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ORIGINAL PAPER-PRODUCTION ENGINEERING

Transmission model of transient flow wave signal in intelligent layered water injection system

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Abstract

Fluid wave code communication is used in layered water injection intelligent monitoring system, but model of fluid transient flow wave signal transmission is still unknown. Based on the fluid energy equation of steady flow, a transmission mathematical model of fluid transient flow wave signal in intelligent layered water injection system was established. The model can accurately describe the transient flow wave transmission characteristics in the tubular string of water injection wells. The transient flow wave signals and influencing factors generated by the ground electric control valve and the downhole water distributor were studied, and the transmission mechanism of the signal in the water injection tubular string was revealed. Studies show that ground and downhole transient flow wave signals are generated by discharge changes caused by changes in the opening degree of the ground valve and the downhole water distributor. The length of the water injection tube has no effect on the downlink transmission of the wellhead signal, but has a certain influence on the uploading of the downhole signal. Numerical calculations show that the flow rate of the water injection tube has a great influence on the amplitude of the pressure signal. The larger flow rate can generate larger signal amplitude, which is beneficial to the signal transmission, signal detection and processing. It was verified by the experiments and simulations that the pressure and flow changes in the downhole and wellhead had good consistency during the transmission of transient flow waves. It is found that the greater the variation of opening degree, the greater the amplitude of transient flow wave signal, which is beneficial to the wave signal transmission. The optimal settings for the valve opening are selected as $100\% \rightleftarrows 0\%$. This study has theoretical guiding significance for the design and performance improvement of fluid wave code communication systems.

Keywords Water injection well · Layered water injection · Fluid wave code communication · Transient flow wave · Water distributor

Abbreviations

BRAN	Branch
SOUR	Source

List of symbols

A_0	The maximum flow cross-sectional area of ground valve hole (m^2)
A_1	The cross-sectional area and internal diameter of water pipeline (m^2)
A_2	The cross-sectional area at the outlet of the ground electric control valve (m^2)
A_3	The cross-sectional area of water injection tube (m^2)
A_d	The cross-sectional area of the water distributor electric control valve cavity (m^2)
A_{vi}	Flow cross-sectional area of the water distributor electric control valve hole (m^2)
A_k	The maximum flow cross-sectional area of the valve opening (m^2)
A_m	The cross-sectional area of the nozzle (m^2)
A_u	The cross-sectional area of ground valve cavity (m^2)
A_V	The flow cross-sectional area of ground valve hole (m^2)
A_w	The cross-sectional area of water distributor 1 offset pipe (m^2)
d_3	The internal diameter of water injection tube (m)

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h_1 Distance from the ground to the first injection layer, (m)
h_2 Distance between injection layers 1 and 2, (m)
g Acceleration due to gravity, (m/s^2)
k_u The ground electric control valve opening
k_{vi} Electric control valve opening
l_1 Length of ground water pipeline, (m)
p_1 Pressure of tube network, (Pa)
p_2 Pressure at the wellhead, (Pa)
p_3 Pressure at the inlet of the first layer water distributor valve, (Pa)
p_4 Reservoir pressures of the water injection layer 1, (Pa)
p_5 Pressure at the inlet of the second layer water distributor valve, (Pa)
p_6 Reservoir pressures of the water injection layer 2, (Pa)
p_{h_1} The pressure loss along the water injection tube (Pa)
p_{l_1} Pressure loss along the ground water pipeline (Pa)
p_{mi} Pressure loss of water nozzle (Pa), $i = 1, 2$
p_{w1} Local pressure loss in the ground water pipeline (Pa)
Δp_u Local pressure loss in ground electric control valve (Pa)
Δp_{vi} Local pressure loss from water distributor electric control valve (Pa), $i = 1, 2$
Q Discharge of water injection tube, (m^3/s)
$Q_{\Delta 1}$ Discharge of the water injection layer 1, (m^3/s)
$Q_{\Delta 2}$ Discharge of the water injection layer 2, (m^3/s)
Re_1 The fluid Reynolds number of the ground water pipeline
Re_2 The fluid Reynolds number of the water injection tube
v_1 Flow rate of water pipeline, (m/s)
v_2 Flow rate at the wellhead, (m/s)
v_3 Flow rate of water injection tube from the ground to the first injection layer, (m/s)
v_4 Flow rate at the inlet of the first injection layer water distributor nozzle, (m/s)
v_5 Flow rate at the outlet of the first injection layer water distributor nozzle, (m/s)
v_6 Flow rate of water injection tube between injection layers 1 and 2, (m/s)
v_7 Flow rate at the inlet of the second injection layer water distributor nozzle, (m/s)
v_8 Flow rate at the outlet of the second injection layer water distributor nozzle, (m/s)
z_1 Ground water pipeline elevation, (m)
z_2 Ground electric control valve elevation, (m)
z_3 Elevation at the inlet of the first layer water distributor valve, (m)
z_4 Elevation of the water injection layer 1, (m)
z_5 Elevation at the inlet of the second layer water distributor valve, (m)
z_6 Elevation of the water injection layer 2, (m)
λ_1 The friction coefficient of the ground water pipeline
λ_2 The friction coefficient of the water injection tube
ξ_1 Total local resistance coefficient of the ground water pipeline
ξ_u The ground electric control valve resistance coefficient
ξ_{vi} Electric control valve resistance coefficient, $i = 1, 2$
ξ_m Nozzle resistance coefficient
μ Fluid viscosity, (mPa s)
ρ Fluid density, (kg/m^3)
σ The fluid shrinkage coefficient

Introduction

Waterflooding technology is widely used to improve oil recovery efficiency in oilfields (Wu et al. 2016, 2018; Ogbeiwi et al. 2018; Ruan et al. 2021). The accurate control of the water injection rate for stratified water injection is a key issue of the water injection technology (Almeida et al. 2007; Zhang et al. 2020). Intelligent stratified water injection technology without ground mechanical operations has been gradually carried out at home and abroad (Liu et al. 2017). Reliable and efficient wireless intelligent measurement has become a core technology in the field of water injection wells. In particular, data transmission technology is the most important part in wireless intelligent measurement technology. Using acoustics to transmit data in tubular strings has been reported, but the severe water and energy losses in these systems have indirectly resulted in the insufficiency and inefficiency of these existing techniques (Che et al. 2021). There have been many applications for using transient flow transmission signals to detect pipe blockages and leaks (Xiao-Jian et al. 2002; Yuan et al. 2015; Liu et al. 2019). Using transient flow waves to transmit signals is an effective way to control water injection and provide real-time guidance and optimization for wireless intelligent measurement and regulation.

Signal transmission techniques using transient flow have been developed and demonstrated in the engineering (Cheng et al. 2018; Li et al. 2022). It's well known that the transient wave transmission signal method is simple to operate. Moreover, the technology is economically efficient and can provide timely intelligent measurement and adjustment optimization decisions (Liu et al. 2017). During the water injection process, the tubular string can be considered as a vertical hollow tube. A mechanical device is used to generate transient flow wave at the bottom of the well, and the wave signal is encoded. Then, the wave signal is transmitted by the tubular string, which is measured and decoded on the wellhead. Therefore, usage of the transient flow waves can pass the downhole measurement information to the wellhead (Qiu et al. 2022). However, the propagation mechanism of transient flow wave is complicated (Hou et al. 2021). Many scholars have studied the propagation mechanism and coding method of transient flow wave signal (Afshar and Rohani 2008; Kandil et al. 2020). However, because the signal transmission in the tubular string is affected by many factors, these influences need to be further studied for transmission mechanisms for transient flow wave signals. It is necessary to find better mathematical models to describe the transmission process and characteristics of transient flow waves. The model proposed in this paper can more accurately describe the transient flow wave transmission characteristics in the tubular string of water injection wells.

Transient flow wave characteristic is very important in long distance transportation and valve operation. Therefore, many experimental and numerical studies were conducted to prevent mistaken operation of valve switches and to ensure the safety of pipelines and pumps (Wu et al. 2015; Garg and Kumar 2020; Urbanowicz et al. 2021). Based on the different pressure transient responses, corresponding algorithms are developed and applied for blockage or leak detection (Haghighi and Shamloo 2011; Fu et al. 2021). All the studies can help to understand the transient flow wave transmission behavior. However, the water hammer response characteristics of the wellbore system are different from those in the pipeline system. Thus, experiment and numerical studies are needed to explain the transient flow wave response characteristics in the wellbore system. Wang et al. (Wang et al. 2008) studied the transient flow wave signal in the water injector, and verified the water hammer propagation model through experiments. Choi et al. (Choi and Huang 2011) conducted a comprehensive study of water hammer effects in injection wells under different design parameters and operating parameters using OLGA simulations. The transient flow wave transmission behavior is more complicated. Combining methods in both pressure and flow rate can help to better understand the transient flow wave transmission in a complex system.

In this paper, a transmission mathematical model of fluid transient flow wave signals in intelligent layered water injection system is established, and the influence of relevant parameters on the transmission of wave signals is studied. Meanwhile, the transient flow transmission characteristics of the wellbore system are sufficiently presented to accurately investigate the transient flow wave transmission in the wellbore system. Firstly, the influence of the flow rate on the transient flow wave in the water injection tubular string is analyzed by numerical calculation. Second, through simulations and experiments, the transmission characteristics of the transient flow wave signal are verified in the water injection tubular string. The transmission of the transient flow wave signal is induced by the change of flow in the injection tubular string. Third, it is verified by experiments that the pressure and flow changes in the downhole and wellhead had good consistency during the transmission of transient flow waves. Therefore, the transient flow wave signal can be selected for downhole and wellhead information transfer. This study can provide clear insights into the use of transient flow waves for intelligent measurement and regulation, and improve accurate control of downhole wireless intelligent water injection. Using this model to optimize the water injection parameters, it is conducive to improving the separate-layer water injection effect, and the more precise control of the injection rate can be achieved. Therefore, this research can improve oil recovery efficiency in oilfields.

