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Research and implementation of a three-dimensional flow imaging algorithm for multiphase flow in horizontal well

The flow pattern is mainly composed of stratified flow in horizontal well multiphase flow, so the conventional single probe logging instrument cannot truly and completely reflect the flow state, and hold up of each phase fluid. Therefore, it is necessary to use the array probe measuring tool in horizontal well. In this paper, firstly, the characteristics of the existing foreign array probe measurement technology are compared. secondly, the wellbore and cross section are shaded using the grid and the simple inverse-distance interpolation algorithm. Thirdly, based on the data measured by SONDEX capacitance array tool and resistance array tool, a three-dimensional horizontal wellbore is drawn using VC++ 6.0 and Open GL language. Fourth, the three-dimensional fluid flow imaging module QRZ view is compiled for multiphase flow in horizontal wells. Finally, the test with the data of three simulation wells shows that QRZ view has good 3D flow imaging effect and is suitable for stratified flow in horizontal well.

Keywords: *Horizontal well, multiphase flow, flow imaging, array probe, stratified flow, holdup*

1. Introduction

The conventional single-probe production logging instrument measures fluid at the central position of a vertical wellbore. It considers the log response to the bubble flow or slug flow in the central shaft of the wellbore as the statusof the cross section of the whole shaft. However, stratified flow is common in the multiphase flow in horizontal wells [1-4]. In this case, the single probe is only immersed in one phase, and as a result, the measured information cannot reflect the actual state of fluid flow in the wellbore. This means the measurement method needs to be changed [5]. In this paper, firstly, the existing array probe measurement technologies at home and abroad are compared and analyzed; secondly, the shaft cross-section grid and the interpolation algorithm are studied using the data measured by SONDEX capacitance array tool (CAT) and resistance array tool (RAT); then, the functional design and programming of the 3D flow imaging software are implemented; and finally, the data of three simulated wells are tested, and the results show that the 3D imaging effectis good for the stratified flow.

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2. Array probe measurement technology

In the low-flow rate multiphase flow in anear horizontal well, the flow pattern is mainly composed of stratified flow as a result of gravity separation. In this case, the logging response of the conventional single-probe instrument at the central position cannot really reflect the flow state and hold up of the downhole fluid. Therefore, it is necessary to change the measurement tool to the array probe logging instrument. At present, the commercial array probe tools are mainly produced abroad, including: Schlumberger flow scanning imager (FSI) [6-9], Atlas multi capacitance flowmeter (MCFM) [10-11], and SONDEX MAPS (CAT, RAT and SAT) [12-13]. The above array probes, designed mainly based on the principles of capacitance, conductance or optics, collect the hold up informationat different positions of the wellbore through full-hole coverage to realise the hold up imaging of fluid flow distribution. At the same time, array probes of micro flowmeters are used to measure the velocity of each phase fluid at different positions of the wellbore. In this way, the velocity imaging of oil, gas and water is realised. This paper conducts studies mainly using the SONDEX MAPS measurement data.

TABLE 1 FOREIGN ARRAY PROBE TOOLS

Measuring items	FSI	MCFM	MAPS
Hold up imaging	Floview GHOST	Array capacitance probes	CAT RAT
Velocity imaging	Micro flowmeter	Multi-electrodearray with cross correlation method	SAT

3. Cross-section grid and interpolation algorithm

In the multiphase flow in a horizontal well, CAT and RAT probes are used to acquire data samples. 12 electrical or resistance probes from CAT or RAT are evenly distributed around the wellbore. Each probe only responds to the fluid information nearby. In order to obtain the parameters of the fluid at an untested position in the middle of the wellbore, the cross-section of the wellbore is required to be gridded, appropriate interpolation should be performed based on the values measured by 12 probes [14-16], and then the 3D fluid flow imaging is realized by computer programming.

3.1 Gridding of wellbore cross-section

Interpolation method is the process of data source diffusion in discrete geometric structure. Because the interpolation method is based on the geometry, it is necessary to discretize the wellbore cross-section. Triangle subdivision can solve the two dimensional problem, and the triangle unit with three nodes is the simplest and often used. Therefore, the triangle unit combination is the easiest way to approach any geometrical shape. As shown in Fig.1, 12 probes of CAT or RAT are uniformly distributed on the wellbore cross-section in a circle. So in this study, the cross section grid is composed of 13 concentric circles equal difference between adjacent radiuses, and the concentric circles are composed of small triangles. Compared to the Delaunay triangulation grid adopted by other researchers, the concentric triangle subdivision grid used here has two advantages: (1) few nodes, which can significantly improve the efficiency of computer drawing; (2) simple formula, which can be easily implemented on the computer, with good effect.

