



A method to optimize the length of flexible hose of the radial jet drilling technology

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Abstract

Radial jet drilling (RJD) technology has been applied to enhance the recovery of difficult-to-produce reserves by multiple horizontal micro-holes. The micro-hole length drilled by high-pressure water jets is of vital importance for the oil and gas recovery effect and is usually tens of meters long for applications in maturing oil fields in China. The water jets are generated by multiple orifices nozzle generally. Many studies focused on improving the self-propelled force generated by water jets to increase the micro-hole length. However, there are few researches on improving the micro-hole extension capacity in terms of optimizing the flexible hose that acts as the drill pipe in conventional drilling technology. This paper firstly studied the relationship between the flexible hose length and the micro-hole extension limit according to the analytical model to calculate the micro-hole extension limit. Then, the method to optimize the flexible hose length and the flow rate was developed aiming to obtain maximum micro-hole extension limit. The results show that the micro-hole extension limit decreases logarithmically with the increase in the flexible hose length under the condition that the takes the maximum value. The optimization model is applied by a field case and is proved to be effective to increase the micro-hole extension limit. This study is significant to improve the micro-hole extension capacity. Moreover, it provides a reference for the design of the hydraulics and selection of flexible hose for the RJD.

Keywords Radial jet drilling · Micro-hole extension limit · Flexible hose · Optimization method · Constraint condition

Abbreviations

a	Contact area coefficient, dimensionless	F_{fd}	Friction on the flexible hose from the diverter, N
b	Friction coefficient, dimensionless	F_{fw}	Friction on the flexible hose from the wall of micro-hole, N
C	Discharge coefficient of nozzle, dimensionless	g	Acceleration of gravity, 9.81 m/s ²
d_i	Nozzle inlet diameter, m	L_{fh}, L_l, L_{Lim}	Flexible hose length, wellbore length and micro-hole extension limit, m
d_{fhi}	Inner diameter (ID) of the flexible hose, m	L_{ct1}, L_{ct2}	Length of the spiral section and straight section of the coiled tubing (CT), m
d_{nf}, d_{nb}	Front and rear orifices of the nozzle, m	m	Self-propelled factor of the nozzle just depending on the structure and material of the multiple orifices nozzle, dimensionless
d_{CTi}	The ID of the CT, m	n_f, n_b	Number of forward and backward orifices of the nozzle, dimensionless
D	Diameter of the reel, m	p_{hd}	Water pressure in the flexible hose in the diverter, Pa
f	Coefficient of friction, dimensionless	$p_p, p_{r,p}$	Pump pressure and rated pump pressure, Pa
F	Resultant force, N	$p_{m,ct}, p_{m,fh}$	Maximum safe working pressure of the CT and flexible hose, Pa
F_j	Self-propelled force by water jets, N	Q	Flow rate, m ³ /s
		ΔL_{fh}	Length of section of the flexible hose in the diverter, m

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α, β, γ	Fitting coefficients, dimensionless
$\lambda_1, \lambda_2, \lambda_3$	Coefficients related to the dimension and material of the tubing or the flexible hose, dimensionless
μ	Water viscosity, Pa·s
ρ	Density of water or working fluid, kg/m ³
ρ_{fh}	Weight of the flexible hose per meter, kg/m

Introduction

Radial jet drilling (RJD) is to drill multiple horizontal micro-holes using high-pressure water jet to break the formation rock to expose the oil and gas formation. This drilling technology applies high-pressure water jets to break the rock instead of the bit of the conventional drilling technology. Since developed in 1980s in the USA (Dickinson and Dickinson 1985), it has been applied to enhance oil and gas production from more than 1.7 million wells (Rahman and Mehrara 2020) and proven to enhance production rates, to reduce decline rates, to reduce near wellbore damage and to recover more resources (Kamel 2016). This technology can increase the production rate of the stimulated wells by 100% to 500% in general (Al-Jasmi et al. 2018; Cinelli and Kamel 2013; Kamel 2016; Teng et al. 2014). The eight-fold and 34-fold production gain of two wells by radial jet drilling was obtained in India (Jain et al. 2017; Maut et al. 2017). This technology is effective because of its technological advantages: (1) It has the ability to drill multiple laterals with tens of meters long, increasing the drainage area, and (2) there is no formation damage because it uses water or KCl solution as drilling fluid rather than traditional drilling mud. It is proved to be effective to enhance oil and gas recovery in China by hundreds of wells application (Kamel 2017; Li et al. 2000; Marbun et al. 2011; Ursegov et al. 2008). Recently, the RJD technology has been applied in the development of shale gas (Huang and Huang 2019) and geothermal resource (Salimzadeh et al. 2019) besides the conventional oil and gas resources. The RJD technology is cost-effective with high efficiency and provides a valuable substitute or supplement to acid, hydraulic fracturing and conventional sidetrack drilling (Buset et al. 2001). The RJD system is shown in Fig. 1, which is different from the conventional drilling system. The operation first anchors the oil tubing and diverter in casing at the designed depth and azimuth. Then, a hole with 30 to 50 mm in diameter on the casing and cement will be milled out by the special miller. The jetting assembly will be run into the well, and a radial horizontal micro-hole will be drilled by high-pressure water jets. The nozzle connected to a flexible hose can generate high-pressure water jets to break the rock and pull the flexible hose forward. The bottom-hole assemblies (BHA) (Maut et al. 2017) used in RJD system are shown in Table 1.

