DOI 10.1007/s12182-012-0213-x

Flow pattern identification in oil wells by electromagnetic image logging

Liu Zaibin[1] and Wu Xiling[2]*

[1] Gas Storage Well and Advanced Technology Development & Application Division, China Special Equipment Inspection and Research Institute (CSEI), Beijing 100013, China
[2] College of Geophysics and Information Engineering, China University of Petroleum, Beijing 102249, China

Abstract: Petroleum production logging needs to determine the interpretation models first and flow pattern identification is the foundation, but traditional flow pattern identification methods have some limitations. In this paper, a new method of flow pattern identification in oil wells by electromagnetic image logging is proposed. First, the characteristics of gas-water and oil-water flow patterns in horizontal and vertical wellbores are picked up. Then, the continuous variation of the two phase flow pattern in the vertical and horizontal pipe space is discretized into continuous fluid distribution models in the pipeline section. Second, the electromagnetic flow image measurement responses of all the eight fluid distribution models are simulated and the characteristic vector of each response is analyzed in order to distinguish the fluid distribution models. Third, the time domain changes of the fluid distribution models in the pipeline section are used to identify the flow pattern. Finally, flow simulation experiments using electromagnetic flow image logging are operated and the experimental and simulated data are compared. The results show that the method can be used for flow pattern identification of actual electromagnetic image logging data.

Key words: Electromagnetic image logging, two phase flow, flow pattern identification, fluid distribution model

1 Introduction

In petroleum production logging, in order to calculate the output of crude oil or natural gas in oil or gas wells or observe the oil or gas content change in the strata, important parameters such as oil, gas and water flux, velocity and pressure drop in the pipeline need to be measured online, and these parameters are different in different multiphase flow models. The most widely used multiphase flow model is the model based on flow patterns, so the flow pattern identification is the foundation of multiphase flow research. Traditional flow pattern identification method has some limitations, and it is quite difficult to identify two-phase flow patterns accurately using the traditional method, so a new method of flow pattern identification is needed and electromagnetic image logging can play an important role. The two-phase flow patterns depend on the type of fluid combination, the flow rates and direction, and the shape, size and inclination of the conduit. In addition, heat and mass transfer rates, momentum loss, rate of back mixing and pipe vibration all vary greatly with the flow patterns. Therefore, it is necessary to identify the patterns and distinguish their correlation with the flow properties (Mahvash and Ross, 2008). Flow image logging is a method to probe the interior of multiphase flow through section measurement in a non-linear way of showing the distribution and movement of the flow in wells by scanning the region detected and applying suitable data processing. It is important for monitoring the dynamic production of vertical, inclined and horizontal wells. Electromagnetic image logging can identify mixed flow patterns based on the electrical property differences between gas, oil and water by using electrode arrays to scan the flow section. Based on previous research on the flow imaging method of electromagnetic measurement in well logging (Wu et al, 1999; 2000; 2008; Wang and Wu, 2009; Zhao and Wu, 2003; Zhao et al, 2007), the two-phase flow pattern identification method is further investigated.

2 Flow pattern transformation

2.1 Two-phase flow pattern

The most familiar two-phase flows in petroleum production are gas-water flow and oil-water flow. For the vertical wells, the basic patterns are bubbly flow, plug flow, churn flow and annular flow, and there are stratified flow and wave flow in horizontal wells (Hoogendoorn, 1959; Oshinowo and Charles, 1974; Dulder and Hubbard, 1975;

* Corresponding author. email: wuxiling@sina.com
Received June 27, 2011

Barnea et al, 1980; Spedding and Chen, 1981; Spedding and Spence, 1993; Trallero et al, 1996; Flores et al, 1997; Petalas and Aziz, 2000). The basic gas-water flow patterns are shown in Fig. 1.

Two-phase flow patterns are so complex that flow pattern identification is particularly difficult. The idea of flow pattern identification from the electromagnetic image logging is to transform the complex flow patterns to simple fluid distribution models, so the flow pattern identification is transformed to the fluid distribution model identification.

