Research on an Lost Circulation Zone Location Method Based on Transient Pressure Wave

Ruida Zhang, Zhongxi Zhu,* Chaofei Wang, and Zhigang Guan

ABSTRACT: Accurately identifying the location of loss zone after lost circulation is the key to subsequent plugging operation. In view of the difficulty of identifying the location of lost circulation zone, a method of identifying the location of loss zone by transient pressure wave signal is proposed. When lost circulation occurs, transient back pressure is applied to the wellhead at the surface choke manifold to produce transient pressure wave. The transient pressure wave propagates downward from the wellhead. The propagation process of transient pressure wave in an annulus system is analyzed, and the position of loss zone is determined according to the change of pressure signal at the choke manifold. Based on the simulation of this method, relevant experiments are also carried out. Aiming at the problem of excessive noise of the pressure wave signal collected in the experiment, variational modal decomposition (VMD) is used to decompose the signal into multiple band-limited intrinsic mode function (BIMF) components. Combined with a Hilbert spectrum, the time–frequency characteristics and energy distribution of each BIMF component are analyzed in turn. The main frequency component is selected to reconstruct the signal to achieve the denoising effect. On this basis, a wavelet modulus maxima method is used to decompose the denoised signal, extract the characteristic points of the signal, identify the loss circulation information in the signal, and then identify the thief zone position by a time–domain method. Through experimental verification, the existence of loss zone will affect the change trend of pressure wave; a VMD−wavelet modulus maxima algorithm can effectively remove the noise of the pressure wave signal and locate the pressure change point. The experimental recognition error range of this method is 0.10−9.22%, which has certain guiding significance for field application.

1. INTRODUCTION

Drilling is an important way of oil and gas exploitation; with the extraction of oil and gas into complex formations, the occurrence of lost circulation cannot be avoided.1−3 Handling of a lost circulation accident is very important. The economic loss and formation pollution caused by a lost circulation accident depend on the speed and quality of handling lost circulation. In this key work, how to accurately identify the lost circulation zone location is the primary problem that drilling engineers have to face. At present, there are many methods to determine the lost circulation zone location, which can be summarized in three categories: geomechanical analysis method, machine learning prediction method, and instrument measurement method. The geomechanical analysis method includes predrilling geomechanical analysis and real-time geomechanical analysis. Its purpose is to judge the possible location of a thief zone according to the geomechanical information.4 The machine learning prediction method is a new direction rising in recent years. Its purpose is to use a machine learning model to predict lost circulation and further put forward prevention suggestions and remedial decisions for drilling engineers according to the predicted lost circulation information, such as lost circulation type and the estimated amount of lost circulation.5−9 Jiang et al. has combined the wellbore temperature transient pressure coupling model established with unscented Kalman filter10 to predict the location and the amount of lost circulation.6 Abbas et al. developed a new model using an artificial neural network (ANN)11 and a support vector machine (SVM)12 to predict the lost circulation of vertical and deviated wells.13 Sabah has used the model of decision tree,14 hybrid artificial neural network,15 and the adaptive neuro fuzzy inference system16 to quantitatively predict the lost circulation. The main purpose is to estimate the well loss and the available prevention and remedy methods.8,17 The instrument measurement method uses logging instruments such as temperature measuring instrument, pressure measuring instrument, radioactive tracer, resistivity logging instrument, and other professional instru-
ments to detect the data change characteristics of different underground positions; according to the lost circulation model established by scholars, the lost circulation position is located with the measured data.4,18,19 However, in practical application, both geomechanical analysis method and machine learning prediction method need to have a certain understanding of the developed block, that is, there are enough analysis data. The former can only provide a guidance for the judgment of lost circulation position when the geomechanical data is insufficient; the latter needs a lot of data from lost circulation wells in this block to train a good machine learning model. Moreover, these two methods only provide prediction and suggestions on the possible occurrence of lost circulation and cannot directly obtain the location of the actual lost circulation zone, so they are difficult to be popularized.20 Different from these two methods, the instrument measurement method does not need to obtain the data of the block in advance, but it only needs the data of the well itself with lost circulation to locate the actual loss location. At present, fracture diagnostic method, temperature measurement method, and radioactive tracer surveys are widely used in instrument measurement methods.21 The fracture diagnostic method needs two measurements, shallow resistivity log and deep resistivity log, and the fracture location is determined according to the difference of the data obtained from the two logs.19,21,22,23 The temperature measurement method also needs two measurements. Comparing the temperature gradient obtained from the two measurements, there will be an obvious temperature difference at the position of loss zone.21,24 A radioactive tracer survey needs to pump mud containing radioactive substances into the well, which determines the location of the leakage layer according to the concentration of radioactive substances at the thief formation.25 Several other instrument measurement methods are also introduced in Table 4. These methods are based on the instrument measurement method, which judges the location of the lost circulation layer according to the downhole data of the lost circulation well measured by the running instrument. Although these methods relying on instrument logging are more reliable, there is also an inevitable disadvantage, that is, the circulation of drilling fluid must be stopped when running instrument logging, which leads to the extension of non-production time. Is there a method to identify the lost circulation zone location without analyzing a large number of adjacent well data and stopping drilling fluid circulation? Chen proposed a new diagnostic method without stopping circulation. He established the transient temperature change model of wellbore and circulating mud in the process of lost circulation, proposed using a microchip in drilling fluid to extract oil well data under the condition of maintaining mud circulation, and judged the loss position according to his model.21,26,27