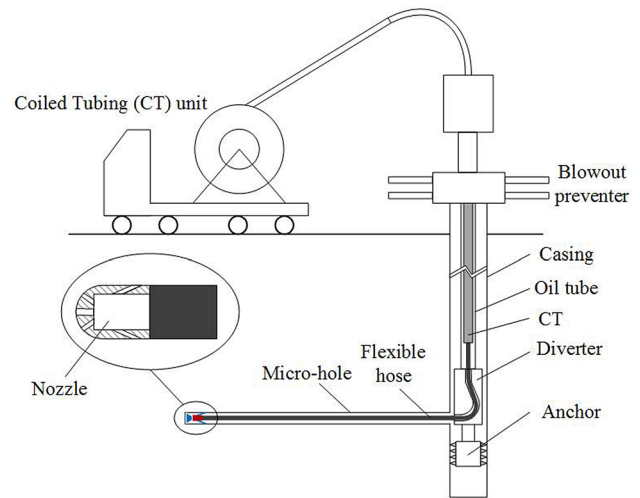


Fig. 1 Schematic of the RJD system

Table 1 The bottom-hole assemblies (BHA) of RJD system

Assembly category	Assembly composition
Working assembly	Tube anchor+diverter+oil tube
Casing and cement milling assembly	Milling bit+flexible shaft+motor+heavy weight drill pipe+coiled tubing (CT)
Jet drilling assembly	Nozzle+flexible hose+joint+CT

The rock-breaking capacity of the water jets and the micro-hole extension limit have always been important researches for the RJD technology. The rock-breaking capacity determines whether the nozzle and flexible hose can pass through the micro-hole or not. And the micro-hole extension limit determines the productivity increasing results (Chi et al. 2015). Therefore, large and long micro-holes are preferred. Over the past decades, lots of researches have focused on the jet nozzle (Li et al. 2020; Liao et al. 2020; Liao et al. 2011; Reinsch et al. 2018). The multiple jets nozzle (Latham et al. 2019) is widely used in RJD, because the high rock-breaking efficiency (Chi et al. 2016) and large self-propelled force (Li et al. 2015) can both be achieved.

To drill the micro-hole further needs enough propulsion force generated by water jets to pull the hose forward. In recent years, many researchers studied the propulsion effect of the nozzle in RJD. Buset et al. studied the self-propelled capacity of multi-jet nozzle (Buset et al. 2001). Guo et al., Ma et al. and Li et al. studied the self-propelling mechanism of multiple jets and put forward their own models of the self-propelling force by theoretical and experimental methods (Guo et al. 2009; Li et al. 2015; Ma et al. 2014). Bi et al. derived the equation to calculate the velocity and impact pressure of the

multiple jets based on Bernoulli equation (Bi et al. 2014). Wu et al. discussed the pulling force of self-propelled straight-swirling integrated jet bit by numerical simulation and experiments (Wu et al. 2016). Hu et al. studied the internal and external flow field of the water jets and predicted the propulsion force in RJD by CFD (Hu et al. 2013). Lu et al. developed a model to design the multi-nozzle bit and studied the rock-breaking efficiency by experiments (Liu et al. 2020). Li et al. established a 3D field simulation model to investigate the self-propelled force of the multi-orifice nozzle based on ANSYS-CFX (Li and Zhang 2020). Du predicted and analyzed the micro-hole length of RJD taking the swirling jet nozzle that is seldom used in the RJD system, but he did not study the resistance of the diverter on the flexible hose (Du et al. 2015). Li doubled the extension ability of RJD by improving the deflector structure design by making use of the hydraulic within the diverter (Li et al. 2018). Wang et al. provided a viable and detailed hydraulics calculation model and design method for RJD for the purpose to make the self-propelled force larger (Wang et al. 2016).