Hydraulic model of separate-layer water injection system

Mechanical model of separate-layer water injection

As shown in Fig. 1, the water injection pipeline of a single well is divided into two parts: ground and downhole. This model has been explained in the author's paper (Li et al. 2023). The ground pipeline starts from the water distribution room and ends at the wellhead. The downhole pipeline starts from the wellhead and ends at the check valve at the bottom of the tube. The downhole pipeline

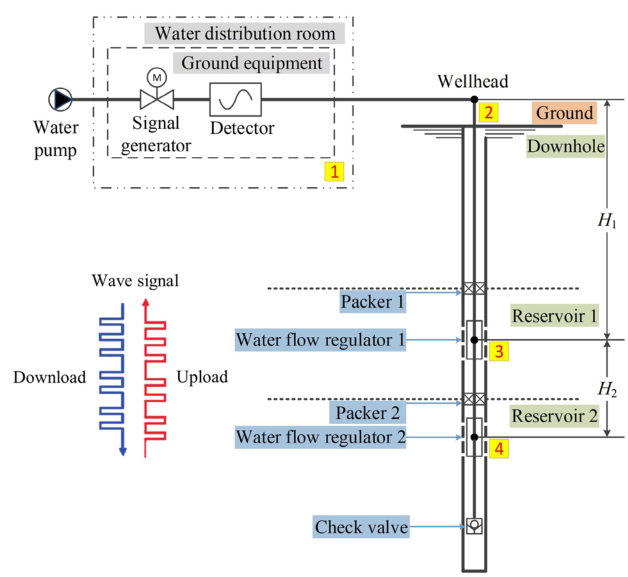

Fig. 1 Typical single well water injection pipeline structure diagram

consists of water injection tube, packer and water distributor. The packer separates each injection layer, and the water distributor realizes the communication and closure with the annulus of the oil jacket through the switch of the water nozzle, and controls the water injection rate of each layer.

In order to realize the ground control command down to the well, the ground valve makes a pulse-like change in the flow rate of the water injection tube by changing the valve opening as required by the control code. This causes a change in wellhead pressure and pressure at the inlet of the downhole distributor electric control valve, which sends a command to the distributor control circuit instructing a change in the flow rate of the water nozzle or preparing to upload downhole data. In order to upload downhole data, the water distributor control circuit controls the opening of the electric control valve to change the water nozzle flow rate according to the voltage pulse formed by the coded data. This causes a change in the flow rate of the water injection tube, which further causes a change in the pressure at the inlet of the water distributor electronic control valve and the wellhead pressure. This transmits information about the opening of each water distributor valve, pressure, and nozzle flow rate to the ground. The use of electric control valve opening to regulate the flow rate to change the wellhead and downhole pressure to achieve two-way wireless transmission of ground control commands and downhole data is called fluid wave code communication.

Based on the typical single-well water injection pipeline structure, a hydraulic theoretical model of a separate-layer water injection system with adjustable water nozzles is established, as shown in Fig. 2. The model includes two water injection layers, and each water injection layer is equipped with a throttle nozzle. The model is based on the fluid Bernoulli equation, and assumes that water is a constant flow and incompressible fluid.

Flow analysis of tubular string in two-layer water injection well

Due to the small difference in formation pressure, assume that $p_4 = p_6$. Two downhole distributors form a parallel pipeline, and the flow rate of each distributor is $Q_{\Delta 1}$ and $Q_{\Delta 2}$, respectively. When the opening of the electric control valve of a water distributor is changed, it will affect the flow of the other water distributor pipeline and cause the redistribution of pipeline flow. According to the parallel network equation of pipeline, there is $\Delta p_{v1} + p_{m1} = \Delta p_{v2} + p_{m2}$, therefore, $Q_{\Delta 2} = Q_{\Delta 1}\sqrt{\frac{\xi_{v1}}{A_d^2} + \frac{\xi_m}{A_m^2} \Big/ \frac{\xi_{v2}}{A_d^2} + \frac{\xi_m}{A_m^2}}$.

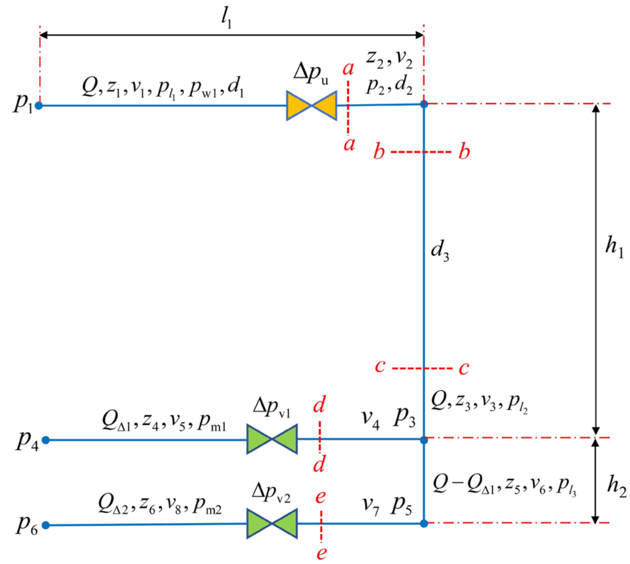

Fig. 2 Schematic diagram of the hydraulic model of separate-layer water injection

Since $\frac{\xi_{vi}}{A_d^2} \gg \frac{\xi_m}{A_m^2}$, then $\begin{cases} Q = Q_{\Delta 1} + Q_{\Delta 2} \\ Q_{\Delta 2} = Q_{\Delta 1}\sqrt{\xi_{vl}/\xi_{v2}} \end{cases}$, the flow rate of each water distributor line is presented as:

$$\begin{cases} Q_{\Delta 1} = \frac{Q}{1+\sqrt{\xi_{v1}/\xi_{v2}}} \\ Q_{\Delta 2} = \frac{Q\sqrt{\xi_{v1}/\xi_{v2}}}{1+\sqrt{\xi_{v1}/\xi_{v2}}} \end{cases} \tag{1}$$

where $i = 1, 2$. $\Delta p_{vi} = \xi_{vi}\frac{\rho Q_{\Delta i}^2}{2A_d^2}$ is local pressure loss from water distributor electric control valve. $A_d = \frac{\pi d_d^2}{4}$ is the cross-sectional area of the valve cavity, d_d is the inner diameter of the valve cavity. $\xi_{vi} = \left(\frac{A_d}{k_{vi}\sigma A_k} - 1\right)^2$ is the resistance coefficient of the electric control valve of the water distributor, $k_{vi} = \frac{A_{vi}}{A_k}$ is the electric control valve opening, A_{vi} is the flow cross-sectional area of the valve hole, A_k is the maximum flow cross-sectional area of the valve opening. $p_{mi} = \xi_m\frac{\rho Q_{\Delta i}^2}{2A_w^2}$ is pressure loss of water nozzle, $\xi_m = \left(\frac{A_w}{A_m} - 1\right)^2$ is the nozzle resistance coefficient, $A_m = \pi d_m^2/4$ is the cross-sectional area of the nozzle, d_m is the diameter of the nozzle.

The flow resistance of each water distribution pipeline is $r_i = \frac{\Delta p_{vi}+p_{mi}}{Q_{\Delta i}} = \frac{\rho Q_{\Delta i}}{2}\left(\frac{\xi_{vi}}{A_d^2} + \frac{\xi_m}{A_m^2}\right) \doteq \xi_{vi}\frac{\rho Q_{\Delta i}}{2A_d^2}$. The parallel line flow resistance is $\bar{\bar{r}} = \frac{1}{\sum_{i=1}^{2}\frac{1}{r_i}} = \frac{\rho}{2A_d^2}\frac{1}{\sum_{i=1}^{2}\frac{1}{\xi_{vi}Q_{\Delta i}}}$, then the total flow resistance of the overall piping of the water injection system is as follows:

$$r = \lambda_1 \frac{l_1}{d_1}\frac{\rho Q}{2A_1^2} + \xi_1 \frac{\rho Q}{2A_1^2} + \xi_u \frac{\rho Q}{2A_1^2} + \lambda_2 \frac{l_2}{d_3}\frac{\rho Q}{2A_3^2} + \overline{\overline{r}} \quad (2)$$

If the pressure difference between the ground water injection pipeline and the formation Δp remains unchanged, when the opening of the electric control valve of a water distributor changes, the flow resistance $\overline{\overline{r}}$ of the parallel pipeline will change, causing changes in the flow rate of the water injection tube is as follows:

$$Q = \Delta p / r \quad (3)$$

Numerical calculations show that the more the number of distributors, the smaller the impact of a change in the opening of a distributor valve on the total pipeline flow.