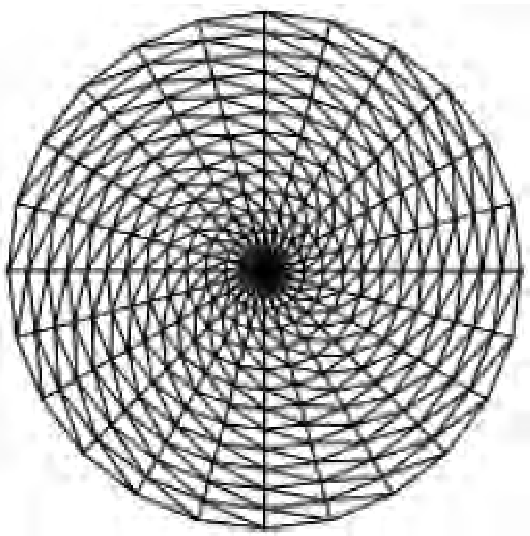

Fig.1 The cConcentric triangle mesh grid subdivision

3.2 Interpolation algorithm

When CAT or RAT is used to carry out flow imaging, in essence, it is the process of reasonably estimating the response values at each unmeasured point in the wellbore cross-section by using 12 probes. Due to the low flow rate in the horizontal well, the flow pattern mainly consists of stratified flow. Therefore, in this paper, the simple inverse-distance interpolation algorithmis used [17].

It is assumed that the continuous change of local hold up in the wellbore cross-section is reasonable, and the correlation between points decreases continuously as the distance increases. In this case, a simple inverse distance weighted interpolation algorithm can be used, considering that the effects of the source value on other points decrease as the distance increases.

Let $P_i(x_i, y_i)$ be the coordinate of a point in the cross-section of the wellbore, D_i be the reciprocal of the distance from the i-*th* probe of CAT or RAT to the unmeasured point $P_i(x_i, y_i)$, and T_i be the response value of the i-*th* probe of CAT or RAT (i = 1, 2, 3... 12) [18-21]. Thus, W_k is the predicted value of the well response at the unmeasured point $P_i(x_i, y_i)$.

$$W_k = \sum_{i=1}^{12} D_{k,i} \cdot T_i \qquad \text{... 1}$$

Under the given weight calculation method and the well bore cross-section grid system, any interpolation algorithm corresponds to an interpolation matrix *I*.

$$I = \begin{bmatrix} D_{1,1} & D_{2,1} & ... & D_{12,1} \\ D_{1,2} & D_{2,2} & ... & D_{12,2} \\ .... & ... & ... & .. \\ D_{1,289} & D_{2,289} & ... & D_{12,289} \end{bmatrix} \qquad \text{... 2}$$

Since the triangular grid system used has 289 points, the matrix *I* has 289 rows and 12 columns. In the matrix, $D_{i,j}$ is the weight of the contribution from i-*th* probe to the j-*th* grid node. In the simple inverse distance weighted interpolation algorithm, $D_{k,i}$ is expressed as follows:

$$D_{k,i} = \frac{1}{\sqrt{\sum_l (x_l - y_l)^2}} \qquad \text{... 3}$$

At the same time, in order to achieve unbiased interpolation, that is, conservative interpolation, the sum of each row in matrix *I* must be 1.

3.3 Holdup calculation method

The CAT or RAT probes record the normalized value (NV), which needs to be converted to the raw response value (RAW). And then, the hold up of each phase is calculated using the linear or non-linear relation method in combination with the calibrated values of oil, gas and water.

If the normalized value of the i-*th* probe is NV<0.2, the raw response is

$$RAW_i = CV_{gas} - \frac{NV_i \times (CV_{gas} - CV_{oil})}{0.2} \qquad \text{... 4}$$

If the normalized value of the i-*th* probe is NV>0.2, the raw response is

$$RAW_i = CV_{oil} - \frac{(NV_i - 0.2) \times (CV_{oil} - CV_{water})}{0.8} \qquad \text{... 5}$$

As with the conventional center-measuring capacitance water meter, it is assumed that the raw response RAW of the CAT or RAT probe is linearly proportional to the water hold up. Thus, the local water hold up measured by the i-*th* probe measured is

$$Y_{wi} = \frac{RAW_i - CV_{oil}}{CV_{water} - CV_{oil}} \qquad \text{... 6}$$

The local water hold up measured by 12 probes is used to determine the water hold up of the cross-section at a certain logging depth, but the low regimes of fluid are different, so the calculation methods should be different.