However, the mechanism of the flexible hose has seldom been studied. To study the friction on the flexible hose is as important as studying the self-propelled force of the water jets. The pressure loss inner the flexible hose accounts for the major part of the whole pressure loss (Ma et al. 2012). The friction on the flexible hose prevents the micro-hole from elongating. In this study, we found that the flexible hose length is a significant factor impacting the ultimate micro-hole length in addition to the self-propelled force. Based on the operational condition of RJD, the relationship between the maximum micro-hole length and the flexible hose length is derived using the theoretical and experimental methods. Then, the model to optimize the flexible hose length is developed.

The micro-hole extension limit

A model has been developed to evaluate the micro-hole extension limit by analysis of forces on the flexible hose. Based on the previous model, the micro-hole extension limit can be calculated by the following equation (Chi et al. 2015):

$$L_{\text{lim}} = \frac{F_j - a \frac{0.83255 \rho Q^2}{C^2 (n_r d_{nr}^2 + n_b d_{nb}^2)^2} - b}{fg \left(\rho_{fh} + \frac{\pi}{4} \rho d_{fhi}^2 \right) + a \lambda_3 \rho^{0.75} \mu^{0.25} \frac{Q^{1.75}}{d_{fhi}^{4.75}}} \quad (1)$$

The meanings of symbols in the above equation are expressed in section “Nomenclature.”

Determination of parameters in Eq. (1)

F_j is the self-propelled force of the multiple jets. Many researchers studied the self-propelled force. Among these models, Li et al. put forward a theoretical self-propelled force model for the multiple orifices nozzle, which was correlated and validated by both numerical simulation results and experimental data (Li et al. 2015). Therefore, we prefer to cite their model to calculate the self-propelled force, which can be expressed as follows:

$$F_j = m \frac{4\rho}{\pi d_i^2} Q^2 \quad (2)$$

where m is the self-propelled factor of the nozzle just depending on the structure and material of the multiple orifices nozzle; d_i is the inner diameter of the nozzle inlet; and Q is the pumping flow rate.

Other parameters can be determined by our previous methods. The values of coefficients a and b are 1.042 N/MPa and 5.385 N, respectively, by linearly data fitting for the flexible hose we used (Chi et al. 2015). According to the experimental results (Li et al. 2015), the value of C and m can be set as 0.8 and 6.0, respectively, in our research.

Constraint conditions

During the RJD operation, the pressure of the pump must be less than the rated value of the pump ensuring safety. The inner fluid pressure in the circulation system should be lower than the pressure bearing capacity of the pump and pipes. Furthermore, the length of the micro-hole should be less than the length of the flexible hose. Therefore, the constraint conditions for RJD are as follows:

$$p_p \leq \min [p_{r,p}, p_{m,CT}, p_{m,fh}] \quad (3)$$

$$L_{\text{lim}} \leq L_{fh} - \Delta L_{fh} \quad (4)$$

where p_p is the pump pressure; $p_{r,p}$ is the rated pressure of the pump; $p_{m,CT}$ is the maximum safe working pressure of CT; $p_{m,fh}$ is the maximum safe working pressure of the flexible hose; and ΔL_{fh} is the length of section of the flexible hose in the diverter, illustrated in Fig. 3.

Determination of the pump pressure

In RJD system, high-pressure water flows from the pump through the spiral and straight sections of the coiled tubing and the flexible hose to the jet nozzle. Water jets are generated by the jet nozzle and break the formation rock to form a micro-hole. The pressure of the pump offsets the pressure

loss of fluid flowing in the circulation system. Because of the unique drilling system (shown in Fig. 1), the circulation system consists of the CT, the flexible hose and the nozzle. According to the previous research, the pump pressure expression (Chi et al. 2015) is as follows:

$$\begin{aligned}
 p_p = & \lambda_1 \frac{\mu^{0.2} \rho^{0.8} Q^{1.8} L_{CT1}}{d_{CTi}^{4.7} D^{0.1}} \\
 & + \left(\frac{\lambda_2 L_{CT2}}{d_{CTi}^{4.75}} + \frac{\lambda_3 L_{fh}}{d_{fhi}^{4.75}} \right) \rho^{0.75} \mu^{0.25} Q^{1.75} \\
 & + \frac{0.83255 \rho Q^2}{C^2 (n_f d_{nf}^2 + n_b d_{nb}^2)^2}
 \end{aligned} \tag{5}$$

