Book Chapter

Research and Application of a Proppant Transport Experimental Device for Complex Fractures in the Unconventional Reservoir

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Abstract

Due to the brittleness of shale and tight reservoir and the development of natural fractures and horizontal beddings, complex fractures will be built by shear slip and tensile failure during multi-staged horizontal well fracturing. Whether proppant can enter complex fractures and form effective support in main fractures and branch fractures determines conductivity of complex fracture and stimulation effect of multi-staged horizontal well fracturing. By means of discretization of disordered complex fractures, the orthogonal three-dimensional physical model of complex fractures is obtained, and the complex fracture experimental device for simulating fractures complexity is developed, and a complete set of proppant transport characteristics experimental device in unconventional reservoir complex fractures is formed. Combined with field parameters and lab experiments, influence of proppant performance parameters and discharge capacity to proppant transport characteristics in complex fractures of unconventional reservoir is studied. And on the basis of experimental results and analysis, sensitivity analysis method is applied to analyse the influence degree of proppant transport characteristics in complex fractures of shale or tight sandstone reservoir. The sensitivity order of influence factors is fracture morphology, proppant performance, liquid viscosity, displacement and proppant concentration. The experimental device and research results can provide strong experimental support for the optimisation of shale or tight sandstone fracturing materials and field parameters.

Keywords

Unconventional Reservoir; Multi-Staged Horizontal Well Fracturing; Proppant Transport; Complex Fractures; Experimental Study

Introduction

To access large shales or tight sandstone gas, multi-stage fracking is typically utilized, and which is repeatedly used in each horizontal well as many as 20 times [1-9]. Unconventional reservoir(shale or tight sandstone) is characterized by brittleness, natural fractures and horizontal bedding developed. Shear slip and tensile failure are easy to occur during fracturing. Artificial fractures are complex fractures instead of single symmetrical wing fracture as shown in Figure 1, the main fractures and branch fractures in complex fractures are orthogonal and interconnected. During fracturing operation, whether proppant can enter complex fractures and form effective support in main fractures and branch fractures determines the conductivity of complex fractures and the stimulation effect of multi-staged horizontal well fracturing [10]. Therefore, the transport of proppant in complex fractures play an important role in the success of multi-staged horizontal well fracturing.

At present, the research of proppant transport in fracture are mainly theoretical aspects. Lab engineering simulation and evaluation experiments are rarely carried out, and most of them are single fracture, and the complexity of the fracture is limited [11-23].

Therefore, it is necessary to master the formation mechanism, morphological analysis and characterization of complex fractures in unconventional reservoir(shale or tight sandstone), and develop an experimental device that can effectively simulate complex fractures. Combined with field parameters, lab experimental research is carried out to quantitatively study the influence of displacement, proppant / fluid type, fracture morphology and other factors on proppant transport in complex fractures, so as to provide strong technical support when optimizing proppant and field parameters for unconventional reservoir(shale or tight sandstone).

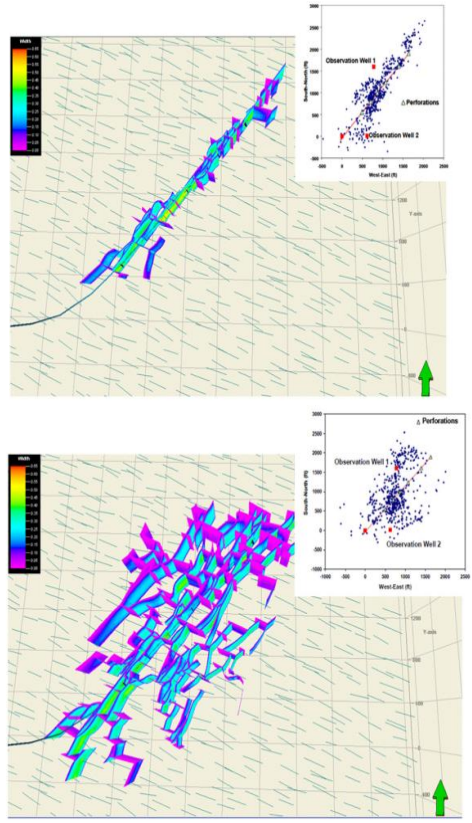

Figure 1: Schematic diagram of single symmetrical wing fracture with gel fracturing (left) and complex fractures with slickwater fracturing (right) [10].

Development of Experimental Device

Design Principle

Multi-staged horizontal well fracturing is easy to produce branch fractures and eventually form complex fractures. In order to study the transport characteristics of proppant in complex fractures, hydraulic fractures and natural fractures intersect and combine in a certain way to form fractures with different structures [14]. Finally, the disordered complex fractures are discretized to obtain an orthogonal three-dimensional physical model of complex fractures, as shown in Figure 2.