Due to the fact that the characteristics of the annulus system is uniform and vertical and is like the fluid pipeline, the problem of lost circulation identification can be solved by combining the pipeline leakage detection method. The impulse response detection method was first proposed in the pipeline leakage detection.28 The principle of this method is to use the water hammer wave generated by instantaneous valve closing to detect the leakage according to the characteristics of the collected pressure waveform.29–31 This method only needs to install a valve and a pressure sensor at the outlet of the tested equipment; the transient pressure signal amplitude is large, which makes it easy to identify.29 At present, many scholars have studied this method from the aspects of time domain,32,33 frequency domain,34–36 and signal processing.35,37,38 Ghazali et al. analyzed the pressure transient leakage signal of the water

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![Figure 1](https://pubs.acs.org/doi/10.1021/acsomega.1c04359)  
**Figure 1.** Schematic diagram of the lost circulation zone location method based on transient pressure wave. (a) Schematic diagram of the model and (b) the schematic diagram of pressure propagation in annulus during lost circulation.
supply network and analyzed the instantaneous frequency characteristics of the signal by using Hilbert transform, cepstrum,\textsuperscript{39} and other methods.\textsuperscript{36} Lee et al. used the method of valve closing to extract the system frequency response function and compared the corresponding time–domain effects of other working conditions such as friction and blockage.\textsuperscript{40} Rubio Scola et al. proposed a fault identification method that can detect blocked and leaking pipelines at the same time and verified it with an example.\textsuperscript{31} Capponi et al. analyzed the pipeline time domain and frequency domain model and proposed to improve the model effect with correction factors.\textsuperscript{42}

Bogdan et al. proposed high-frequency pressure monitoring (HFPM) for fracturing monitoring. He defined the reflection coefficient based on the increase of the effective borehole cross-sectional area in the presence of fractures and identified the downhole working conditions according to the pressure change curve collected at the wellhead.\textsuperscript{43} However, this method requires pump shutdown and pressure measurement. In this paper, a new method is proposed, which is to locate the loss zone in the drilling process without stopping the circulation of drilling fluid. This paper mainly studies four aspects: first, the transient change process of pressure wave in an annulus model with lost circulation is analyzed; then, the established model accurately locates the location of the thief point; next, experiments are carried out to collect wellhead pressure signals with different loss depths; and finally, a specific signal processing method is proposed to calculate the depth of the loss zone.

2. MATHEMATICAL MODEL

Shown in Figure 1a is the vertical well model with lost circulation. The loss zone divides the annulus system into upper and lower parts, namely, annulus 1 and annulus 2. To generate pressure wave, a valve and pressure sensor are added at the choke manifold. When the drilling fluid circulates and returns, the valve will be closed instantaneously and the transient pressure wave will be generated due to the water hammer effect.\textsuperscript{35} When the transient pressure wave propagates downward to the loss zone, it will decompose, reflect, and refract many times in the annulus system. The pressure signal reflected to the choke manifold valve contains the lost circulation information of the annulus system. The position of the lost circulation zone can be determined by analyzing the variation characteristics of the pressure wave signal.