If the fluid (oil, gas and water) in the wellbore is well mixed, then the arithmetic average of the values measured by 12 probes can be taken as the water hold up of the cross section.

$$Y_w = \frac{\sum_{i=1}^{12} Y_{wi}}{12} \qquad \text{... 7}$$

If the fluid (oil, gas and water) in the wellbore flows in a stratified flow, the stratified flow hold up model and the weighted interpolation algorithm should be used to calculate the water hold up of the cross section.

$$Y_w = \frac{\sum_{i=1}^{12} A_i Y_{wi}}{\sum_{i=1}^{12} A_i} \qquad \text{... 8}$$

where, RAW_i is the raw response value of the i-*th* probe; NV_i is the normalized value recorded by the i-*th* probe; CV_{oil}, CV_{gas} and CV_{water} are the calibrated values of the probe in oil, gas and water, respectively; Y_{wi} is the local water hold up of the i-*th* probe; and A_i is the projected area of the i-*th* probe.

4. Three-dimensional flow imaging software

Based on the above gridding method and interpolation algorithm, the 3D flow imaging software (QRZ view) for oil-gas-water flow in horizontal wells is designed successfully using the visual C++ language and open GL technology [22-23]. The software design flow chart is shown in Fig.2.

4.1 Software start up interface

The software start up interface is shown in Fig.3. The data on the well shaft are the normalized values (NVs) of CAT or RAT probes, STDEP represents the starting depth, ENDEP denotes the ending depth, RLEV represents the log interval, and depth indicates the depth of the current section.

4.2 File formats supported

This software supports *.txt format file, which is converted from *.las file by forward or CIF log log software platform. And the data file header includes the starting depth, ending depth, and logging interval. The file header ends with the "END" string, followed by the curve name, and then the data of the curve.