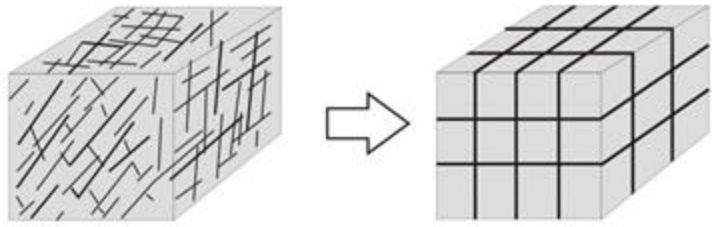

Figure 2: Schematic diagram of discretised complex fractures model [14]

Device Design

Based on the orthogonal three-dimensional physical model of complex fractures, and in order to observe the transport characteristics of proppant in the fracture, 4 × 4 × 4 pieces of plexiglass used to form 3 × 3 × 3 vertical and horizontal cross complex fracture, as shown in Figure 3.

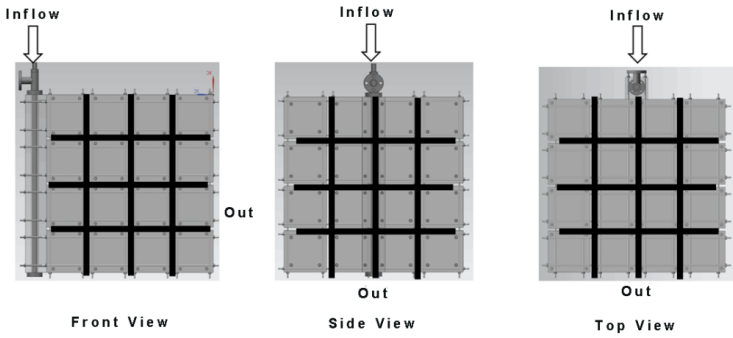

Figure 3: Schematic diagram of complex fractures device design

There are 4 layers of the complex fracture device with 16 pieces of plexiglass in each layer. Fractures are formed between plexiglass. Different thickness gaskets are used to adjust the width of the plexiglass, and layers are assembled from top to bottom, as shown in Figure 4.During the assembly process, different fracture models can be obtained by reserving fracture in different plexiglass. Some different types of fractures models, as shown in Figure 5.

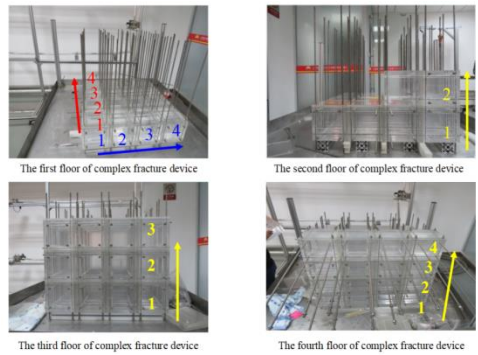

Figure 4: Assembly process of complex fractures device

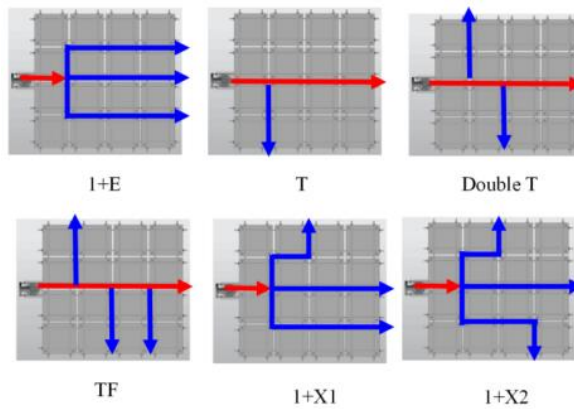

Figure 5: Different types of fractures models

Device Parameters

On the basis of complex fracture device, fluid tank, screw pump,flowmeter, sand storage tank, sand supply pump, liquid circulation pump, image and data acquisition are connected, and finally the experimental device of proppant transport characteristics in complex fracture of unconventional reservoir is formed. The flow chart and the physical diagram are shown in Figure 6 and Figure 7 respectively.