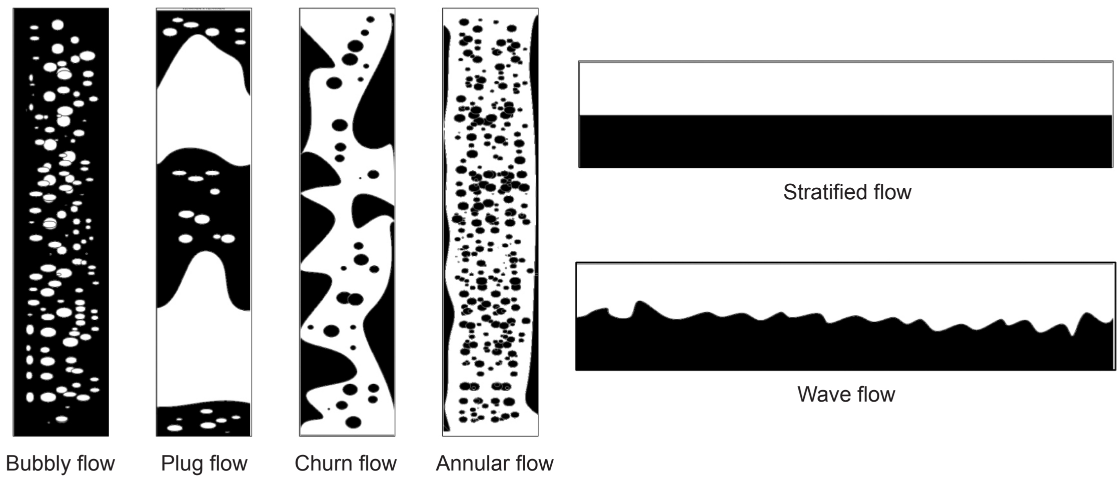


Fig. 1 Schematic diagram of gas-water flow patterns in vertical and horizontal wells

2.2 Fluid distribution model

The division of two phase flow according to the fluid flow distribution state in the pipeline space at any one moment, is a general static definition. At the same time, the flow pattern can also be considered as a continuous change of the flow distribution state in the pipeline section over time, and this is a local dynamic definition. The advantage of the latter is: first, although the flow pattern change is complicated, the distribution states of two phase flow in the pipeline section are limited to several kinds, and can generally be divided into uniform distribution, stratified distribution, core distribution and eccentric distribution; second, the fluid distribution model is based on the flowing section of oil and gas wells, which is always vertical to the well axis, namely the fluid distribution model has nothing to do with the well deflection angle, so in the flow pattern identification process, vertical or horizontal pipe flow does not need to be distinguished. The flow patterns have different characteristics, but the fluid distribution in the cross section of the flow pipe has the same pattern. Eight models are built up in a simple form, i.e. uniform distribution light (ul) and heavy (uh) fluids, stratified distribution light (sl) and heavy (sh) fluids, annular distribution light (al) and heavy (ah) fluids and eccentric distribution light (el) and heavy (eh)