Transmission characteristics analysis of transient flow wave download

The model is based on the fluid Bernoulli equation (Moradi et al. 2020), and assumes that water is a constant flow and incompressible fluid. Assuming that the fluid is in a turbulent state, Bernoulli equation is established by analyzing the fluid parameters of the pipeline *a-a* profile (Fig. 2), it is written:

$$p_1 + z_1\gamma + \frac{\rho v_1^2}{2} = p_2 + z_2\gamma + \frac{\rho v_2^2}{2} + p_{l_1} + p_{w1} + \Delta p_u \quad (4)$$

where $v_1 = \frac{Q}{A_1}$, $A_1 = \frac{\pi d_1^2}{4}$, A_1 and d_1 are the cross-sectional area and internal diameter of water pipeline. $v_2 = \frac{Q}{A_2}$, $A_2 = \frac{\pi d_2^2}{4}$, A_2 and d_2 are the cross-sectional area and internal diameter at the outlet of the ground electric control valve. $p_{l_1} = \lambda_1 \frac{l_1}{d_1}\frac{\rho Q^2}{2A_1^2}$, $\lambda_1 = \frac{0.3164}{Re_1^{0.25}}$ is the resistance coefficient of the ground water pipeline, $Re_1 = \frac{4\rho Q}{\mu\pi d_1}$ is the fluid Reynolds number of the ground water pipeline (Kargarpour 2019). $p_{w1} = \xi_1 \frac{\rho Q^2}{2A_1^2}$ is local pressure loss in the ground water pipeline,ξ_1 is the total local resistance coefficient of the ground water pipeline. $\Delta p_u = \xi_u \frac{\rho Q^2}{2A_1^2}$ is local pressure loss in ground electric control valve,$\xi_u = \left(\frac{A_u}{\sigma k_u A_0} - 1\right)^2$ is the ground electric control valve resistance coefficient, $A_u = \frac{\pi d_u^2}{4}$ is the cross-sectional area of valve cavity, d_u is the valve cavity inner diameter, A_0 is maximum flow cross-sectional area of valve hole, $k_u = A_V/A_0$ is the electric control valve opening, A_V is the flow cross-sectional area of valve hole. $\sigma = 0.63$ is the fluid shrinkage coefficient. Since $z_1 \doteq z_2$, then Eq. (4) can be converted to:

$$p_2 = p_1 + \frac{\rho Q^2}{2A_1^2} - \frac{\rho Q^2}{2A_2^2} - \lambda_1 \frac{l_1}{d_1}\frac{\rho Q^2}{2A_1^2} - \xi_1 \frac{\rho Q^2}{2A_1^2} - \xi_u \frac{\rho Q^2}{2A_1^2} \quad (5)$$

The ground valve opening affects the injection tube flow rate. When the electric control valve increases from one opening to another, the injection tube flow rate increases from Q_1 to Q_2, and the flow rate change at the ground valve outlet is as follows:

$$\Delta Q = Q_2 - Q_1 \quad (6)$$

The pressure change (signal amplitude) at the outlet of the ground valve is as follows:

$$\Delta p_2 = \frac{\rho Q_1^2}{2A_1^2}\left[\lambda_1 \frac{l_1}{d_1} - 1 + \left(\frac{d_1}{d_2}\right)^4 + \xi_1 + \xi_{u1}\right] - \frac{\rho Q_2^2}{2A_1^2}\left[\lambda_1 \frac{l_1}{d_1} - 1 + \left(\frac{d_1}{d_2}\right)^4 + \xi_1 + \xi_{u2}\right] \quad (7)$$

Equation (7) illustrates that the change in flow rate caused by a change in the opening of the ground electric control valve generates the wellhead pressure signal.

It is assumed that the fluid in each water distributor is in turbulent flow. By analyzing the fluid parameters in the *c–c* profile of the water injection tube (Fig. 2), the Bernoulli equation Eq. (8) from the ground to the inlet of the electric control valve of the downhole distributor 1 is established, it is written:

$$p_2 + z_2\gamma + \frac{\rho v_3^2}{2} = p_3 + z_3\gamma + \frac{\rho v_4^2}{2} + p_{h_1} \quad (8)$$

where $v_3 = Q/A_3$, $A_3 = \pi d_3^2/4$, A_3 and d_3 are the cross-sectional area and internal diameter of water injection tube. $v_4 = Q_{\Delta 1}/A_w$ is the water distributor 1 offset pipe flow rate, A_w is the cross-sectional area of water distributor 1 offset pipe. d_w is the offset pipe diameter. $p_{h_1} = \lambda_2 \frac{h_1}{d_3}\frac{\rho Q^2}{2A_3^2}$ is the pressure loss along the water injection tube, $\lambda_2 = \frac{0.3164}{Re_2^{0.25}}$ is the friction coefficient of the water injection tube, $Re_2 = \frac{4\rho Q}{\mu\pi d_3}$ is the Reynolds number of the fluid in the water injection tube.

It is assumed that the vertical depth of the well is $h_1 = z_2 - z_3$. Since the number of distributors is 2, according to the distribution of the flow rate of each distributor line, the discharge of the first layer is $Q_{\Delta 1} = \frac{Q}{1+\sqrt{\xi_{v1}/\xi_{v2}}}$, thus:

$$p_3 = p_2 + h\gamma + \frac{\rho Q^2}{2A_3^2} - \frac{\rho Q^2}{2\left(1 + \sqrt{\xi_{v1}/\xi_{v2}}\right)^2 A_w^2} - \lambda_2 \frac{l_2}{d_3}\frac{\rho Q^2}{2A_3^2} \quad (9)$$

When the ground valve opening increases, according to the theory of conservation of mass, the flow rate of the injection tube increases from Q_1 to Q_2. The flow rate at the outlet of the ground valve changes to $\Delta Q = Q_2 - Q_1$, causing the flow rate change (signal amplitude) at the inlet of the downhole water distributor electric control valve to be:

$$\Delta Q_{\Delta 1} = \frac{Q_2 - Q_1}{1 + \sqrt{\xi_{v1}/\xi_{v2}}} \tag{10}$$

The pressure at the outlet of the ground valve increases from p_{21} to p_{22} with a pressure change of $\Delta p_2 = p_{22} - p_{21}$, causing the pressure change (signal amplitude) at the inlet of the downhole distributor electric control valve to be:

$$\Delta \overline{p}_3 = \Delta p_2 - \left(\frac{\lambda_2 h_1}{d_3} + \frac{A_3^2}{\left(1 + \sqrt{\xi_{v1}/\xi_{v2}}\right)^2 A_w^2} - 1 \right) \frac{\rho}{2A_3^2}\left(Q_2^2 - Q_1^2\right) \tag{11}$$

Equation (11) illustrates that the change of the opening of the ground valve causes the change of the flow rate of the water injection tube, which further induces the generation of downhole pressure signal. This can be seen as a transmission of the signal. The transfer function of the signal download can be written:

$$T_1 = \left| \frac{\Delta \overline{p}_3}{\Delta p_2} \right| = 1 - \frac{\left[\frac{\lambda_2 l_2}{d_3} + \frac{A_3^2}{\left(1+\sqrt{\xi_{v1}/\xi_{v2}}\right)^2 A_w^2} - 1 \right] \frac{A_1^2}{A_3^2}\left(Q_2^2 - Q_1^2\right)}{Q_1^2\left[\lambda_1 \frac{l_1}{d_1} - 1 + \left(\frac{d_1}{d_2}\right)^4 + \xi_1 + \xi_{ul}\right] - Q_2^2\left[\lambda_1 \frac{l_1}{d_1} - 1 + \left(\frac{d_1}{d_2}\right)^4 + \xi_1 + \xi_{u2}\right]} \tag{12}$$

Transmission characteristics analysis of transient flow wave upload

Assuming that the fluid is in a turbulent state, the Bernoulli equation is established by analyzing the fluid parameters of the first layer *d-d* profile (Fig. 2), it is written:

$$p_3 + z_3\gamma + \frac{\rho v_4^2}{2} = p_4 + z_4\gamma + \frac{\rho v_5^2}{2} + \Delta p_{vi} + p_{mi} \tag{13}$$

where $v_5 = Q_{\Delta i}/A_m$ is the nozzle flow rate. Since $z_3 \doteq z_4$, so,

$$p_3 = p_4 + \frac{\rho Q_{\Delta i}^2}{2A_m^2} - \frac{\rho Q_{\Delta i}^2}{2A_w^2} + \xi_{vi}\frac{\rho Q_{\Delta i}^2}{2A_d^2} + \xi_m \frac{\rho Q_{\Delta i}^2}{2A_w^2} \tag{14}$$

Assume that the formation pressure is constant, the ground electric control valve is fully open. The electric control valve opening of water distributor 1 is changed, and the opening of the electric control valve of another water distributor remains unchanged. When the opening of water distributor 1 is reduced, the resistance coefficient of the electric control valve goes from $\xi_{v11} \to \xi_{v12}$, and the flow rate of the nozzle of this water distributor goes from $Q_{\Delta 11} \to Q_{\Delta 12}$. The flow rate change (signal amplitude) generated at the inlet of the electric control valve of downhole water distributor 1 is as follows:

$$\Delta Q_{\Delta 1} = Q_{\Delta 11} - Q_{\Delta 12} \tag{15}$$

The pressure difference (signal amplitude) generated at the inlet of the electric control valve of downhole water distributor 1 is as follows:

$$\Delta p_3 = \frac{\rho Q_{\Delta 12}^2}{2}\left(\frac{1}{A_m^2} - \frac{1}{A_w^2} + \frac{\xi_{v12}}{A_d^2} + \frac{\xi_m}{A_w^2} \right) - \frac{\rho Q_{\Delta 11}^2}{2}\left(\frac{1}{A_m^2} - \frac{1}{A_w^2} + \frac{\xi_{v11}}{A_d^2} + \frac{\xi_m}{A_w^2} \right) \tag{16}$$

where $Q_{\Delta 11} = Q_1/2$ is the water nozzle flow rate before the change in the opening of the electric control valve of water distributor 1, $Q_1 = Q_{max}$ is the flow rate of the water injection tube before the change in the opening of distributor 1. $Q_{\Delta 12} = Q_2 \Big/ \left(1 + \sqrt{\xi_{v12}/\xi_{v2}}\right)$ is the water nozzle flow rate after the change in the opening of the electric control valve of water distributor 1. Q_2 is the flow rate of the water injection tube after the change in the opening of water distributor 1, expressed as:

$$\frac{Q_2}{Q_{max}} = \sqrt{\frac{\left[\frac{\lambda_1 l_1}{d_1} + \xi_1 + \xi_u + \frac{\lambda_2 h_1}{d_3}\left(\frac{d_1}{d_3}\right)^4 + \frac{\xi_{v11}}{n^2}\left(\frac{d_1}{d_w}\right)^4\right]}{\left\{\frac{\lambda_1 l_1}{d_1} + \xi_1 + \xi_u + \frac{\lambda_2 h_1}{d_3}\left(\frac{d_1}{d_3}\right)^4 + \frac{\xi_{v12}\left(\frac{d_1}{d_w}\right)^4}{\left[1+(n-1)\sqrt{\frac{\xi_{v12}}{\xi_{v2}}}\right]\left(1+\sqrt{\frac{\xi_{v12}}{\xi_{v2}}}\right)}\right\}}} \tag{17}$$

where ξ_{v1} is the resistance coefficient of the electric control valve of water distributor 1, ξ_{v11} is the resistance coefficient of the electric control valve of water distributor 1 before the change of opening degree, ξ_{v12} is the resistance coefficient of the electric control valve of water distributor 1 after the change of opening degree. ξ_{v1}, ξ_{v2} are the resistance coefficients of the electric control valves of water distributors 1 and 2, and $\xi_{v11} = \xi_{v2}$.