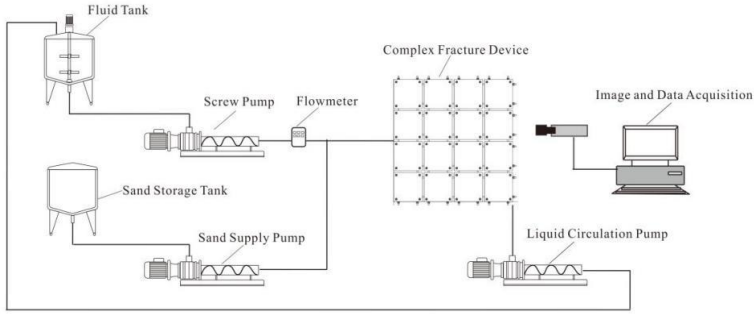

Figure 6: The flow chart of the experimental device of proppant transport characteristics in complex fractures

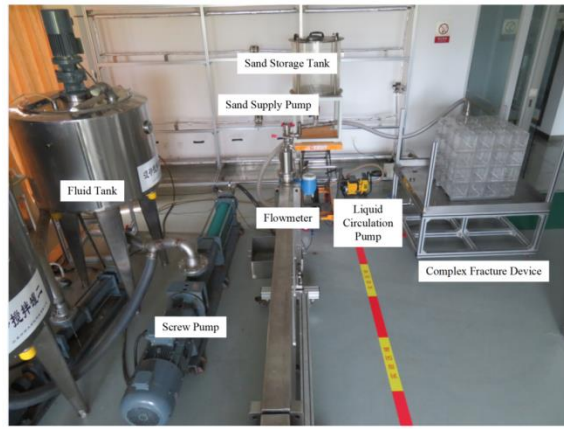

Figure 7: The overall appearance of the experimental device of proppant transport characteristics in complex fractures

The functional parameters of the experimental device are shown in Table 1. The highlight of the device is that there are 27 fracture nodes. As the experimental requirements changing, the direction and width of fractures can be adjusted at different nodes, so as to obtain the complex fractures with different geometry and widths, which is helpful to complete the simulation experiment of proppant transport characteristics in complex fractures.

Table 1: Functional parameters of proppant transport characteristics complex fractures experimental device.

Item	Parameter Value
Unit size of complex fractures device	600 mm * 600 mm * 600 mm
The length and number of main fractures	600 mm, 1 fractures
The length and number of second fractures	600 mm, 3 fractures
The length and number of third fractures	600 mm, 3 fractures
Horizontal fractures	600 mm, 3 fractures
Fractures height	150~600 mm
Fractures width	1~10 mm
Fractures nodes	27
Maximum displacement	200 L/min
Pressure resistance	1.2 MPa
Suitable proppant types	various proppant particles of 20 ~ 140 mesh
Suitable liquid type	slickwater、linear gel

Experimental Methods

Determination of Experimental Parameters

According to the principle of Reynolds similarity [14], the field displacement of multi-staged horizontal well fracturing is converted into the lab experimental displacement, and the calculation formula (1) is as follows:

$$v_e = \frac{v_f}{h_f \times w_f \times 2} \times (h_e \times w_e) \quad (1)$$

Where V_e - lab experimental displacement, m^3 / min;
v_f-field displacement, m^3 / min;
h_f - the height of artificial fracture , m;
w_f -the width of artificial fracture , mm;
h_e -the height of the fracture in the complex fracture experimental device, m;
w_e -the width of the fracture in the complex fracture experimental device, mm.

Record of Experiment Process

The highspeed video camera in the data acquisition and control system is used to record the experimental process, and record the transport characteristics of proppant in the complex fracture experimental device under different experimental conditions, as shown in Figure 8.Some experimental results are shown in Figure 9.

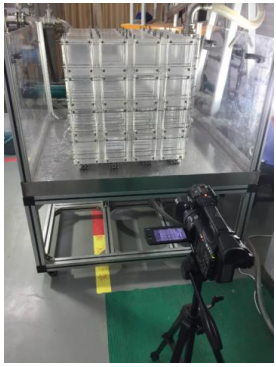

Figure 8: Highspeed video camera record proppant transport characteristics in complex fractures

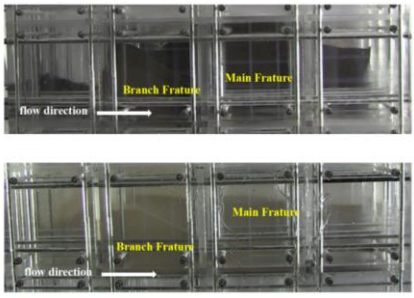

Figure 9: The different experimental results of proppant transport in complex fractures

Experimental Scheme

In order to study the influence of proppant performance, displacement, sand concentration, liquid viscosity and fracture morphology on proppant transport characteristics in complex fractures, the experimental scheme design is shown in Table 2.

Table 2: Experimental scheme of proppant transport in complex fractures.