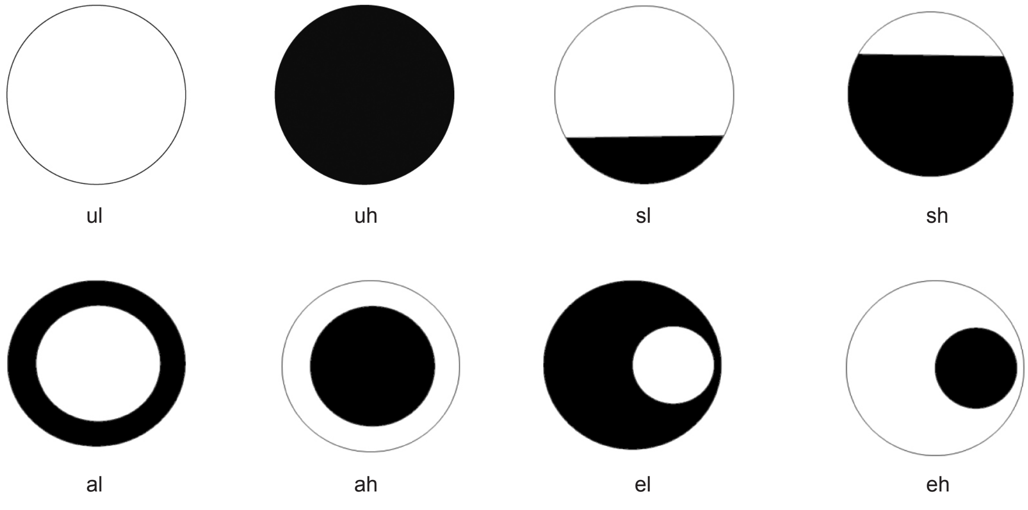


Fig. 2 Fluid distribution models. The white part means light fluid (gas and oil), and the black part means heavy fluid (water)

fluids. The sketch map of the fluid distribution models is shown in Fig. 2.

Except for the uniform models, other kinds of models can be divided into several detailed models. The stratified model is divided by the location of the layer interface and the annular and eccentric models are divided by the diameter of the inner circle. Detailed parameters of different models are shown in Table 1.

Based on the scanning measurement of the flow section, electromagnetic image logging is used to identify the fluid distribution models. To study the characteristics of different fluid distribution measured signals, the electromagnetic image logging response signals of all the eight fluid distribution models are simulated.

Table 1 Parameters of fluid distribution models

Stratified model		Annular model		Eccentric model	
Location of layer interface, mm	Corresponding water holdup	Inner circle diameter, mm	Corresponding water holdup	Inner circle diameter, mm	Corresponding water holdup
15.0	7.21%	12.0	99.0%	6.0	99.75%
25.0	15.09%	24.0	96.0%	12.0	99.0%
35.0	24.26%	36.0	91.0%	18.0	97.75%
45.0	34.25%	48.0	84.0%	24.0	96.0%
55.0	44.7%	60.0	75.0%	30.0	93.75%
60.0	50.0%	72.0	64.0%	36.0	91.0%
65.0	55.3%	84.0	51.0%	42.0	87.75%
75.0	65.75%	96.0	36.0%	48.0	84.0%
85.0	75.74%	108.0	19.0%	54.0	79.75%
95.0	84.91%	—	—	—	—
105.0	92.79%	—	—	—	—

3 Electromagnetic image logging response simulations

3.1 Mathematical principle

The basic mathematical principle of the electromagnetic image logging is the Radon transform and the Radon inverse transform, just like other image reconstruction problems. The generalized Radon transform is defined as follows: in two-dimensional space, there is a continuous bounded function $f(x, y)$ and beeline L, then the line integral of $f(x, y)$ along L

$$Rf(x,y)=\int_L f(x,y)\mathrm{d}l \tag{1}$$

is called the Radon transform of $f(x, y)$, where dl is linear micro-element for L and R is the Radon transform operator.

The Radon inverse transform formula is

$$f(x,y)=-\frac{1}{2\pi^2}\lim_{\varepsilon\to 0}\int_{\varepsilon}^{\infty}\frac{1}{q}\int_0^{2\pi}Rf_1(x\cos\theta+y\sin\theta+q,\theta)\mathrm{d}\theta\mathrm{d}q \tag{2}$$

where, $Rf_1(q,\theta)$ is the partial derivative of the Radon transform $Rf(q,\theta)$ for q.

The Radon transform and its inverse transform are defined in two-dimensional space, but electromagnetic image logging uses a three-dimensional electromagnetic sensor array and all fluids in the detecting space will affect the measurement, therefore, the Radon transform must be extended to three-dimensional space.