2.1. Transient Pressure Wave Transfer Model in Annulus. Figure 1b shows the propagation process of pressure wave in annulus under the condition of lost circulation. If there is no friction in the annulus system, the water hammer pressure wave $\Delta H$ generated by valve closing will be transmitted downward from the upper part of the annulus without attenuation. When the pressure wave $\Delta H$ reaches the thief point of the loss zone, as the pressure difference inside and outside of the annulus increases, the flow at the thief point increases, $dq$. At the same time, due to the change of fluid flow, the pressure wave $\Delta H$ will be decomposed into two pressure waves, $dH$ and $\Delta H = dH$. The pressure wave $dH$ is reflected upward, and the residual pressure wave $\Delta H - dH$ continues to propagate downward and refract. In Figure 1b, $Q_0$, $g_0$, and $H_0$ are the steady-state flow, steady-state loss, and steady-state pressure of the fluid in the annulus system during circulation.

The following are assumed:

- The drill string and borehole are concentric.
- There is no friction in the annulus system.
- There are refraction and reflection coefficients in the process of pressure wave transmission.
- The shaft wall is vertical and uniform without bending and a diameter change.
- Wellbore heat transfer is not considered.
- The propagation velocity of water hammer pressure wave in the annulus remains unchanged.
- The bottom hole pressure head and the outlet head of the choke manifold connected to the outside are constant.
- The drilling fluid is incompressible and circulates at a constant rate.

The inertial water hammer pressure $\Delta H$ is generated by the instantaneous change of fluid velocity, and its relationship with the change of velocity and the propagation velocity of water hammer wave is as follows:

$$\Delta H = \frac{(\Delta V \cdot a)}{g} \quad (1)$$

where $\Delta H$ is the variation of excitation pressure, MPa, $\Delta V$ represents the flow rate change, m/s, $a$ represents the propagation velocity of water hammer wave, m/s, and $g$ represents gravitational acceleration, m/s$^2$. When the annular cross-sectional area $S$ remains unchanged, the change of annular flow $\Delta Q$ is:

$$\Delta Q = \Delta V \cdot S \quad (2)$$

According to formulas 1 and 2, the water hammer pressure can be defined by the following formula:

$$\Delta H = \frac{(\Delta Q \cdot a)}{(Sg)} \quad (3)$$

Equation 4 defines the transient pressure at the choke manifold valve, which is a linear superposition of the following four waves:

1. Each reflected and refracted wave propagating to the valve after the transient pressure wave reaches the loss zone.
2. Each reflected and refracted wave transmitted to the valve after the transient pressure wave reaches the bottom hole.
3. Each reflected and refracted wave propagating to the valve after reaching the loss zone again.
4. The wave that propagated from the bottom hole to the valve is reflected and refracted again to the valve through the bottom hole.

$$p(L, t) = H_0 + \Delta H + \Delta H \sum_{n=1}^{\infty} \beta^2 a \left( t - \frac{2nL_1}{a} \right)$$

$$+ \Delta H \sum_{n=1}^{\infty} (-1)^n a^2 \left( t - \frac{2nL_1}{a} \right)$$

$$+ \Delta H \sum_{n=1}^{\infty} (-1)^n a^2 \left( t - \frac{2n(L+L_1)}{a} \right)$$

$$+ \Delta H \sum_{n=1}^{\infty} (-1)^n a^2 \left( t - \frac{2n(L+L_1)}{a} \right) \quad (4)$$
where $\alpha$ is the step function, $L$ indicates the well depth, $m$, $L_1$ indicates the depth of the thief zone, $m$, $\alpha$ and $\beta$, respectively, represent the refractive coefficient and reflection coefficient of the pressure wave at the thief point of loss zone. In the case of $\Delta H - dH$, far less than $H_0$, $\alpha$, and $\beta$ are, respectively, 

$$
\alpha = 1 - \frac{1}{1 + 4\frac{\Delta Q}{\Delta H}}
$$

$$
\beta = \alpha - 1
$$

Defoamina of the above formula gives the following:

$$
\frac{p(L, t) - H_0}{\Delta H} = 1 + \sum_{n=1}^{\infty} \beta^n a^n \left( t - \frac{2nL_1}{a} \right)
$$

$$
+ \sum_{n=1}^{\infty} \left( -1 \right)^n \alpha^n a^n \left( t - \frac{2nL}{a} \right)
$$