Therefore, the flow rate change of the injection tube caused by the change in the nozzle opening is as follows:

$$\Delta Q = Q_{\Delta 12}\left(1 + \sqrt{\frac{\xi_{v12}}{\xi_{v2}}}\right) - 2Q_{\Delta 11} \tag{18}$$

Assuming that the ground electric control valve is fully open, only the electric control valve opening of distributor 1 is changed, and another water distributor has the same initial opening as water distributor 1; by analyzing the fluid parameters in the *b*-*b* section of the pipeline (Fig. 2), the Bernoulli equation at the wellhead of the injection well to the formation is established as follows:

$$p_2 + z_2\gamma + \frac{\rho v_3^2}{2} = p_4 + z_4\gamma + \frac{\rho v_5^2}{2} + \Delta p_{v1} + p_{m1} + p_{h_1} \tag{19}$$

Since $h_1 = z_2 - z_4$, the pressure at the outlet of the ground valve (injection wellhead) is as follows:

$$p_2 = p_4 - h_1\gamma + \frac{\rho v_5^2}{2} - \frac{\rho v_3^2}{2} + \Delta p_{vl} + p_{m1} + p_{h_1} \tag{20}$$

Assuming that the formation pressure is constant, the opening of water distributor 1 is reduced, the resistance coefficient of its electric control valve is $\xi_{v11} \to \xi_{v12}$. The nozzle flow rate of water distributor 1 is $Q_{\Delta 11} \to Q_{\Delta 12}$, the flow rate of the injection tube is $Q_1 \to Q_2$. Then the wellhead flow rate change (signal amplitude) when the opening of water distributor 1 is reduced as follows:

$$\Delta Q = nQ_{\Delta 11} - Q_{\Delta 12}\left(1 + \sqrt{\frac{\xi_{v12}}{\xi_{v2}}}\right) \tag{21}$$

Then the pressure change (signal amplitude) at the wellhead caused by a decrease in the opening of distributor 1 is as follows:

$$\Delta\overline{p}_2 = \frac{\lambda_2 h_1}{d_3}\frac{\rho Q_2^2}{2A_3^2} + \xi_{v12}\frac{\rho Q_{\Delta 12}^2}{2A_d^2} + \xi_m\frac{\rho Q_{\Delta 12}^2}{2A_w^2} - \left(\frac{\lambda_2 h_1}{d_3}\frac{\rho Q_1^2}{2A_3^2} + \xi_{v11}\frac{\rho Q_{\Delta 11}^2}{2A_d^2} + \xi_m\frac{\rho Q_{\Delta 11}^2}{2A_w^2}\right) \tag{22}$$

Equation (22) illustrates that the change of the opening of the downhole water distributor causes the change of the flow rate of the water injection tube, which further induces the generation of wellhead pressure signal. The transfer function of the signal upload can be written:

$$T_2 = \left|\frac{\Delta\overline{p}_2}{\Delta p_3}\right| = \frac{\frac{\lambda_2 h_1}{d_3}\frac{Q_2^2}{A_3^2} + \xi_{v12}\frac{Q_{\Delta 12}^2}{A_d^2} + \xi_m\frac{Q_{\Delta 12}^2}{A_w^2} - \left(\frac{\lambda_2 h_1}{d_3}\frac{Q_1^2}{A_3^2} + \xi_{v11}\frac{Q_{\Delta 11}^2}{A_d^2} + \xi_m\frac{Q_{\Delta 11}^2}{A_w^2}\right)}{Q_{\Delta 12}^2\left(\frac{1}{A_m^2} - \frac{1}{A_w^2} + \frac{\xi_{v12}}{A_d^2} + \frac{\xi_m}{A_w^2}\right) - Q_{\Delta 11}^2\left(\frac{1}{A_m^2} - \frac{1}{A_w^2} + \frac{\xi_{v11}}{A_d^2} + \frac{\xi_m}{A_w^2}\right)} \tag{23}$$

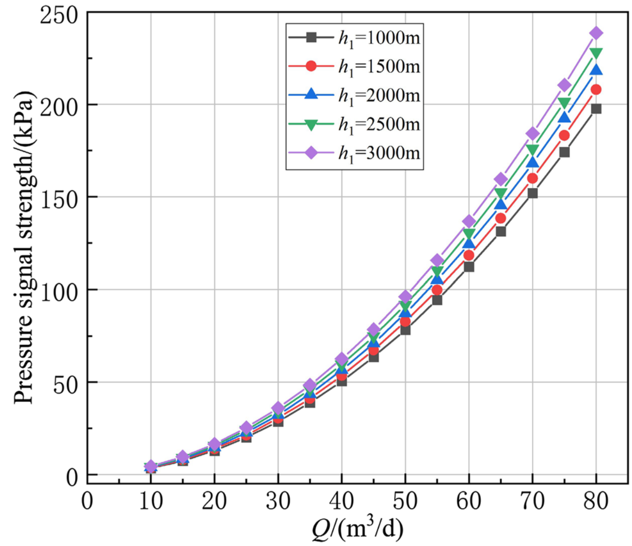

Fig. 3 Influence of flow rate on the pressure signal generated by the ground valve

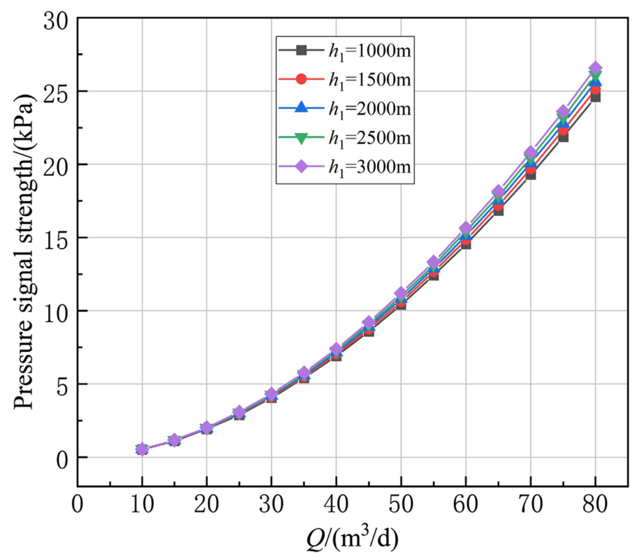

Fig. 4 Influence of flow rate on the pressure signal generated by the downhole distributor

Numerical simulation analysis

The numerical calculation conditions in this paper are as follows: $l_1 = 500$ m; $d_1 = 30$ mm; $Q = 80\text{m}^2$/d; water viscosity $\mu = 1$ mPa·s; $\rho = 1000$ kg/m³; $d_2 = 60$ mm; $\xi_1 = 0.75$; $d_u = 30$ mm, $A_u = 706\text{mm}^2$, $A_0 = 140\text{mm}^2$; $\sigma = 0.63$; $d_3 = 62$ mm; $h_1 = 3000$ m; $d_w = 24$ mm; $d_m = 8$ mm; $d_d = 24$ mm, $A_d = 452\text{mm}^2$, $A_k = 50.25\text{mm}^2$.

Influence of flow rate on transient flow wave signal

Assuming that the fluid is water, the Reynolds number Re > 2300 of the fluid in the ground water pipeline and injection tabular string, and the fluid in the tube is in turbulent flow. The amplitude of the transient flow wave signal is squarely related to the flow rate, so the flow rate has a large effect on the pressure signal. The opening of each water distributor in the downhole is 50%, and the opening of the ground valve is increased from 1 to 100%. According to Eq. (7), the relationship between the amplitude of the pressure signal generated by the ground valve and the flow rate of the tube is shown in Fig. 3.

Assuming that the ground valve is fully open, the opening of downhole distributor 1 is reduced from 50 to 25%, and the opening of all other distributors is 50%. According to Eq. (16), the relationship between the amplitude of the pressure signal generated by distributor 1 and the flow rate of the tube is shown in Fig. 4.

As can be seen from Figs. 3 and 4, the tube flow rate seriously affects the pressure signal amplitude. Since the water distributor nozzle flow rate is much smaller than the injection tube flow rate, and the opening range of the water distributor is much smaller than that of the ground valve, the pressure signal amplitude generated by the water distributor is much smaller than the signal generated by the ground valve. The greater the length h_1 of the water injection tube, the greater the pressure signal intensity.

Transmission characteristics of transient flow wave in the tubular string

Assume that the maximum flow rate of the injection tube $Q_{max} = 75\ m^2/d$, the opening of the electric control valve of each water distributor downhole is 50%, and the opening of the ground control valve increases from 1 to 100%. According to Eq. (11), the relationship between the amplitude of the pressure signal transmitted downhole and length of the water injection tube is shown in Fig. 5. According to Eq. (12), the transfer function value of the signal downstream is related to the length of the tube as shown in Fig. 6.