For n-dimensional space, the Radon transform of function $f(X)$ is

$$Rf(t,\zeta)=\int f(X)\delta(t-\zeta\cdot X)\mathrm{d}X \tag{3}$$

where $X=(x_1,x_2,\cdots,x_n)$, $t=\zeta\cdot X=\zeta_1x_1+\zeta_2x_2+\cdots+\zeta_nx_n$, $|\zeta|=1$, ζ is unit vector, and $\mathrm{d}X=\mathrm{d}x_1\mathrm{d}x_2\cdots\mathrm{d}x_n$.

As one kind of tomography, the electromagnetic image logging measurement is to achieve the process of Radon transform and image reconstruction is to achieve the process of Radon inverse transform. Numerical simulation can replace actual measurement to a certain extent, but the precondition is that the simulation model must be consistent with the actual physical status.

3.2 Sensor simulation model

Considering the practical application conditions of flow section logging, the electromagnetic image logging sensor structure is designed. Five electrode layers are set in the longitudinal direction. The second and the fourth layers are the main electrode layers for signal transmission and reception and other three layers are shielding electrodes in order to reduce three-dimensional diffusion and limit the signal in the main electrode plane. The five vertical electrodes are embedded in the insulating layer and placed in front of a moveable support arm. The 16 electrodes of every layer are arranged equidistantly in circumference. When the sensor is going down, the arm is closed to ensure the probe can go through a small space, and when measuring, the arm is open to ensure all electrodes are on the boundary circle of the flow section so that the instrument will not affect the original flow state of the fluid and the natural flow pattern would not be changed. The schematic diagrams of the three-dimensional structure and main electrode layer horizontal structure of the electromagnetic image logging sensor array are shown in Fig. 3 and Fig. 4.

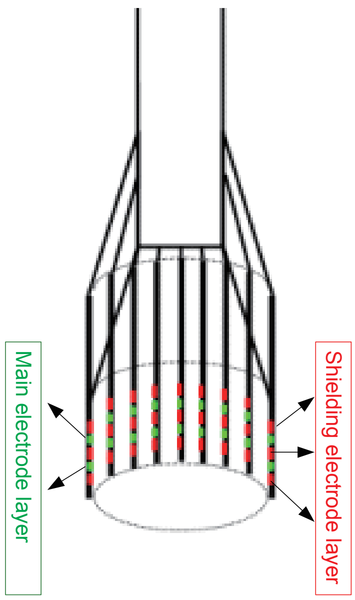


Fig. 3 Schematic diagram of three-dimensional electromagnetic sensor array

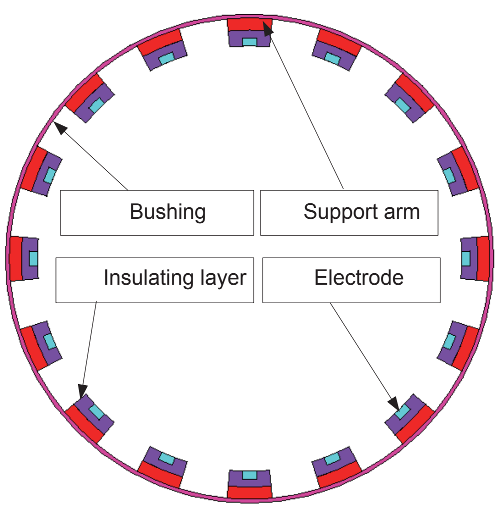
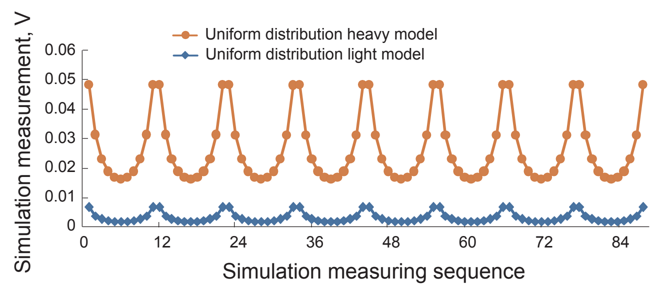