$$
+ \sum_{n=1}^{\infty} \left( -1 \right)^{n+1} \alpha^n a^n \left( t - \frac{2n(L + L_1)}{a} \right)
$$

$$
+ \sum_{n=1}^{\infty} \left( -1 \right)^n \beta^n a^n \left( t - \frac{2n(L + L_1)}{a} \right)
$$

$$
$$

2.2. Simulation Analysis. The vertical well annulus system with lost circulation as shown in Figure 1b is simulated, and its parameters are shown in Table 1. The transient pressure curve of the valve at the choke manifold is obtained according to eq 7, as shown in Figures 2 and 3. Since the pressure wave is not generated instantaneously, the valve closing is divided into three processes, those are, the transient pressure change processes when the valve opening are 75, 50, and 25%, respectively. The valve closing time is set and the three processes are superimposed. Figure 2 shows the two cases of the superimposed valve closing excitation process and non-superimposed valve closing process when the depth of the loss zone is 1000 m. The change trend of the two pressure curves is basically the same, and there is an obvious sudden drop in the pressure waveform at the time, which is caused by the reflection of the pressure wave decomposed by the loss zone to the valve. Comparing the characteristics of the two waveforms at the sudden drop time, it is found that the sudden drop time of the first pressurization wave is determined by the pressure wave generated in the valve closing process. Therefore, the position of thief zone can be identified according to the characteristic information of the sudden drop in the first pressurization wave. The position of the thief zone can be determined by the pressure wave velocity $a$ and sudden drop period $\Delta t$ according to the following formula.

![Figure 2. Simulate the pressure change process of the valve at the choke manifold.](https://doi.org/10.1021/acsomega.1c04359)

![Figure 3. Pressure change trend when lost circulation occurs at different depths.](https://doi.org/10.1021/acsomega.1c04359)
\[ L_1 = a \frac{\Delta t}{2} \quad (8) \]

Figure 3 compares the change trend of transient pressure at the valve when the loss zone is located at two different positions \((L_1 \text{ and } L_2)\) and normal circulation. The pressure drop of the waveform is obvious, and the position of the pressure drop is different when lost circulation occurs at different depths. Therefore, the lost circulation zone depths \(L_1\) and \(L_2\) can be determined by eq 8 according to \(\Delta t_1, \Delta t_2\) and pressure wave velocity \(a\), which are 1000 and 2000 m underground, respectively.

3. DATA PROCESSING METHOD

Figure 4 shows the collected pressure signal. The waveform of the pressure wave is obvious and has obvious jump after excitation. Therefore, it belongs to a non-stationary and nonlinear signal. However, the signal waveform has serious burrs and contains more noise, so it is difficult to extract useful information directly. This is because the pump and other equipment interfere with the pressure sensor during the experiment, so it is necessary to denoise the collected signal.

3.1. VMD Algorithm Principle. At present, the wavelet threshold method and empirical mode decomposition (EMD)\(^{44}\) algorithm are widely used to denoise the signal, but the denoising effect of the former is greatly affected by the characteristics of the signal and the selected wavelet basis function; the latter is limited by its own mathematical method, and the decomposed signals have the phenomenon of modal aliasing.\(^{45,46}\) The variable mode decomposition algorithm (VMD)\(^{47}\) proposed by Dragomiretskiy et al. adopts the variational framework to obtain the band-limited intrinsic mode function (BIMF) based on the classical Wiener filter, which can effectively avoid the problems of mode aliasing, over envelope, boundary effect, and so on.\(^{45,47,48}\) It is more sensitive to low-frequency characteristics and is more suitable for processing the pressure wave signal with useful information contained in the low-frequency band.\(^{49,50}\) It overcomes the disadvantage that the wavelet threshold algorithm needs to select the basis function and can decompose the complex nonstationary and nonlinear signal into the sum of multiple BIMFs and a residual based on the time scale of the signal. Therefore, it is more appropriate to apply this method to process the collected pressure wave signal.