λ_1 and λ_2 are coefficients related to the CT dimension and material. λ_3 is a coefficient related to the flexible hose dimension and material. Based on our experimental results, the values of coefficient λ_1 and λ_3 are 0.2328 and 0.4444, respectively. The value of λ_2 is 0.2399 based on the research of Ma et al. (2012).

Optimization method of the flexible hose length

For the convenience of illustration, we use the parameters obtained from field application listed in Table 2. The parameters of the CT and flexible hose are listed in Table 3 according to the previous field test.

The maximum flow rate

From the micro-hole extension limit expression above, it is concluded that the flow rate is the most important factor that impacts the micro-hole extension limit. For a particular nozzle, the flow rate is the key parameter that the micro-hole extension limit and the rock-breaking capacity both improve when the flow rate increases. We obtained the influence of the flow rate on the pump pressure and the micro-hole extension limit, shown in Fig. 2. Obviously, both

Table 2 Parameters of the main well and RJD system

Parameter	Value	Parameter	Value
Main wellbore depth (m)	1751	n_f	6
f	0.30	d_f (mm)	0.9
$p_{m,ct}$ (MPa)	70	n_b	8
$p_{m,fh}$ (MPa)	70	d_b (mm)	1.1
$P_{r,p}$ (MPa)	105	ρ (kg·m ⁻³)	1000
d_i (m)	0.009	μ (mPa·s)	1.005

Table 3 Parameters of the CT and flexible hose

Type	OD (m)	ID (m)	Total length (m)	Weight per meter (kg·m ⁻¹)	Reel diameter (m)
CT	0.03810	0.03175	1800	/	2.5
Flexible hose	0.0127	0.0076	40	0.521	/

the pump pressure and micro-hole extension limit increase with the increase in flow rate. The micro-hole extension limit increases linearly with the increase in the flow rate. The pressure loss of the circulation system increases with an increase in the flow rate, resulting in high pump pressure for the reason that in Eq. (5), as flow rate increases, the friction pressure of fluid flowing in the circulation system will increase. Moreover, there is a maximum value of the flow rate because the pump pressure must be under the safety working pressure. The flow rate will reach the maximum value under the condition that the pump pressure reached the limited value of the RJD system. The maximum flow rate can be obtained by drawing the variation curves of the pump pressure and the micro-hole extension limit as the flow rate increases. For example, the rated pump pressure is set as 60 MPa, the maximum flow rate is 56.4 L/min, and the micro-hole extension limit will be 24.6 m.

The optimum length of the flexible hose

As shown in Fig. 3, the micro-hole extension limit decreases with the increase in the flexible hose length under the condition that the pump pressure takes the maximum value. The reason for this tendency is that the maximum flow rate decreases as the flexible hose length increases because of the increasing

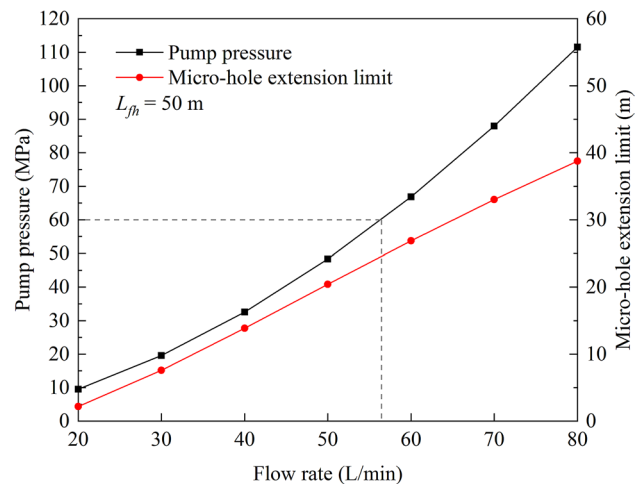


Fig. 2 Effect of the flow rate on the pump pressure and micro-hole extension limit