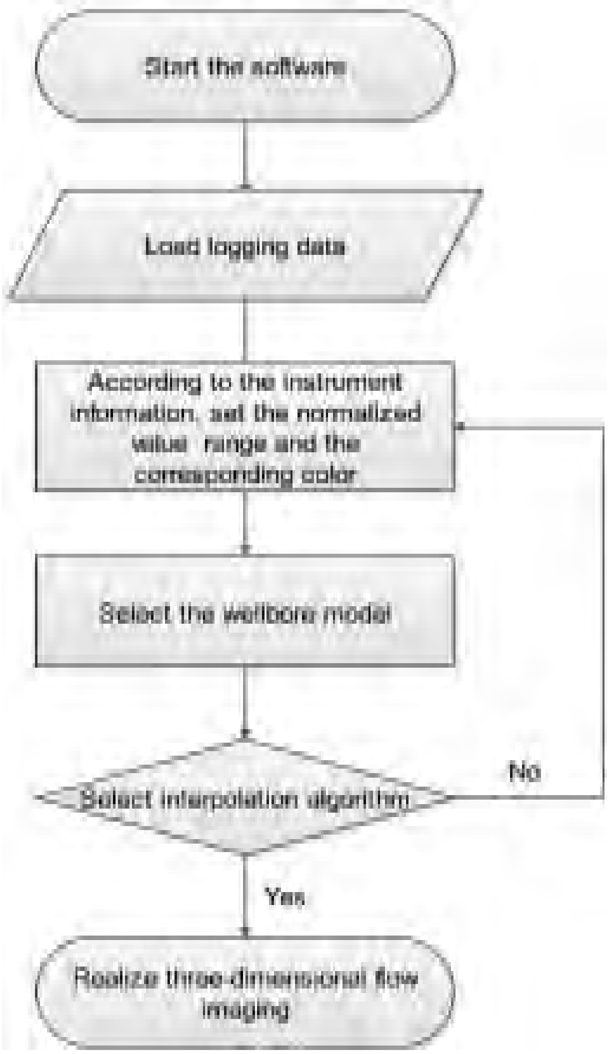

Fig.2 Software design flow chart

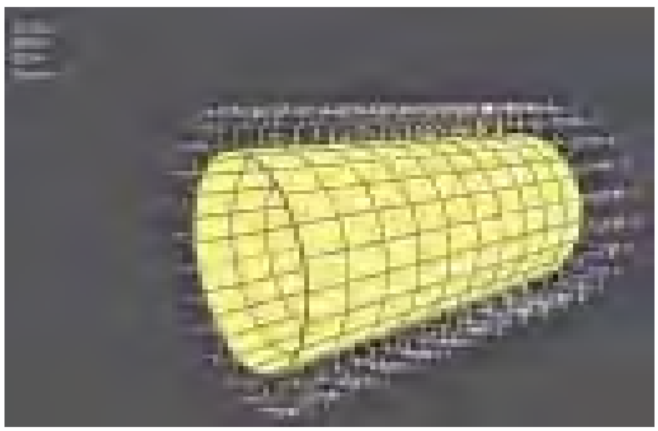

Fig.3 Software interface

4.3 Basic functions

As shown in Figs.5-9, the basic functions of the software include: firstly, allowing the user to customize the range of the hold up rate and the corresponding colour; secondly, allowing the user to change the wellbore model, such as

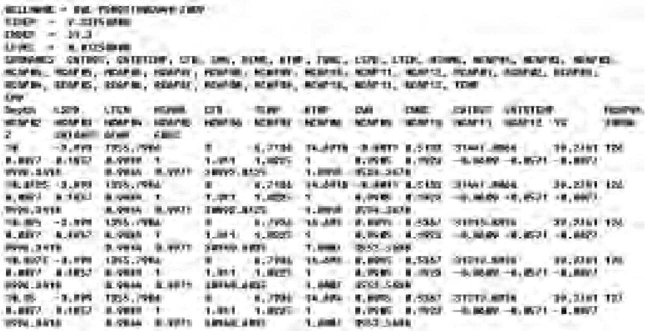

Fig.4 File formats supported

Fig.5 Dialog box of colour settings

Fig.6 Hollow wellbore

hollow wellbore, non-meshed wellbore, solid cross-section wellbore and meshed section wellbore; thirdly, allowing the user to rotate the wellbore in any direction with a mouse (there is a mouse control along the X and Y axes, and the slider on the Z axis is controlled by the slider control in the dialog box); and fourth, pause and play functions in animation settings.

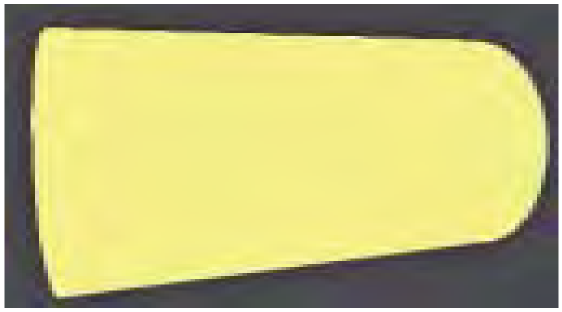

Fig.7 Wellbore without grid

Fig.8 Solid wellbore

Fig.9 Wellbore withgridded section

5. Example validation and analysis

The photograph was obtained from the multiphase flow simulation laboratory of CNPC Xibu Drilling Engineering Company Limited, and compared to the results of the 3D flow imaging software. The pipe in the simulation test was 16m long, with an inner diameter of 0.124m. The test medium was diesel oil (red), tap water (yellow or blue) and air (white). This author applied the flow pattern classification standards from Trallero (1997) for oil-water two-phase flow and Keskin (2007) for oil-gas-water three-phase flow in horizontal pipe [24-25]. And then, the author tested the three types of flow patterns, namely oil-water two-phase stratified flow (ST) in the horizontal well and the oil-gas-water three-phase stratified-stratified (ST-ST) flow and intermittent-stratified (IN-ST) flow in the horizontal well.

5.1 Oil-water two-phase stratified flow (ST) in the horizontal well

Fig.10 shows the comparison between the actual test photograph and the QRZ view images of theoil-water two-phase flow in the horizontal well. At this time, the pipe deviation angle is 0 degree, the total flow rate of oil and water is 100m^3/d, the water cut is 40%, and the measuring velocity is 20m/min. It can be seen from the figure that the images of QRZ view are consistent with the actual photo when the oil-water two-phase flow is stratified (ST).