The BIMF decomposed by the VMD algorithm is defined by the following formula:

\[ u_k(t) = A_k(t) \cos(\phi_k(t)) \quad (9) \]

where \(u_k(t)\) is the modal function, \(A_k(t) \geq 0\) is the envelope function, \(\phi_k(t) \geq 0\) is a phase function, and \(\phi_k(t)\) is an increasing function. Each mode has its center frequency \(\omega_k\). On this basis, the constrained variational model needs to be solved to determine the bandwidth of each BIMF. Therefore, the following model needs to be solved:

\[
\begin{align*}
\min_{\{u_k, \omega_k\}} & \left\{ \sum_k \left| \delta(t) + \frac{j}{\pi t} \ast u_k(t) \right| e^{-j\omega_k t} \right|^2 \\
\text{s. t.} & \quad \sum_k u_k(t) = f
\end{align*}
\]

(10)

where \(u_k = \{u_1, u_2, ..., u_k\}\) represents all BIMF components that decomposed, \(\omega_k = \{\omega_1, \omega_2, ..., \omega_k\}\) represents the center frequency of these BIMFs. The quadratic penalty term \(\alpha\) is introduced and the constrained variational model is solved by the Lagrange multiplier method.

\[
L(\{u_k\}, \{\omega_k\}, \lambda) = \alpha \sum_k \left| \delta(t) + \frac{j}{\pi t} \ast u_k(t) \right| e^{-j\omega_k t} \right|^2 \\
+ \left| f(t) - \sum_k u_k(t) \right|^2 \\
+ \lambda(t, f) - \sum_k u_k(t)
\]

(11)

In eq 11, \(\alpha\) is the penalty parameter, \(\lambda\) is the Lagrange multiplier, \(\ast\) is the convolution operation, and \(< >\) is the inner product operation.

As shown in eqs 12 and 13, when solving the model, the number of decomposed BIMF \(K\) and noise tolerance \(\gamma\) can be set (because the collected pressure wave signal contains strong...
noise, so it is set as $\gamma = 0$). Also, the output accuracy is the end condition of the iterative solution of the variational model.

\[
\hat{\lambda}^{n+1}(\omega) = \hat{\lambda}^n(\omega) + f(\omega) - \sum_{k=1}^{k} \hat{\omega}_k^{n+1}(\omega) 
\]

\[\varepsilon > \sum_{k=1}^{k} (\|\hat{u}_k^{n+1} - \hat{u}_k^n\|^2 / \|\hat{u}_k^n\|^2) \]

3.2. Signal Denoising Based on Dominant Frequency Extraction. The linear superposition of the decomposed BIMF components can accurately reconstruct the original signal, but this reconstruction cannot achieve the effect of denoising.\textsuperscript{50} Therefore, the time–frequency and energy characteristics of the signal can be analyzed, and the BIMF containing the most useful information can be selected accordingly to screen out the noise component.\textsuperscript{51} The Hilbert joint spectrum can combine three signal characterization scales of time, frequency, and energy. These three scales can be displayed in a picture by MATLAB, from which the changes of signal frequency and energy with time can be analyzed intuitively.

As shown in eq 14, multiple BIMFs and an allowance were decomposed by the VMD algorithm:

\[f(t) = \sum_{j=1}^{n} c_j + r_n\]  

where $f(t)$ is the original signal, $c_j$ represents the $j$th BIMF component, and $r_n$ represents the decomposition allowance.

After Hilbert transform of the BIMF, the original signal can be expressed as:

\[H(\omega, t) = f(t) = \sum_{j=1}^{n} c_j(t) e^{j\omega_j(t)} dt\]

As shown in eq 15, the Hilbert spectrum can combine time, frequency, and energy, from which we can see the change of signal frequency and energy with time. Therefore, the BIMF can be analyzed and identified according to the Hilbert joint...
spectrum of the BIMF to extract useful signals for reconstruction and denoising.

The collected pressure wave signal is decomposed by the VMD algorithm in five layers. Figure 5 shows the Hilbert joint spectrum of each BIMF. The abscissa in the figure represents the time scale of the signal, the ordinate on the left represents the frequency scale of the signal, and the color scale diagram on the right shows the energy scale of the signal. It can be seen from the Hilbert joint spectrum that the VMD algorithm decomposes the transient pressure wave signal from high frequency to low frequency. BIMF1–BIMF4 have high frequency and the energy is always evenly distributed. Only the energy and frequency distribution of BIMF5 are concentrated at the time when the transient pressure waveform appears. Therefore, BIMF5 is selected as the main frequency component to reconstruct the signal. As shown in Figure 6, the original signal is compared with the denoised signal. It can be seen from Figure 6 that this method can filter a large amount of high-frequency noise and retain most of the characteristics of the original signal.