Fig. 4 Main electrode layer horizontal structure profile of the electromagnetic sensor array

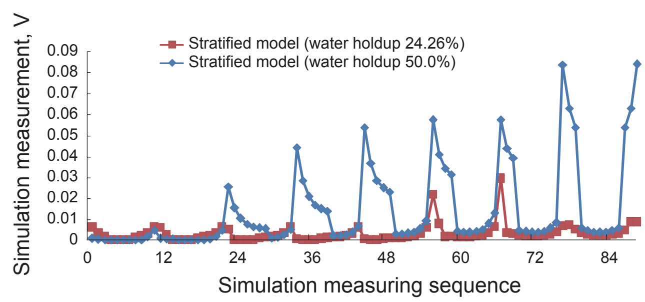
According to the physical model and typical fluid distribution models, the finite element method is used to simulate the measurement response. Both oil and gas are hydrocarbon, their conductivity is less than 10-16-10-9 S/m and their relative capacitivity is 1.0-2.5. Groundwater often contains salt ions, and its conductivity is 0.1-10 S/m, and the relative capacitivity is 56.0-81.0. In the simulation model, the conductivity of oil and gas is set as 10-10 S/m and relative capacitivity is set as 1.0. The conductivity of groundwater is set as 1 S/m and relative capacitivity is set as 80.0. The electromagnetic excitation wave frequency is set to be 3 MHz. The simulation parameters are in strict accordance with the actual physical model to ensure that the simulation results are comparable with the measured results.

3.3 Response signal analysis

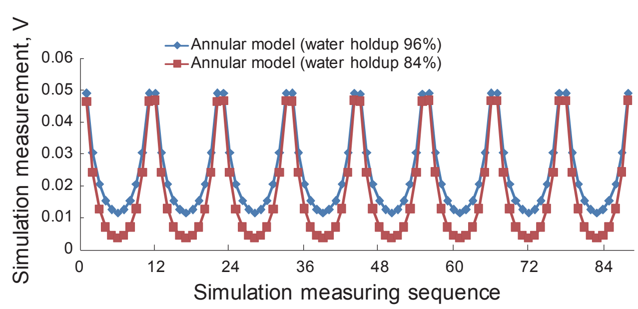
Fig. 5 shows the simulation measurement signals of the basic fluid distribution models. Different fluid distribution models correspond to different signal curve characteristics, which can be observed from the figure. The signal curve of the uniform and annular distribution models has a good



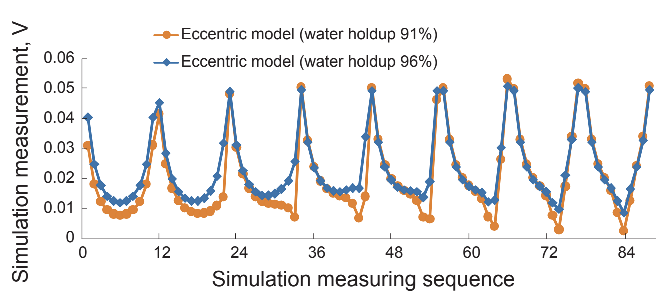
(a) Uniform model



(b) Stratified model



(c) Annular model



(d) Eccentric model

Fig. 5 Simulation measurement signals of basic fluid distribution models cyclicity, but the stratified model curve has a step change. The signal processing method is used to extract signal characteristics which is relevant with the fluid distribution models, so the models can be separated by the measurement signal characteristics.

Through simulation and analysis of different fluid distribution models, the relationship between the measurement signal characteristics and the fluid distribution models can be obtained, that is the curve shape of the measured signal depends on the fluid distribution. For different fluid distribution models, the curve shape is different. If the fluid distribution is centrosymmetric, the curve will show periodic repetition such as the "U"-type of uniform and annular models. For the same kind of distribution model, the numerical value of simulated signal mainly depends on the proportion relationship between the light and heavy phase, i.e. the water holdup. In this sensor model and measurement mode, the greater the water holdup, the smaller the measured value.