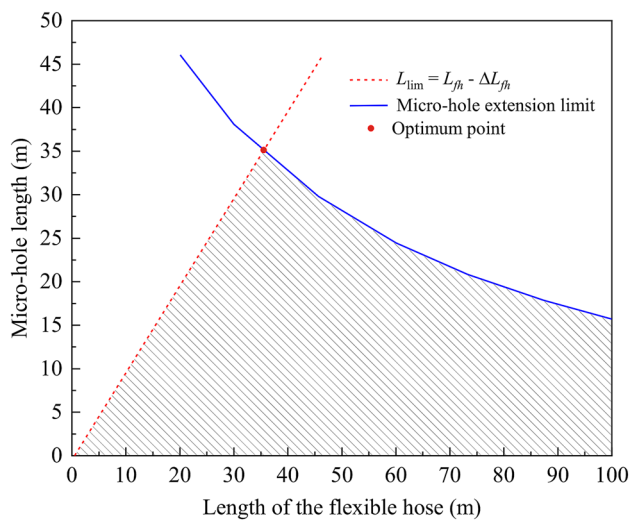


Fig. 3 Effects of the length of the flexible hose on the micro-hole extension limit when pump pressure is 70 MPa

pressure loss. As a result, the shorter the flexible hose is, the more hydraulic energy can be applied by the nozzle to provide force to drag the flexible hose forward. However, the length of flexible hose should meet the condition of Eq. (4), of which the critical state is the gray dashed line shown in Fig. 3. The result of the micro-hole extension limit should be in the shaded area. According to the optimization theory, the intersection of two lines in Fig. 3 is the optimum point, and the corresponding values of the horizontal and vertical coordinates are the optimum length of the flexible hose and the maximum extension limit, respectively.

Based on the change of the micro-hole extension limit versus the length of the flexible hose, the approximate relationship between the micro-hole extension limit and the flexible hose length by data fitting (shown in Fig. 4) is expressed as:

$$L_{lim} = \alpha \ln(L_{fh} + \gamma) + \beta \tag{6}$$

where α , β and γ are fitting coefficients.

Combining Eq. (4) and Eq. (6), the optimum length of the flexible hose can be derived by the following equations:

$$\alpha \ln(L_{fh} + \gamma) - L_{fh} + \beta + \Delta L_{fh} = 0. \tag{7}$$

There is only an unknown parameter in Eq. (7), and the equation can be solved by iteration or drawing curves. On the basis of the above analysis, the optimum length of the flexible hose can be obtained by the flow chart shown in Fig. 5.

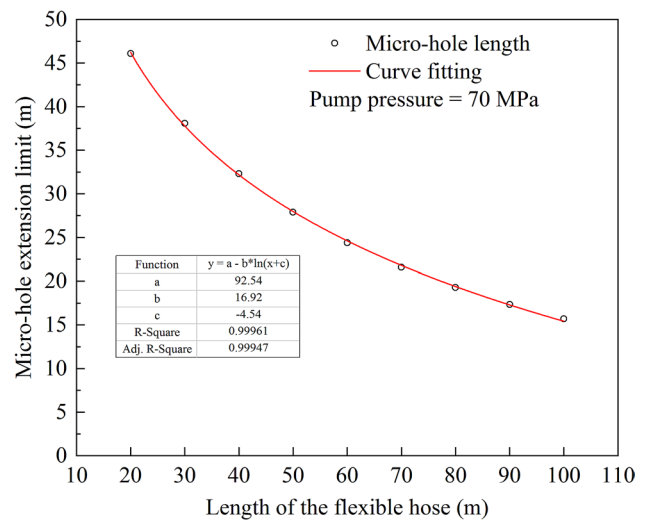


Fig. 4 The relationship between the micro-hole extension limit and the flexible hose length by data fitting