3.3. Wavelet Modulus Maxima Method for Locating a Signal Mutation Point. After filtering a large amount of noise, how to determine the mutation point of the pressure signal is the focus of determining the thief point of lost circulation. Wavelet transform is a signal processing method commonly used in signal analysis, which can realize the local analysis of signals in the time domain and frequency domain.\textsuperscript{32–34} It has the characteristics of multiple time windows and frequency windows and is very suitable for detecting transient abnormal signals contained in normal signals.\textsuperscript{55–57} The wavelet modulus maxima method extracts the modulus maxima of an approximate signal and detail signal decomposed by wavelet transform to locate the mutation point of signal.\textsuperscript{58} This method can effectively detect the mutation point of the signal. Its specific principle is as follows:

1) Suppose the signal $f(t)$ is mutated at $t_x$ ($t \in (0, n)$), the continuous wavelet transform is calculated for the input signal $f(t)$. For any function $f(t) \in L^2(\mathbb{R})$, its continuous wavelet transform $W_f(a, b)$ is

$$
W_f(a, b) = \langle f, \psi_{a,b} \rangle = \frac{1}{\sqrt{|a|}} \int f(t) \psi\left(\frac{t-b}{a}\right) \, dt
$$

where $\psi_{a,b}$ is a wavelet sequence, $a$ represents the expansion factor, and $b$ represents the translation factor.

2) Determine the threshold $T > 0$, and the wavelet modulus $|W_f(t)|$ of the signal $f(t)$ under the scale $s$ meets the following conditions:

$$
|W_f(t)| \geq T
$$

If $t_x$ satisfies the above conditions in multiple scales, then $t_x$ is a mutation point of signal $f(t)$ in different scales $s$.

Because the pressure wave signal belongs to a low-frequency signal, the modulus maximum of the low-frequency approximate signal after wavelet decomposition should be taken. Through comparison, it is found that when the number of wavelet decomposition level is 5, the effect of locating the signal mutation point is better. The specific steps are shown in Figure 7.

DB4 wavelet is used to decompose the denoised signal in five layers and take its modulus maximum. Figure 8 shows the decomposed approximate signal $A_5$ of the fifth layer and all detail signals $D_1–D_5$. It can be seen that the approximate signal $A_5$ can identify the signal mutation point, while the feature points in detail signals $D_1–D_5$ are located disorderly.
so it is difficult to extract useful information. Figure 9 compares the location of the mutation point identified by the denoised signal and the approximate signal A5. It can be seen that the wavelet modulus maximum method can effectively locate the sudden drop point of the first pressurization wave in the transient pressure wave signal, so as to obtain the reflection time difference $\Delta t$ of the pressure wave and realize the identification of the position of the loss zone in combination with the wave velocity $a$.

### 4. RESULTS AND DISCUSSION

According to the experimental results, the lost circulation zone location method based on transient pressure wave is verified. The established experimental wellbore is a vertical well, and the parameters are shown in Table 2. After the signal data collected in the experiment are processed by the above VMD-wavelet modulus maximum method, the reflection time difference of pressure wave $\Delta t$ in the actual signal can be analyzed. The pressure wave velocity in the annulus system is calculated according to the parameters in Table 2, and the pressure wave velocity during the experiment is set as $a = 1394$ m/s.

Combining the positioning time difference $\Delta t$ and wave velocity $a$, the position of the loss zone can be determined using eq 8. Table 3 shows the verification results of nine groups of experiments, including the actual loss position, positioning time difference, calculated loss position, and relative error. The detection effects of this method under different loss depths are compared.