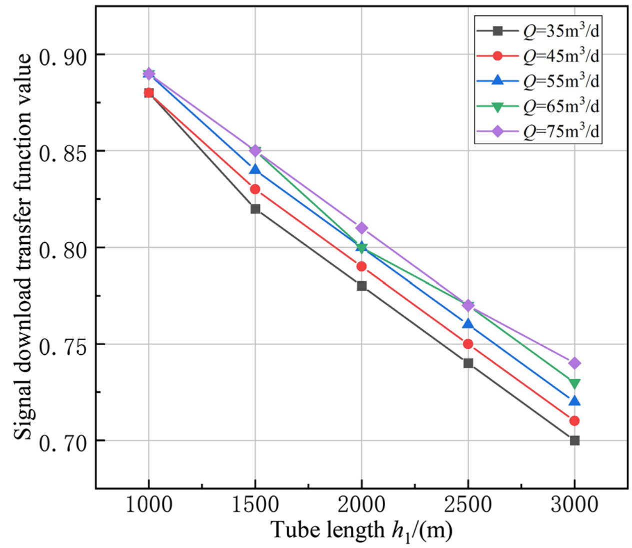

Fig. 6 Influence of tube length on pressure signal download transfer function

It can be seen from Figs. 5 and 6 that the amplitude of the pressure signal transmitted downhole is independent of the length of the injection tube, indicating that the length of the injection tube has basically no effect on the transmission of the ground pressure signal downhole. The amplitude of the

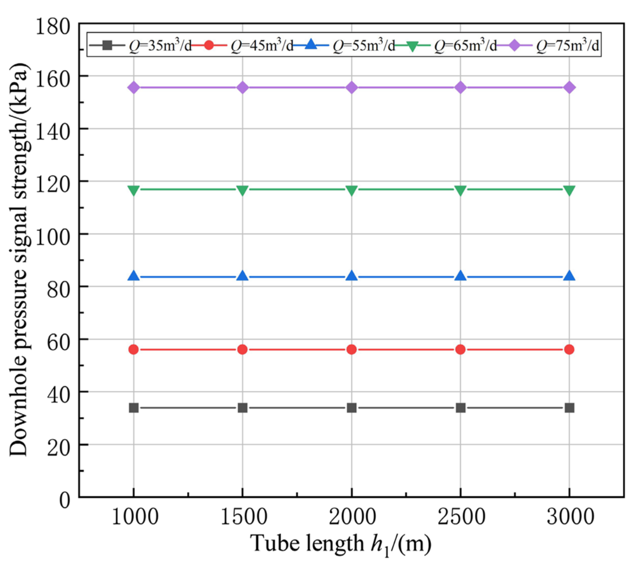

Fig. 5 Influence of tube length on pressure signal download

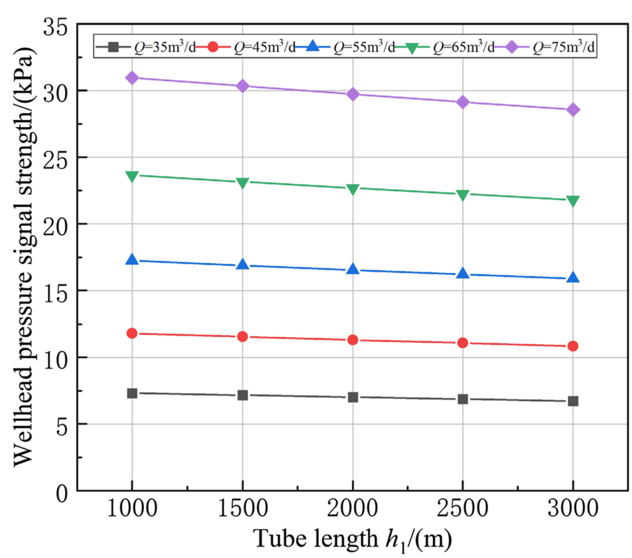

Fig. 7 Influence of tube length on pressure signal upload

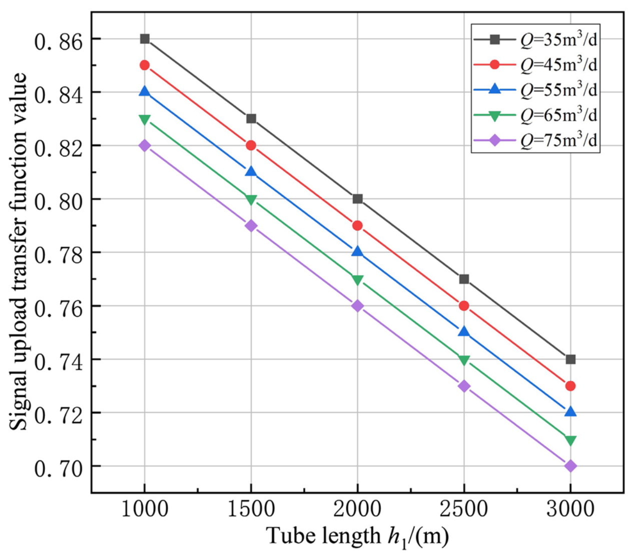

Fig. 8 Influence of tube length on pressure signal upload transfer function

pressure signal generated by the ground valve increases with the length of the injection tube, so the value of the transfer function of the signal downstream gradually decreases with the increase of the length of the injection tube.

Assuming that the ground control valve is fully open and the maximum flow rate of the injection tube $Q_{max} = 75$ m^2/d, the opening of downhole water distributor 1 is reduced from 50 to 25%, and the opening of another distributor is 50%. According to Eq. (22), the magnitude of the pressure signal uploaded to the wellhead in relation to the length of the tube is shown in Fig. 7. According to Eq. (23), the transfer function value of the signal upload is related to the length of the tube as shown in Fig. 8.

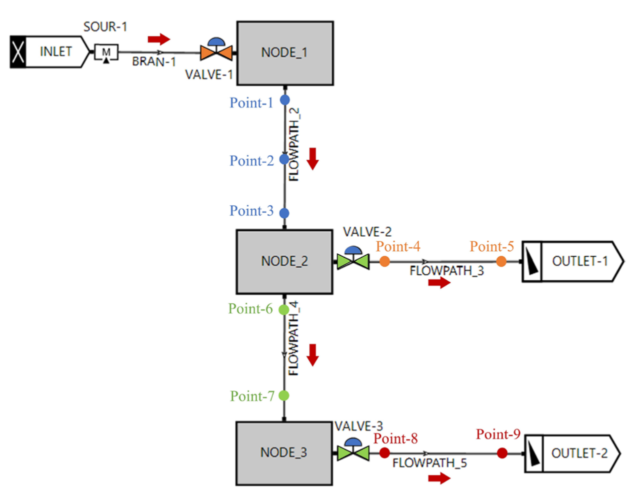

Fig. 9 Model of water injection well

It can be seen from Figs. 7 and 8 that the amplitude of the pressure signal uploaded to the wellhead decreases linearly with the increase in the length of the injection tube. In Fig. 7, the slopes of the curves are different. When the length of the water injection pipe is constant, the greater the flow rate of the water injection pipe, the stronger the signal strength of the wellhead pressure. The transfer function value of the signal upload decreases gradually with increasing length of the injection tube. In Fig. 8, the slopes of the curves are same. This indicates that when the length of the injection pipe is determined, a fixed-value change of the upload signal transfer function is caused with a fixed-value change in the flow rate of the injection tube.

Simulations of transient flow wave signal

OLGA software is the earliest developed transient simulation software for oil and gas mixed pipeline flow (Choi and Huang 2011), the simulation calculations have been recognized by famous oil companies around the world. Figure 9 shows an injection well simulation model by using OLGA 2020, INLET is the closure node, SOUR-1 is the starting point of the ground water pipeline source. Assuming a constant flow rate of 1 kg/s, OUTLET-1 and OUTLET-2 are the outlet nodes; BRAN-1 is the ground water pipeline, $l_1 = 50$ m; VALVE-1 is the electric control valve of ground water pipeline; VALVE-2 is the electric control valve of water distributor of the first injection layer; VALVE-3 is the electric control valve of water distributor of the second injection layer; NODE_1 is the injection wellhead node; NODE_2 is the injection well first layer node; NODE_3 is the injection well second layer node, FLOWPATH_2 is the distance from the injection tube wellhead to the first injection layer,