Example analysis by a field case

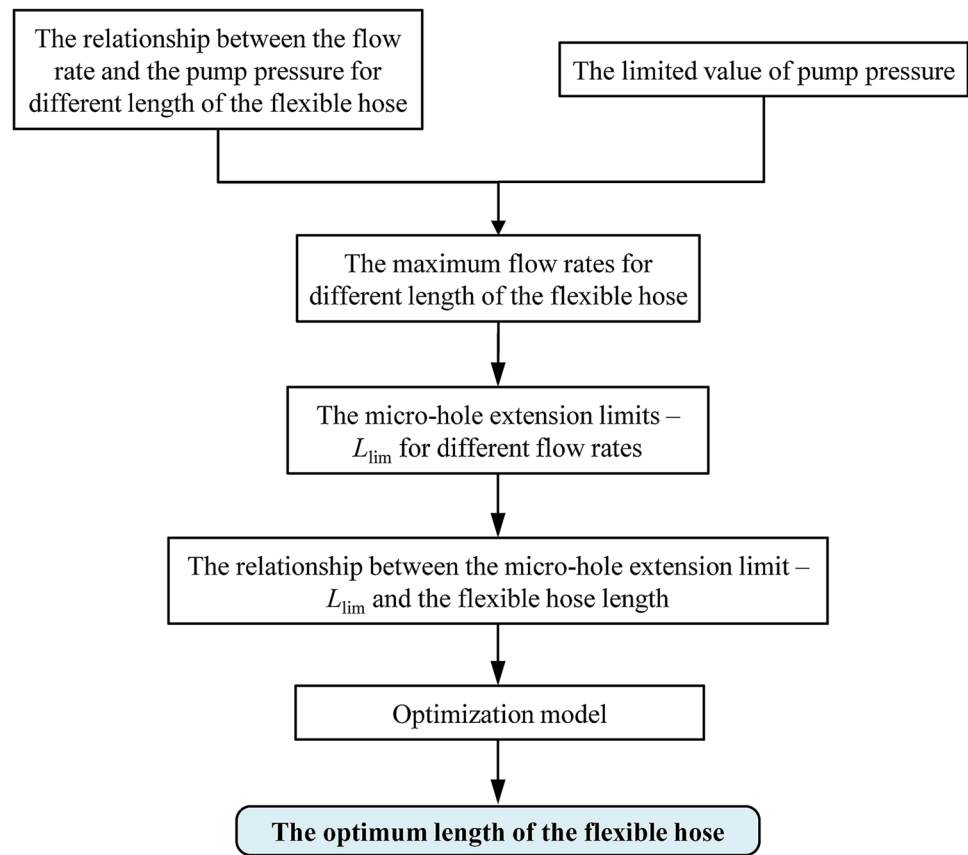
In this part, an example is given according to the method to optimize the length of the flexible hose in RJD by using a field case. Well Q2-3-313 is a vertical well which was closed because of low production rate. RJD technology was applied within depth ranging from 1743 m to 1759 m to develop the residual oil (Gao 2012). As a result, six micro-holes were jetted, and the maximum length of micro-hole is 30.0 m. The maximum operation flow rate is 60 L/min. Other parameters use ones listed in Tables 2 and 3.

According to the parameters and model presented in Sect. 2, the predicted maximum micro-hole length is 26.91 m. The prediction error is 10.3%, which is acceptable for field application. The predicted pump pressure is 54.9 MPa, which is within the range during the operation, i.e., 50–55 MPa. The prediction above verifies that the micro-hole extension limit model is valid and can be used to optimize the length of the flexible hose.

According to the parameters in tables and the flow chart, the application of the optimization method follows steps:

- Step 1: Determine the maximum value of pump pressure. According to the field case, the rated pump pressure is 60 MPa. The maximum value of pump pressure is 60 MPa by the constraint conditions.
- Step 2: Obtain flow rates for different length of flexible hose at $p_p = 60$ MPa. Then, calculate values of the micro-hole extension limit for different flow rate just obtained.
- Step. 3: Get the relationship between the micro-hole extension limit and the flexible hose according to the results from Step 2 and Step 3.

Fig. 5 Flow chart of optimization of the length of the flexible hose for RJD



Step 4: The length of the diverter track is assumed to be 0.5 m in this example. The optimum length of the flexible hose is 32.05 m. And the micro-hole extension limit is 31.55 m, which is 5.2% longer than the operated maximum micro-hole length.

Conclusions

A method to optimize the length of the flexible hose has been developed according to the micro-hole extension limit prediction model that is verified by a field case. The conclusions in this study are as follows:

- (1) The constraint conditions must be met in RJD for the equipment capability and safety requirement.
- (2) The micro-hole extension limit decreases logarithmically with the increase in the length of the flexible hose under the condition that the pump operates at the constant pump pressure.
- (3) Optimizing the length of the flexible hose can maximize the performance of the pump, contributing to the

largest micro-hole extension limit. The optimization model is applied by a field case and is proved to be effective to increase the micro-hole extension limit.

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Declarations

Conflict of interest The authors declare that they have no conflict of interests

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