4 Flow pattern identification

4.1 Signal processing

Since the shape of the response curve is related to the fluid distribution model, different models can be identified by the characteristics of the response data. The statistical parameters of the simulation data of the eight distribution models are computed by Origin 8.0 software. We computed the mean of the 11 measurement values obtained from the same transmitting electrode, and there are 16 means in all. Then we computed the difference between the maximum and the minimum of the means, and named it as "D(V)". There are 20 parameters in all which compose the feature vector as shown in Table 2.

Table 2 The parameters computed from simulation data

Parameter name	Parameter range	Parameter name	Parameter range
Mean	0.01041-0.41145	Imin	19-171
sd	0.00133-0.14714	Max	0.02009-0.67642
se	0.00010-0.01109	Imax	13-167
CIL	0.00969-0.41125	Range	0.00390-0.67572
CIU	0.01113-0.41165	Sum	1.83206-72.41566
P25	0.00028-0.41071	Median	0.00857-0.41080
P75	0.01144-0.41125	Var	0.000002-0.02165
IQR	0.00054-0.20714	CoefVar	0.00324-0.75751
P95	0.02008-0.67641	Kurt	-1.01343-7.84884
Min	0.00008-0.41052	D	0.000007-0.29474

4.2 Fluid distribution model identification

The fluid distribution models are identified using SPSS Clementine Client 11.1 software which can choose the most suitable parameter. The test results show that any single parameter cannot distinguish all the models, so the parameter combination or substep method is considered. The parameter combination method requires repeated dichotomous classification using multiple parameters to form a rule set or decision tree, and the required parameters are automatically chosen by the software. The identification process of substep method is step by step, and one model can be identified by one parameter in each step. The flow chart of the fluid distribution model substep method is shown in Fig. 6. First, we input all the simulation data. Second, we compute the feature vectors. Third, we identify the stratified model by parameter CoefVar. Last, we identify the eccentric and annular models by parameter D. With this method, the main fluid distribution models are distinguished.

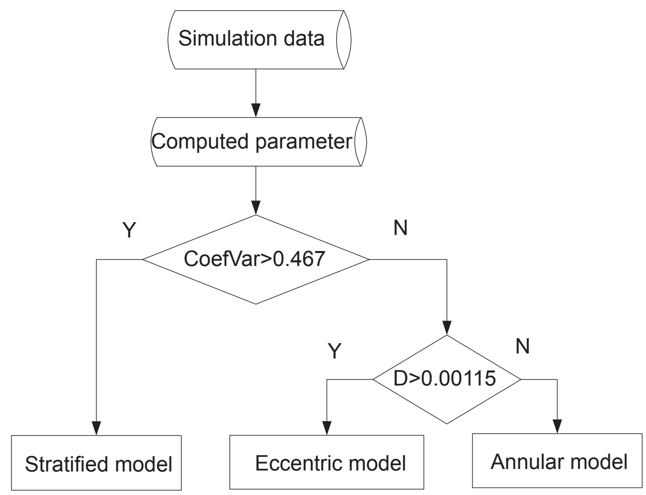


Fig. 6 Fluid distribution model identification

4.3 Basic two-phase flow pattern identification

The flow pattern identification by electromagnetic image logging is to identify the combination of fluid distribution models. We use number 1-8 to denote the eight fluid distribution models in Fig. 2, and the basic two-phase flow pattern can be expressed as a specific string of numbers as its own ID, as shown in Table 3.

Table 3 The basic two-phase flow patterns and their ID

Two-phase flow pattern	ID
Bubbly flow	…25252…
Plug flow	…25152…
Churn flow	…75757…
Annular flow	…68586…
Stratified flow	…33333…
	…44444…
Wave flow	…34343…

Notes: the number in ID means fluid distribution model. 1: ul; 2: uh; 3: sl; 4: sh; 5: al; 6: ah; 7: el; 8: eh.