#### Table 2. Experimental Equipment Parameters

| parameter                       | numerical value |
|---------------------------------|-----------------|
| casing outer diameter (mm)      | 245             |
| casing inner diameter (mm)      | 221             |
| elastic modulus of water (Pa)   | $2.2 \times 10^9$ |
| elastic modulus of steel (Pa)   | $2.06 \times 10^{11}$ |
| drill pipe outer diameter (mm)  | 127             |
| drill pipe inner diameter (mm)  | 109             |
| temperature (°C)                | 25              |
| simulated wellbore depth (m)    | 30              |

#### Table 3. Experimental Result

| actual loss depth (m) | positioning time difference (s) | calculation of loss depth (m) | Error (%) |
|-----------------------|---------------------------------|------------------------------|----------|
| 9                     | 0.0141                          | 9.83                         | 9.22     |
|                       | 0.0136                          | 9.49                         | 5.39     |
|                       | 0.0138                          | 9.62                         | 6.94     |
| 15                    | 0.0226                          | 15.75                        | 5.00     |
|                       | 0.0215                          | 14.99                        | 0.10     |
|                       | 0.0212                          | 14.78                        | 1.49     |
| 21                    | 0.0280                          | 19.52                        | 7.05     |
|                       | 0.0312                          | 21.75                        | 3.55     |
|                       | 0.0285                          | 19.86                        | 5.41     |
It can be seen from Table 3 that when the loss zone is at three depths, the difference between the loss depth located by this method and the actual loss depth is small and the error range is 0.10–9.22%, which is within the acceptable range.

As shown in Figure 10, this paper introduces the lost circulation zone location method based on transient pressure wave in two parts. The first part is the principle and simulation analysis of the method; the second part includes the experimental results show that the method has simple operation, rapid response, active excitation, and obvious waveform characteristics; for the loss zone in different depths, the calculation error of this method is small, and the thief position of the lost circulation zone can be located effectively. In conclusion, the principle of this method is feasible and has certain practical significance for field application.

Table 4 compares the characteristics of several methods for locating the thief point of the loss zone, compared with the existing methods, such as fracture diagnostic method, temperature survey and pressure transducer surveys, etc. The proposed lost circulation zone location method based on transient pressure wave does not need to stop the circulation and no logging tools are required. All instruments and operations are completed on the ground, the operation is simple, the pressure wave signal waveform is obvious, the data acquisition and analysis time is fast, and the loss cost can be reduced.

6. EXPERIMENTAL SECTION

6.1. Experimental Equipment. Figure 11 shows the schematic diagram of the experimental equipment. Three leakage valves are set on the vertical wellbore with a total height of 30 m. The three valves are located at the well depths of 9, 15, and 21 m, respectively. A valve is set at the choke manifold at the upper part of the wellbore to generate water hammer pressure wave. The model number of the high-frequency pressure sensor used in the experiment is PCB113B24. It has the advantages of fast response and wide measurement amplitude and frequency range.

6.2. Experimental Method. The experimental operation steps are as follows: inject water into the water tank and turn on the pump for circulation. After 10 min of normal circulation, open the leakage valve set on the wellbore to create lost circulation condition (only one leakage valve is opened each time, and the leakage position and amount are changed through multiple experiments). After the fluid circulation in the wellbore is stable again, record the steady-state leakage amount. The valve at the choke manifold is controlled by the main control computer; the valve is closed instantly to a certain opening and then opened quickly, and the sensor data from before valve closing excitation to the disappearance of pressure waveform is recorded.

Table 4. Characteristics of Several Loss Zone Detection Methods

| method                          | principle                                                                 | require stop circulation | additional equipment required |
|---------------------------------|---------------------------------------------------------------------------|--------------------------|-------------------------------|
| fracture diagnostic method      | Difference between deep and shallow resistivity logs in the presence of the lost zone | Y                        | logging tool                  |
| temperature survey              | Difference in the mud temperature and the formation temperature            | Y                        | temperature logging tool      |
| radioactive tracer surveys      | The concentration of the radioactive material is different at the point of loss | Y                        | radioactive material          |
| pressure transducer surveys     | Measure the differential pressure change caused by lost circulation         | Y                        | pressure transducer           |
| spinner surveys                 | The flow becomes faster at the loss zone                                    | Y                        | flowator                      |
| continuous temperature measurement | Locating loss zones with continuous temperature measurement data           | N                        | drilling microchip            |
| transient pressure wave surveys | The variation characteristics of the transient pressure wave signal in the presence of the loss zone | N                        | valve, pressure sensor        |

*Note: Y is YES and N is NO.*
Figure 11. Schematic diagram of experiment.

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C.W. and Z.G. curated the data, Z.Z. and R.Z. designed the methodology and numerical simulation and wrote the original draft, Z.G. supervised the study, and Z.Z. and R.Z. reviewed and edited the paper. All authors have read and agreed to the published version of the manuscript.

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