Number	Proppant type	Experimental displacement L/min	Sand concentration kg/m^3	Liquid type	Fracture morphology
1	40/70mesh，ceramsite	15	200	Slickwater	1+E
2	50/100mesh，ceramsite	15	200	Slickwater	1+E
3	70/140mesh，ceramsite	15	200	Slickwater	1+E
4	70/140mesh，quartz sand	15	200	Slickwater	1+E
5	40/70mesh，ceramsite	12.5	200	Slickwater	1+E
6	40/70mesh，ceramsite	17.5	200	Slickwater	1+E
7	40/70mesh，ceramsite	15	150	Slickwater	1+E
8	40/70mesh，ceramsite	15	250	Slickwater	1+E
9	40/70mesh，ceramsite	15	200	linear gel	1+E
10	40/70mesh，ceramsite	15	200	Slickwater	T
11	40/70mesh，ceramsite	15	200	Slickwater	Double T
12	40/70mesh，ceramsite	15	200	Slickwater	TF

Experimental Results and Analysis

The Influence of Proppant Performance to Transport

The characteristics of transport in the main fracture are shown in Figure 10 (left). The balance heights(proppant vertical transport distance) of 40/70 mesh ceramsite, 50/100 mesh ceramsite, and 70/140 mesh ceramsite are 120mm, 100mm, and 92mm respectively. By comparing 70/140 mesh ceramsite with 70/140 mesh quartz sand, 70/140 mesh quartz sand is relatively consistent in the main fracture, and the balance height is 75mm.
The characteristics of transport in the branch fractures are shown in Figure 10 (right). The balance heights of 40/70 mesh ceramsite, 50/100 mesh ceramsite, 70/140 mesh ceramsite, and 70/140 mesh quartz sand are 32mm, 114mm, 100mm, 82mm respectively, and the front edge (proppant horizontal transport distance) are 371mm, 448mm, 525mm, and 600mm respectively.

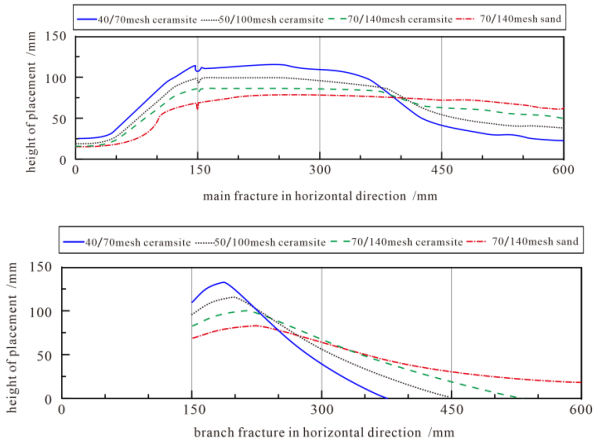

Figure 10: The transport characteristics of proppants in the main fracture (left) and branch fractures (right) with different proppant performance (granularity, density).

The balance heights of the same proppant in the main fractures is longer than that in the branch fractures, and the slope of proppant dune is relatively smoother when the same proppant transport in the main fracture, which is caused by stronger scouring effect of liquid on the proppant dune.

During field operation, in order to form longer and effective proppant fractures.Under the condition of satisfying the proppant strength, proppant with small granularity and low density should be used as far as possible, so that the proppants can be transport further in the fractures.

The Influence of Displacement to Transport

The transport characteristics in the main fracture are shown in Figure 11 (left). When the experimental displacement are 12.5L/min, 15.0L/min, and 17.5L/min, the balance heights of proppant in the main fractures are 120mm, 111mm, 100mm respectively.

The transport characteristics in branch fractures are shown in Figure 11(right). When the experimental displacement are 12.5L/min, 15.0L/min, and 17.5L/min, the balance heights of the proppant in the branch fractures are 136mm, 128mm, 106mm respectively, and the front edge of proppant in branch fractures is 401mm, 432mm, and 485mm respectively.