(a) Real photograph from the test

(b) QRZ view image from side view

(c) QRZ view image from front view

5.2 Oil-gas-water three-phase stratified-stratified (ST-ST) flow in the horizontal well

Fig.11 shows the comparison between the actual test photograph and the QRZ view images of the oil-gas-water three-phase flowin the horizontal well. At this time, the pipe deviation angle is 0 degree, gas flow rate is 100m^3/d, the total flow rate of oil and water is 50 m^3/d, the water cut is 60%, and the measuring velocity is 20m/min. It can be seen from the

Fig.10 OW-PD0QT100CW40 (ST)

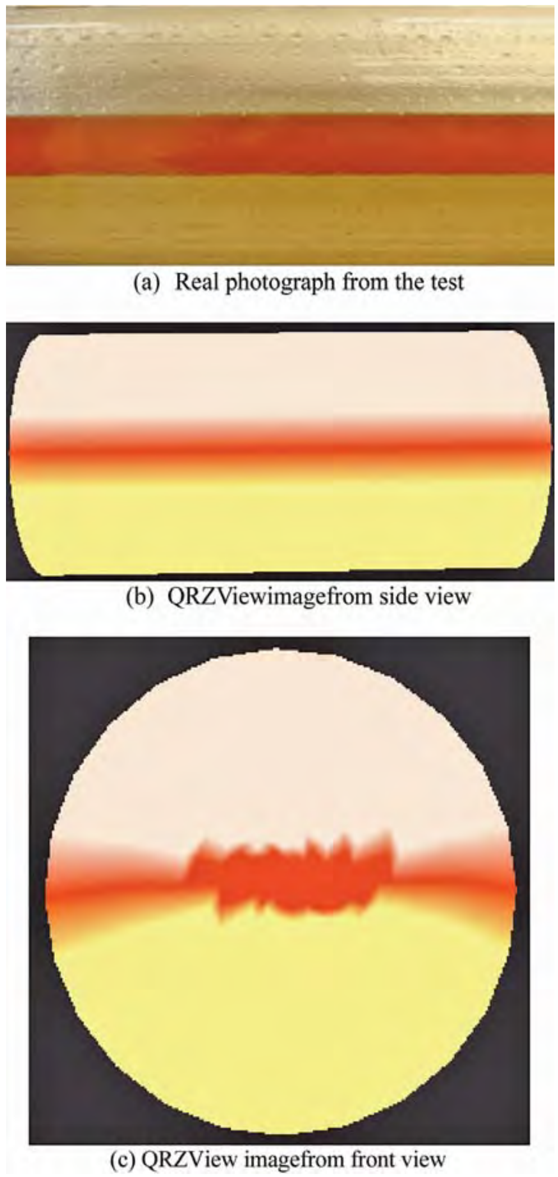

Fig.11 GOW-PD0G100QT50CW60 (ST-ST)

figure that the images of QRZ view are consistent with the actual photo when the oil-gas-water three-phase flow is stratified-stratified (ST-ST).

(a) Real photograph from the test

(b) QRZ view image from side view

(c) QRZ view image from front view

5.3 Oil-gas-water three-phase intermittent-stratified (IN-ST) flow in the horizontal well

Fig.12 shows the comparison between the actual photograph and the QRZ view images of the oil-gas-water three-phase flow in the horizontal well. At this time, the pipe deviation angle is 0 degree, gas flow rate is 500m^3/d, the total flow rate of oil and water is 300m^3/d, the water cut is 30%, and the measuring velocity is 16m/min. It can be seen from the figure that the images of QRZ view are consistent with the actual photo when the oil-gas-water three-phase flow is intermittent-stratified (IN-ST).

Fig.12 GOW-PD0G500QT300CW30 (IN-ST)

(a) Real photograph from the test

(b) QRZ view image from side view

(c) QRZ view image from front view

6. Conclusions

1. The concentric triangle gridding method is simple and practicable with Visual C++ MFC. At the same time, it has fewer nodes, highly efficient computer graphics and good imaging results.
2. The simple inverse distance interpolation algorithm is simple and practicable, and in the case of stratified flow, the imaging results are good.
3. QRZ view can realizethe basic 3D imaging of two-phase flow and three-phase flow in horizontal wells, which is suitable for stratified flow and has certain application value.

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