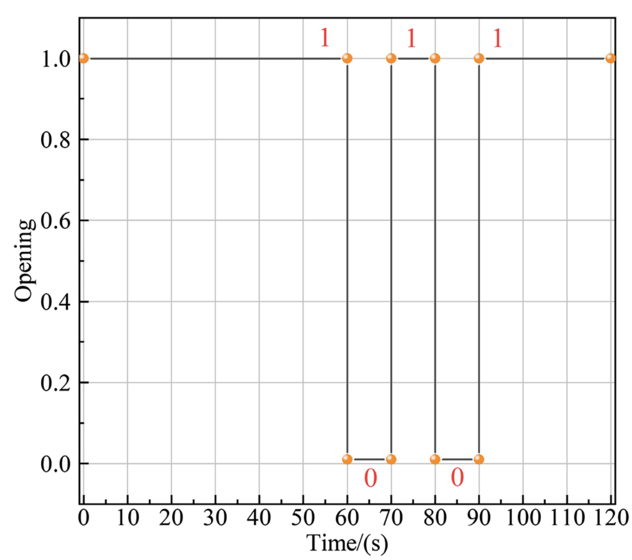

Fig. 10 Variation of ground electric control valve opening with time

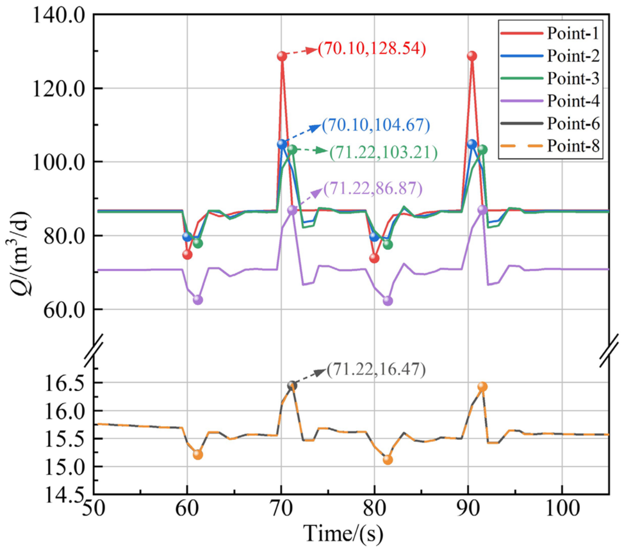

Fig. 11 Opening1 = Opening2 = 100%, flow rate changes at monitoring points

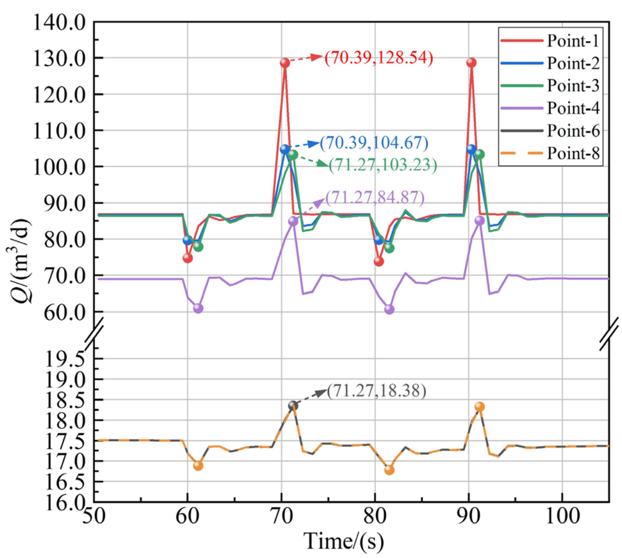

Fig. 12 Opening1 = 50%, Opening2 = 100%, flow rate changes at monitoring points

$h_1 = 1200$ m; FLOWPATH_3 is the first injection layer horizontal distance, $l_2 = 10$ m; FLOWPATH_4 is the distance from the first injection layer to the second FLOWPATH_4 is the distance from the first injection layer to the second injection layer, $h_2 = 200$ m; FLOWPATH_5 is the horizontal distance of the second injection layer, $l_3 = 10$ m; the ground electric control valve is used to control the flow rate of injection water, which is injected directly from the injection tube to the bottom of the well to act on the formation. A total of nine monitoring points were set up to monitor the pressure and flow changes in the injection tube and reservoir during the water injection process. Among them, monitoring points 1, 2 and 3 are at 10 m, 600 m and 1200 m from the wellhead; monitoring points 6 and 7 are at 1210 m and 1400 m from the wellhead; monitoring points 4 and 5 are at 2 m and 10 m from the NODE_2 node; and monitoring points 8 and 9 are at 2 m and 10 m from the NODE_3 node.

Set the opening variation of VALVE-1, as shown in Fig. 10. The opening of VALVE-2 is opening1. The opening of VALVE-3 is opening2. When Opening1 = Opening2 = 100%, the variation of the flow rate at the monitoring point is obtained as shown in Fig. 11. When Opening1 = 50%, Opening2 = 100%, the variation of the flow rate at the monitoring point is obtained as shown in Fig. 12. From Figs. 11 and 12, it is obtained that the flow variation at the monitoring point is consistent with the VALVE-1 opening variation, and there is a delay in the monitoring point peak. The intensity of flow rate variation amplitude is gradually weakened along the injection tube transmission. The magnitude of the change in flow rate generated by the valve opening is greater than the magnitude of the change in flow rate generated by the valve closing. The change in valve opening has an influence on the distribution of flow.

Experiment of transient flow wave signals in tubular strings

Experiment Introduction

Two-way signal transmission wireless intelligent water injection technology can be applied by the ground pressure pulse to the downhole intelligent water distributor for deployment, while the downhole test data can also be transmitted to the ground through the downhole signal generation device. In order to verify the accuracy of the transient flow wave calculation formula, an experiment was carried out, as shown in Figs. 13 and 14. Experiments have been conducted to verify the transient flow wave transmission characteristics in the tube string (Ming et al. 2023).The experiment condition is that the depth of the injection well 1400 m, a two-layer of layered water injection, the length h_1 of the simulated tubular string from the water distribution room (injection room) to the first layer Section 1200 m, the length h_2 of the tubular string between the first layer and the second layer 200 m. The average temperature is 25 °C. The test can simulate the transient flow wave signal generated by the ground valve and downhole distributor, and measure the change of downhole pressure and flow rate caused by the change of ground valve opening and the change of wellhead pressure and flow rate caused by the change of downhole distributor opening.

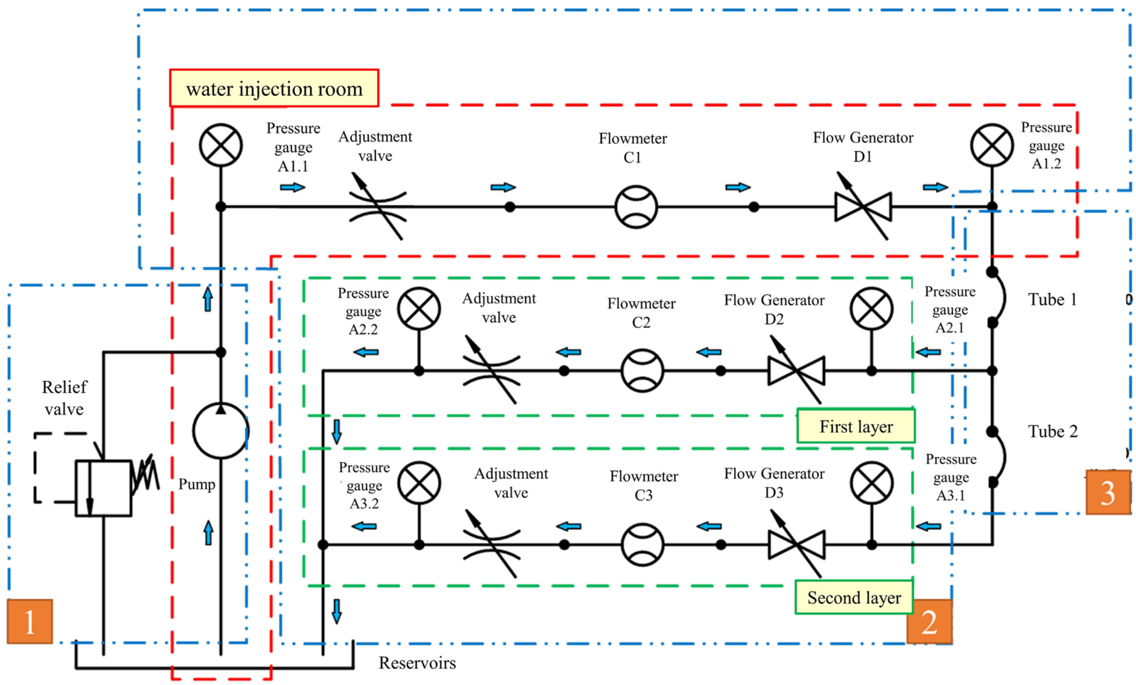

Fig. 13 Diagram of two-layer stratified water injection test

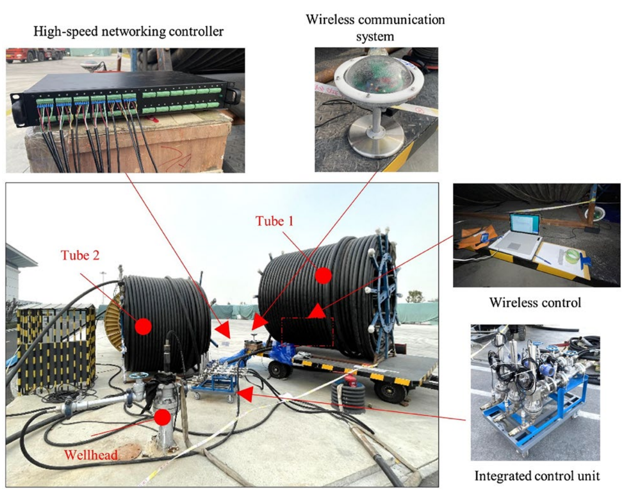

Fig. 14 Two-layer layered water injection test platform

Install the wave generator D1 at the beginning of the tube. It represents the transient flow wave signal at the wellhead generated by the variation of the ground valve opening. Install pressure sensor A1.2 near the wave generator D1, and record the measured pressure as P_1. Install flowmeter C1 near the wave generator, and record the measured discharge as Q_1. Install pressure sensor A2.1 near the wave generator D2, and record the measured pressure as P_2. Install flowmeter C2 near the wave generator, and record the measured discharge as Q_2.Similarly, install pressure sensor A3.1 near the wave generator D3, and record the measured pressure as P_3. Install flowmeter C3 near the wave generator D3, and record the measured discharge as Q_3.

The control valve D1 produces a continuous 'on–off' signal with a constant flow rate of Q_1. The first layer flow rate is set to Q_2. The second layer flow rate is set to Q_3. Stable transient flow wave fluctuations are generated in the pipeline and the values of P_1, P_2, P_3, Q_1,Q_2 and Q_3 are recorded. There are 8 groups of working conditions in this test. Test initial flow distribution conditions are grouped as shown in Table 1.

