frac{1}{1 + e^{-s}} \]  
\[ (5) \]

The information enters the output layer through the hidden layer, and then is processed and output by the output layer through the excitation function.

The input of the y-th neuron in the output layer is \( Z_k \), and its general expression is:

\[ Z_y = \sum_{y=1}^{q} V_{kj} B_k - t_y \]  
\[ (6) \]

In the formula: \( V_{kj} \) - The connection weights between the k-th neuron in the hidden layer and the y-th neuron in the output layer.

\( t_y \) - Threshold of the y-th neuron in the output layer.

After the above process, a forward propagation is completed. When the output value is greater than the prescribed expected value, the complex nonlinear mapping relationship is fitted by repeated calculation of error back propagation. The BP neural network trains the sample data obtained from the experiment and outputs a predicted value to compare with the water content of crude oil at the standard point. If the error is within the predetermined range, the training will be terminated. On the contrary, the back propagation of the error will be carried out, and the weights and thresholds of each layer will be adjusted to continue training until the target accuracy is achieved.[12].

After the above training, the weights and thresholds of BP neural network can be obtained. The weights and thresholds are transplanted to the hardware of the microwave crude oil water content sensor to eliminate the influence of mineralization components and content, and to realize the accurate measurement of water content by the microwave crude oil water content sensor.

5. Comparison of generalization ability of BP neural network with error before and after correction
This test has a total of 840A large amount of data can train the neural network sufficiently to make the output value of predicted water content closer to the real value. The learning rate is set to 0.01, the maximum number of training is set to 500, and the training goal is set to 0.01. In the experiment, 720 groups of learning samples and 120 groups of testing samples were collected. Using MATLAB R2014a programming processing, the mean square error of BP neural network algorithm using adaptive \( \alpha \) gradient descent algorithm is smaller, which improves the detection accuracy and convergence speed of the algorithm for predicting water content of crude oil. The optimal error at 250 steps is 0.00017064, which has obvious advantages in error correction for predicting water content of crude oil.
Fig. 4 Comparison of predicted and expected water content before and after BP neural network training

Adaptive the comparison of predicted and expected water content before and after training of BP neural network based on Ir gradient descent algorithm is shown in Fig. 4. It can be seen from the figure that the expected output value (water content at calibration point) is compared with the predicted output value (water content detection value after training of BP neural network). It is found that most of the predicted output value is not far from the expected output value, and even some data basically coincide with the expected output value. It embodies the advantages of BP neural network model in error correction of crude oil water content detection. Fig. 5 shows more intuitively that the detection error of water content of crude oil is greatly reduced after BP neural network checking, and the detection error is reduced from 13.912% before checking to 1.821% after checking.

Fig. 5 Comparison of BP Neural Network Error Correction before and after
6. Comparison of error correction between multiple linear regression model and BP neural network model

6.1. Establishment of Multivariate Linear Regression Model

Multivariate linear regression is a method to determine the relationship between multiple independent variables and dependent variables by fitting, obtain the parameters of multivariate linear regression, substitute them into the original hypothesis equation, and determine the trend of dependent variables by regression equation. It is used to study the linear relationship between a dependent variable and multiple independent variables.[13]

Multivariate linear regression model is used to express the relationship between the content of two-component salinity (NaCl and CaCl$_2$) and the ratio of the two components to the measured value of microwave crude oil moisture sensor.

\[
\delta(\tau, \mu, \rho) = \alpha_0 + \alpha_1\tau + \alpha_2\mu + \alpha_3\rho + \alpha_4\tau^2 + \\
\alpha_5\mu^2 + \alpha_6\rho^2 + \alpha_7\tau\mu + \alpha_8\tau\rho + \alpha_9\mu\rho + \varepsilon
\]

(7)

In the formula: $\alpha_0 ~ \alpha_9$ - with solution coefficient;
\(\tau\) - Correction of water content;
\(\tau\) - Detection of water content;
\(\mu\) - The ratio of CaCl$_2$ to NaCl in water-bearing crude oil;
\(\rho\) - The total content of CaCl$_2$ and NaCl in water-bearing crude oil.

Using MATLAB R2014a to compile the program, the expression of the multiple linear regression model is obtained as follows:

\[
\delta = -0.5162 + 3.2702\tau - 0.4047\mu \\
+ 59.4449\rho - 1.954\tau^2 - 0.00410\mu^2 \\
- 226.235\rho^2 + 0.4926\tau\mu - 78.664\rho\tau \\
+ 1.3707\mu\rho
\]

(8)

In the case of different calibrated water content, the measured values of NaCl and CaCl$_2$ with arbitrary proportion and content are substituted into the formula (8) to compare the water content after error correction with the water content before error correction. The detection error before calibration of multivariate linear regression model is 13.912%, and after calibration of multivariate linear regression model, the detection error is 9.978%.
6.2. Error Contrast Analysis

![Graph showing error contrast analysis](image)

**Fig. 6** Absolute error comparison between neural network and multiple linear regression prediction

In order to more concretely and intuitively express the influence of the two models on the detection accuracy of the microwave phase-shifting crude oil moisture sensor when correcting the content and proportion of the two components salinity, the error values of the two models after correcting are calculated and counted, as shown in Figure 6. It can be seen that the detection error of BP neural network model is significantly smaller than that of multiple linear regression model, and BP neural network model is also better than multiple linear regression model in the stability of error detection. When the multiple linear regression model is used to detect the water content of crude oil, the error fluctuates uncertainly. If the model is used to detect the water content error of crude oil in situ, it can not fully reflect the true value of the water content of crude oil. Generally speaking, BP neural network model has better effect in correcting the detection error of microwave phase-shifting crude oil moisture sensor. It also indirectly shows that the generalization ability of BP neural network in error correction is stronger than that of multivariate linear regression because of its non-linear results.

Field water cut detection technology is developing towards digital oilfield, which has the advantages of accuracy, convenience and labor liberation. The establishment of BP neural network model for on-line detection of field data is of great significance to the detection of water content of crude oil produced in oil fields at any time and anywhere.

7. Conclusion
The composition and content of salinity have a direct impact on the detection accuracy of microwave crude oil moisture sensor. Through the analysis of experimental data, the following conclusions are drawn:

(1) Bicomponent salinity (The influence of NaCl and CaCl₂ on the microwave phase-shifting moisture content sensor is mainly reflected in that with the increase of NaCl and CaCl₂ content in oil-water mixture, the detection value of water content increases gradually. K represents the main trend slope (k > 0), and the relative error can reach 11.1%).
(2) For the microwave phase-shifting crude oil moisture sensor, the BP neural network is used to establish the mathematical model, and the adaptive Ir gradient descent algorithm is used to train the experimental data in the BP neural network to obtain the weights and thresholds that can meet the accuracy requirements. The model parameters mentioned above can be transplanted into the measuring system of the sensor controller to eliminate the influence of these interference factors and reduce the error of moisture content detection from 13.912% to 1.821%. The on-line high-precision detection of moisture content detection sensor by microwave phase-shift method can be realized.

(3) Through the generalization ability and learning ability of BP neural network, the two-component salinity (NaCl and CaCl₂) can correct the detection error of microwave phase-shifting crude oil moisture sensor under different water content, different salinity content and proportion. The uncertainty caused by multi-factor interference is solved, and the on-line detection accuracy of high water content crude oil is improved. It has certain practical value and significance.

(4) Comparing the error correction between the multiple linear regression model and BP neural network model, it is found that BP neural network model is superior to the multiple linear regression model in terms of detection accuracy, stability and generalization.

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