For electromagnetic image logging, the detecting area is the flow section which is perpendicular to the well axis and the measurement data reflect the fluid distribution. After identification, one number can be obtained for each measurement. The measurement through the cross-section is continuous, and a series of numbers (ID) means continuous fluid distribution models, so the flow pattern is identified.

The disadvantage of this method is multiple solutions. The typical flow pattern may be expressed more than one ID and different flow patterns may have the same ID. The basic flow patterns and their ID in Table 3 are enough for actual production needs.

5 Flow pattern identification experiment

5.1 Flow simulation experiment

The electromagnetic wave propagation speed is so fast that in a measurement period the fluid is at rest relative to the sensor, so in the laboratory the fluid flow logging process can be simulated by the static distribution model experiments. Connecting a network analyzer as both an excitation and measuring device of electromagnetic waves and using a newly developed electromagnetic image logging experimental instrument, the uniform fields include all air and all water and air-water flow with different water holdup experiments are operated. 176 independent full-cycle measurements are recorded in each experiment. Air, tap water and brine are used to simulate natural gas, underground water and strata brine. The water holdup is set to be 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% from all air to all water so that the uniform and stratified models are simulated. Three experiment measurements with the water holdup of 35%, 75% and 85% are used to investigate the precision of water holdup resolution. The resistivity of the brine is 1Ω·m and the electromagnetic wave frequency is 3 MHz, the power is 10 dBm.

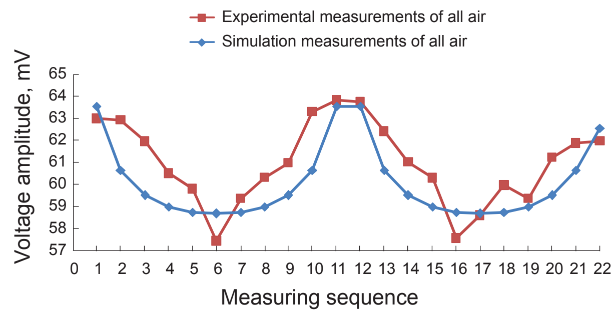
5.2 Characteristics comparison of the measurement data in a uniform field

The uniform field in this experiment means single-phase air and single-phase brine with a resistivity of 1Ω·m. The characteristics of uniform distribution experimental measurements can be used to test the accuracy of numerical simulation. As the measured signal curve of the uniform field has periodic characteristics, only 22 all air measurements of emission electrodes 1 and 2 are shown in Fig. 7 for example.

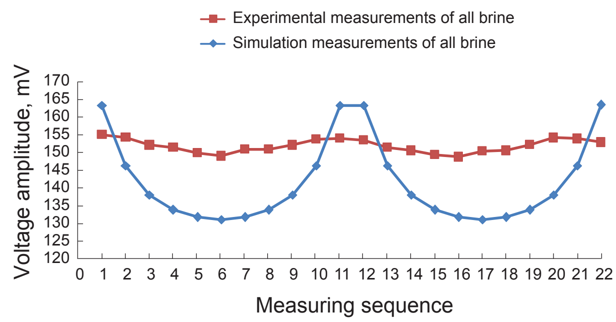
For the uniform distribution, the shape of the numerical simulation measurement curve is a continuous regular "U" and the repetitive cycle is 11. The shape of the experimental curve is a continuous irregular "V" and the repetitive cycle is also 11. As shown in Fig. 7, the measurement responses of the numerical simulation and the physical model experiment are consistent. This is because for the uniform field, the measured value is only related to the electrode location. For a certain excitation electrode, the measured value of the electrode which is furthest away from the excitation electrode is minimum, and the value of the nearest electrode is maximum.

5.3 Characteristics comparison of stratified distribution measurement data

Taking the water holdup 50% for example, we analyze the characteristics of the stratified distribution measurement data. Fig. 8 shows the contrast between the measured and simulation data of water holdup 50% stratified distribution model.