Transient flow wave signal download test in tubular strings

In intelligent water injection, transient flow wave pulses are created by ground valves to adjust downhole intelligent water distributors. As shown in Fig. 15, the ground valve D1 opening is first adjusted from 100 to 25%, and then from 100 to 50%. Test 1–10 conditions are shown in Table 1. In test 1, the water injection only in the first formation. The variation of the ground valve D1 opening causes pressure and flow rate changes at the wellhead and downhole. The ground pipeline flow rate changes synchronously with the ground control valve opening, and the downhole pressure and flow signals are consistent with the ground control valve opening. This means that the ground valve opening changes the flow rate to

Table 1 Test initial flow rate distribution conditions

	Test number	Q_1 (m^3/d)	Q_2 (m^3/d)	Q_3 (m^3/d)	D1-Opening	D2-Opening	D3-Opening
Transient flow wave signal download	1	25	25	0	100% ⇄ 25% 100% ⇄ 50%	100%	0%
	2	30	20	10	100% ⇄ 0%	100%	100%
	3	25	20	5	100% ⇄ 0%	100%	100%
	4	36	18	18	100% ⇄ 0%	100%	100%
Transient flow wave signal upload	5	25	25	0	100%	100% ⇄ 25% 100% ⇄ 50%	0%
	6	30	20	10	100%	100% ⇄ 0%	100%
	7	25	20	5	100%	100% ⇄ 0%	100%
	8	36	18	18	100%	100% ⇄ 0%	100%
	9	30	20	10	100%	100%	100% ⇄ 0%
	10	36	18	18	100%	100%	100% ⇄ 0%

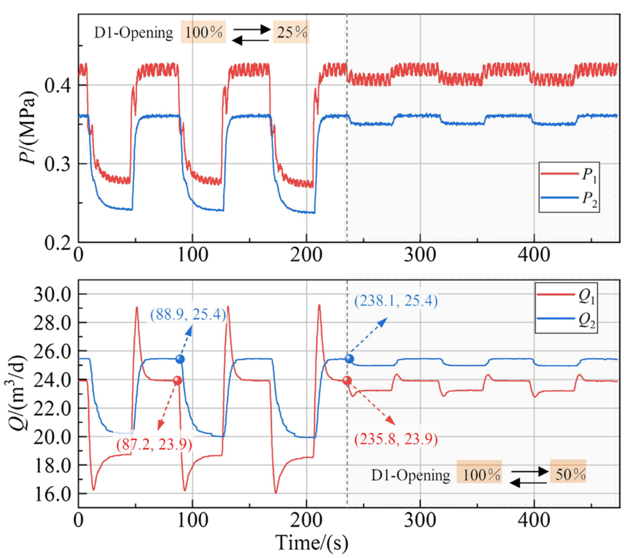

Fig. 15 Pressure and flow wave variations of test 1

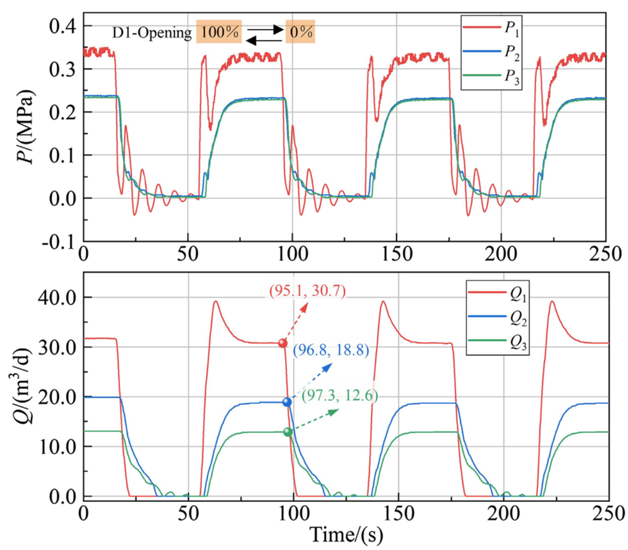

Fig. 16 Pressure and flow wave variations of test 2

form transient flow wave, and the transient flow wave is transmitted to the downhole, which is consistent with the theoretical analysis. By comparison, it is found that the greater the variation of opening degree, the greater the amplitude of transient flow wave signal, which is beneficial to the wave signal transmission. Therefore, the optimal settings for the valve opening are selected as 100% ⇄ 0%. The transmission time of the wave from D1 to D2 can be calculated to be about 1.7 s.

As shown in Fig. 16, the ground valve D1 opening is adjusted from 100 to 0%. Its pressure and flow rate change amplitude were large, which is conducive to the transmission of transient flow wave. Similarly, the transmission time of the wave from D1 to D2 can be calculated to be about 1.7 s. The transmission time of the wave from D1 to D3 can be calculated to be about 2.2 s. There are small fluctuations in the pressure wave, while the flow wave is more stable. Therefore, the flow signal can be selected for downhole and wellhead information transfer. This can provide a test basis for wireless intelligent water injection.

As shown in Figs. 17 and 18, the ground valve D1 opening is adjusted from 100 to 0%. When the two injection layers are different with water injection flow rates, the pressure and flow wave trends remain the same. However, when the water injection rate is small, the flow wave amplitude is smaller and the intensity of the flow wave signal is lower. Pressure wave amplitude variation is still

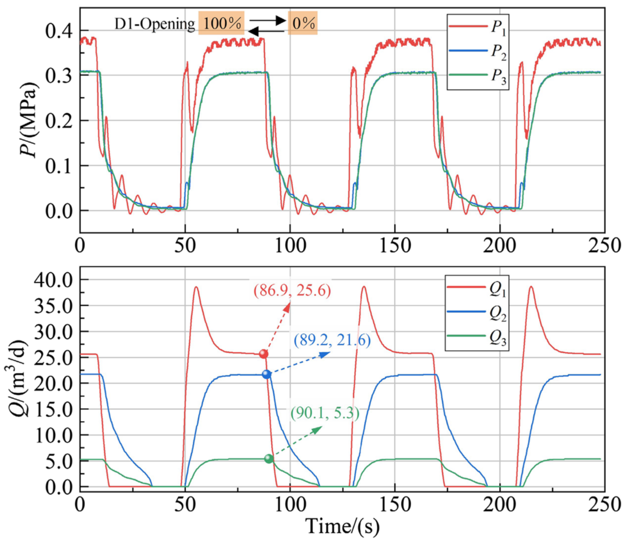

Fig. 17 Pressure and flow wave variations of test 3

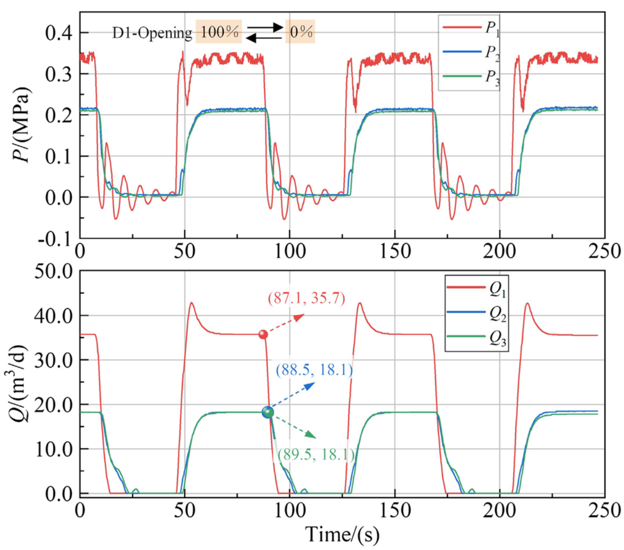

Fig. 18 Pressure and flow wave variations of test 4

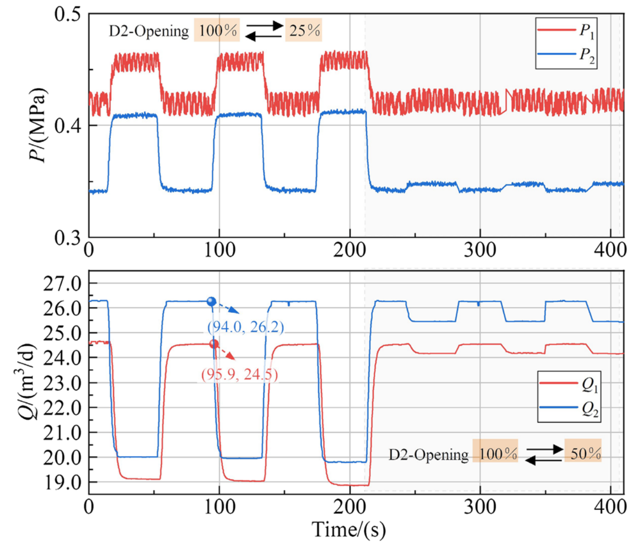

Fig. 19 Pressure and flow wave variations of test 5

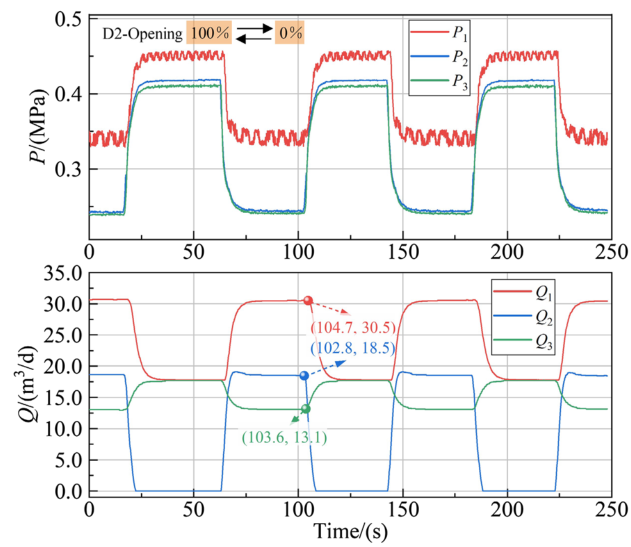

Fig. 20 Pressure and flow wave variations of test 6

large and its intensity is greater. The greater the difference in water injection rate between the two layers, the greater the magnitude of pressure change. For example, the second layer is injected with 5 m^3/d. Thus, pressure wave and flow wave signals can be combined to transmit wellhead and downhole information. In the test 3, the transmission time of the wave from D1 to D2 can be calculated to be about 2.3 s. In the test 4, the transmission time of the wave from D1 to D2 can be calculated to be about 1.4 s. Therefore, the smaller the difference in water injection rates between the two layers, the shorter the transient flow wave propagation time.

Transient flow wave signal upload test in tubular strings

The regulation information of the downhole distributor nozzle needs to be transmitted to the wellhead in time. Therefore, this section carried out a transient flow wave signal upload test. As shown in Figs. 19 and 20, the first layer generator valve D2 opening is also first adjusted from 100 to 25%, and then from 100 to 50%. The water injection only in the first formation. The first layer generator valve D2 opening causes pressure and flow changes at the downhole and wellhead. The first layer flow rate changes synchronously with the flow valve (D2) opening, and the wellhead pressure

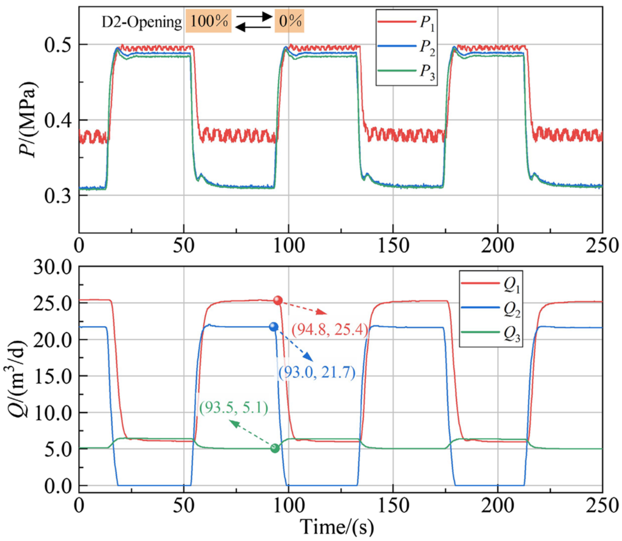

Fig. 21 Pressure and flow wave variations of test 7

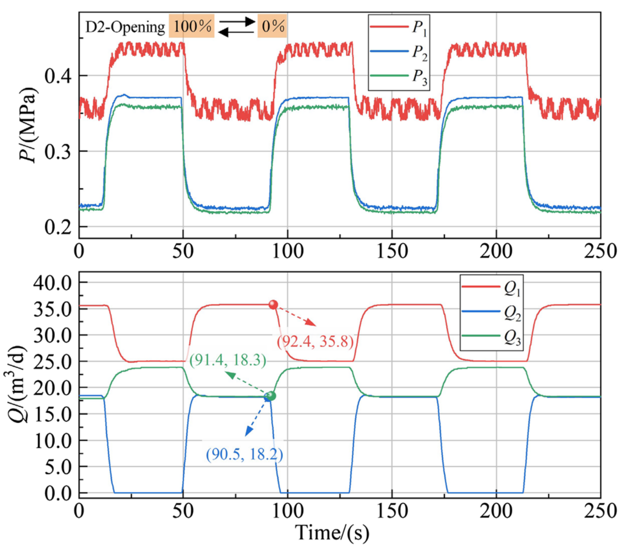

Fig. 22 Pressure and flow wave variations of test 8

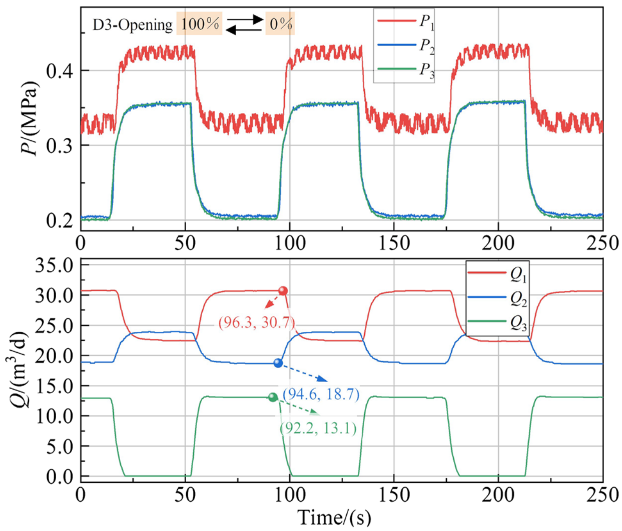

Fig. 23 Pressure and flow wave variations of test 9

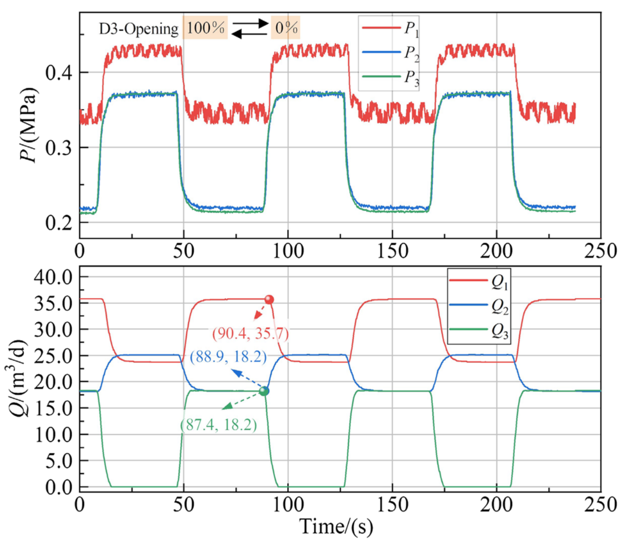

Fig. 24 Pressure and flow wave variations of test 10

and flow signal changes in line with the first layer generator valve opening. The pressure changes in the opposite trend to the flow rate, as the flow rate increases, the pressure is decreasing. This means that the first layer generator valve opening changes the flow rate to form transient flow wave, and the transient flow wave is transmitted to the wellhead, which is consistent with the theoretical analysis. The transmission time of the wave from D2 to D1 can be calculated to be about 1.9 s. Compared with signal download, the pressure and flow rate changes for the same valve opening change are smaller in magnitude. In addition, the transmission time is longer. Similarly, in test 6, the transmission time of the wave from D2 to D1 can be calculated to be about 1.9 s.

As shown in Figs. 21 and 22, the first layer generator valve D2 opening is adjusted from 100 to 0%. When the injection rates of two water injection layers are different, the pressure and flow wave change amplitudes are different. When the water injection rate is small, the amplitude of the flow wave is smaller and the intensity of the flow wave signal is lower. The greater the difference in water injection rate between the two layers, the greater the magnitude of pressure change. Thus, pressure wave and flow wave signals can be combined to transmit wellhead and downhole information. In the test 7, the transmission time of the wave from D2 to D1 can be calculated to be about 1.8 s. In the test 8, the transmission time of the wave from D2 to D1 can be calculated to be about 1.9 s. Through comparative tests 6, 7, and 8, the flow rate Q of the water injection tube seriously affects the amplitude of the transient flow wave signal generated by the ground valve and the water distributor, and the signal amplitude generated by the ground valve is much larger than that generated by the water distributor. It is consistent with the numerical calculation. The magnitude of pressure and flow changes resulting from the same change in valve opening is smaller than that of the signal transmission downstream.

As shown in Figs. 23 and 24, the second layer generator valve D3 opening is adjusted from 100 to 0%. Under the same conditions, the magnitude of pressure and flow changes caused by changes in D3 opening is larger than that caused by D2. In the test 9, the transmission time of the wave from D3 to D1 can be calculated to be about 4.1 s. In the test 10, the transmission time of the wave from D3 to D1 can be calculated to be about 3 s. Similarly with signal download, the smaller the difference in water injection rates between the two layers, the shorter the transient flow wave upload propagation time. Therefore, the difference in water injection in each layer has an impact on the signal transmission of transient flow wave.

Conclusions

In this paper, a transmission mathematical model of fluid transient flow wave signals in intelligent layered water injection system was established. The transmission characteristics of fluid transient flow wave in layered water injection tubular strings are investigated through theoretical analysis, simulation and experiments. The results show that:

(1) The wellhead transient flow wave signal is generated by the flow change of the water injection tabular string caused by the change of the ground valve opening; the downhole transient flow wave signal is generated by the flow change of the nozzle caused by the change of the water distributor opening.

(2) Numerical calculations show that the length of the water injection tube basically has no effect on the down-transmission of ground pressure signals, but has a certain influence on the uploading of downhole pressure signals.

(3) Through numerical calculation and experimental verification, the flow rate of the water injection tube seriously affects the transient flow wave signal amplitude generated by the ground valve and the water distributor, and the signal amplitude generated by the ground valve is much larger than that generated by the water distributor.

(4) A change in the opening of a certain water distributor not only causes a change in the flow rate of the nozzle, but also causes a redistribution of the flow in the pipelines of the other water distributors. At the same time, it will have a certain impact on the flow rate of the water injection tube.

(5) It is verified by experiments and simulations that the pressure and flow changes in the downhole and wellhead can maintain good consistency during the transmission of transient flow waves. Therefore, the transient flow wave signal can be selected for downhole and wellhead information transfer. This can provide a test basis for wireless intelligent water injection.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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