(a) Contrast between the simulation and measured data of all air field



(b) Contrast between the simulation and measured data of all brine field

Fig. 7 Contrast between the simulation and measured data of all air and all brine fields

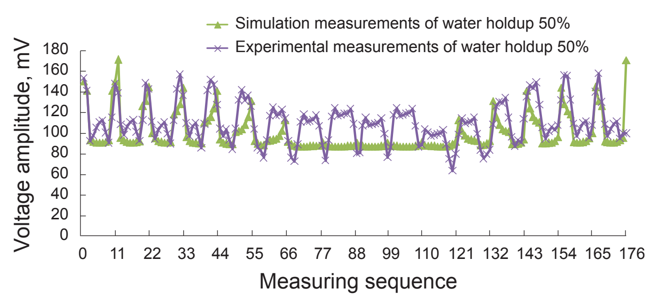


Fig. 8 Contrast between the measured and simulation data of water holdup 50%

The measurement response characteristics of stratified distribution is completely different from that of a uniform field. The measurement data of stratified flow are high and low potentials. In one measurement cycle (11 values), if the receiving electrode is in the brine, the measured voltage amplitude is relatively high but lower than all brine, and if the receiving electrode is in the air, the measured voltage amplitude is relatively low but higher than all air. The measurement value is decided by the fluid around the receiving electrode.

From the comparison of the characteristics of the uniform and stratified distribution, the numerical simulation and experimental response data have the same characteristics and change rules. Therefore, the flow pattern identification method based on simulation can be used for the actual electromagnetic image measurement data. In practical application, the relevant characteristic parameters must be amended according to the relationship between simulation and measured data of all gas and all water distribution.

5.4 Flow pattern identification method validation

The method of flow pattern identification investigated in this paper is validated with 27 groups flow simulation experiment measurement data including uniform and stratified distribution models, as shown in Table 4. Four groups identification results do not accord with the actual models (water holdup 10% and 90% respectively stratified distribution model), and the absolute error is 14.8%. Considering the original error of the experimental data is larger than the simulation data, the results are acceptable.

Table 4 Flow pattern identification method validation results

Fluid	Water holdup	Result	Consistency	Fluid	Water holdup	Result	Consistency
Air/water	0%	1	yes	Air/brine	0%	–	–
Air/water	10%	1	no	Air/brine	10%	1	no
Air/water	20%	3	yes	Air/brine	20%	3	yes
Air/water	30%	3	yes	Air/brine	30%	3	yes
Air/water	35%	3	yes	Air/brine	35%	3	yes
Air/water	40%	3	yes	Air/brine	40%	3	yes
Air/water	50%	3	yes	Air/brine	50%	4	yes
Air/water	60%	4	yes	Air/brine	60%	4	yes
Air/water	70%	4	yes	Air/brine	70%	4	yes
Air/water	75%	4	yes	Air/brine	75%	4	yes
Air/water	80%	4	yes	Air/brine	80%	4	yes
Air/water	85%	4	yes	Air/brine	85%	4	yes
Air/water	90%	2	no	Air/brine	90%	2	no
Air/water	100%	2	yes	Air/brine	100%	2	yes

Notes: Result means fluid distribution model, as shown in Table 3.

6 Conclusions

In this paper, complicated flow patterns are expressed as several combinations of simple and limited fluid distribution models, and the flow pattern identification is transformed into the model identification. With the finite element analysis method, the electromagnetic image logging responses of fluid distribution models are simulated, and the measurement response characteristics of the fluid distribution models are analyzed. The flow pattern identification is achieved using signal processing. With the network analyzer and developed electromagnetic array sensors, the gas-water two-phase flow in a horizontal pipe is measured in the experimental equipment. The comparison shows that the experimental and simulation data have the same characteristics and the method of flow pattern identification in this paper can be used to process the actual logging data.

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(Edited by Hao Jie)