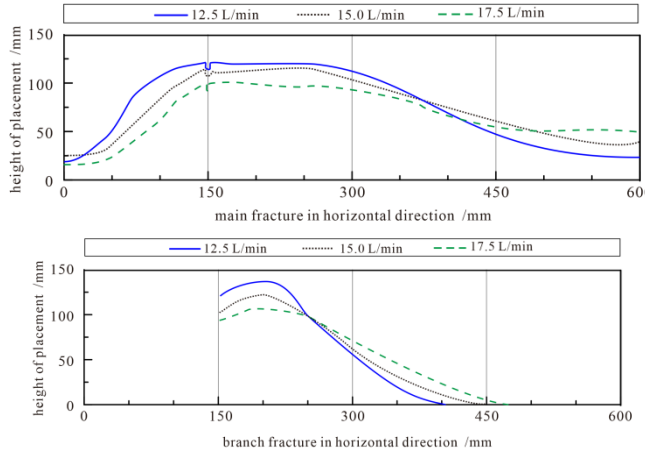

Figure 11: The transport characteristics of proppants in the main fracture (left) and branch fractures (right) with different displacement

By compraring the experimental results under same displacement conditions, it is similar to the experimental results

when proppant performance is used as a variable. The transport characteristics in the main fracture is caused by the stronger scouring effect of the liquid on the proppant dune in the main fracture. The larger the displacement, the stronger the scouring effect, which resulting in a longer balance stage of the proppant dune than in the branch fractures, and the slope of the proppant dune is relatively flat.

During field operation, large displacement can make the proppant transport further in the complex fractures, which is beneficial to increase the length of the proppant fractures, but will reduce the proppant concentration at the near wellbore fractures. In order to maximize the near wellbore fracture conductivity, the displacement should be reduced slowly step by step during later stage, so as to cause proppant settling near wellbore, and to increase the accumulation of proppant at the near wellbore fractures.

The Influence of Sand Concentration to Transport

The transport characteristics in the main fracture are shown in Figure 12 (left). When the sand concentration are 150 kg/m^3, 200 kg/m^3, and 250 kg/m^3, the balanced heights of proppant in the main fracture are 133mm, 121mm, 111mm respectively.

The transport characteristics in the branch fractures are shown in Figure 12 (right). When the sand concentration are 150 kg/m^3, 200 kg/m^3, and 250 kg/m^3, the balance heights of the proppant in the branch fractures are 136mm, 127mm, 112mm respectively, and the fronts edge of proppant in the branch fractures are 422mm, 450mm, 479mm respectively.

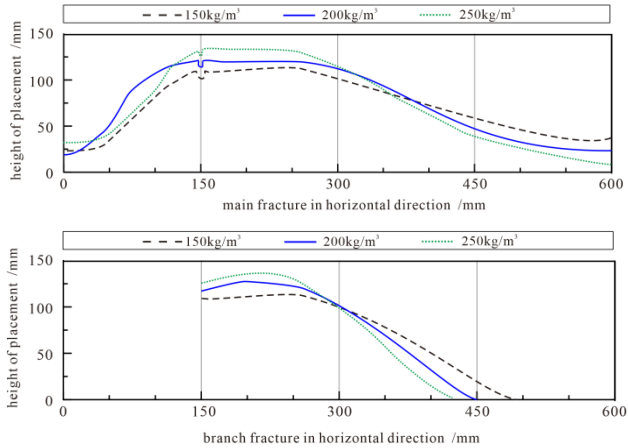

Figure 12: Propant transport characteristics in the main fracture(left) and branch fractures (right) with different sand concentrations

By comparing the conditions of different sand concentrations, it's contrary to the experimental results when the displacement is used as a variable. At the same displacement, the balance stage of the proppant in the main fracture is longer than in branch fractures, and the slope of the proppant are relatively flatter as a result of stronger scouring effect of the liquid and larger displacement.

During field operation, lower sand concentration is beneficial to the proppant transport further in the complex fractures, which is helpful to increase the length of the proppant fractures, but it will reduce the proppant concentration at the near wellbore fractures. In order to maintian the near wellbore fracture open, the sand concentration should be increase slowly step by step during later stage , so as to cause proppant settling at the near wellbore, and to increase the accumulation of proppant at the near wellbore, and finally to provide low resistance to flow at the near wellbore fracture.

The Influence of Fluid Viscosity to Transport

The transport characteristics in the main fracture are shown in Figure 13 (left). When the viscosities of the fracturing fluid are

2mPa·s (slickwater) and 34mPa·s (linear gel), the balanced heights of proppant in the main fracture are 121mm and 95mm respectively.

The transport characteristics in branch fractures are shown in Figure 13 (right). When the viscosities of fracturing fluid are 2mPa·s (slickwater) and 34mPa·s (linear gel), the balance heights of the proppant in branch fractures are 127mm and 95mm respectively, and the fronts edge of proppant in branch fractures are 450mm and 600mm respectively.

By compraing different fluid viscosities, the experimental results are similar to the results when displacement is a variable. For different fracturing fluids, the balance stage of the proppant in the main fracture is longer ,and the slope of proppant dune is relatively gentled. As the viscosity increases, the transport capacity is relatively increased, and the settlement speed of proppant decreases, which has an influence on the formation and accumulation of the proppant dunes.

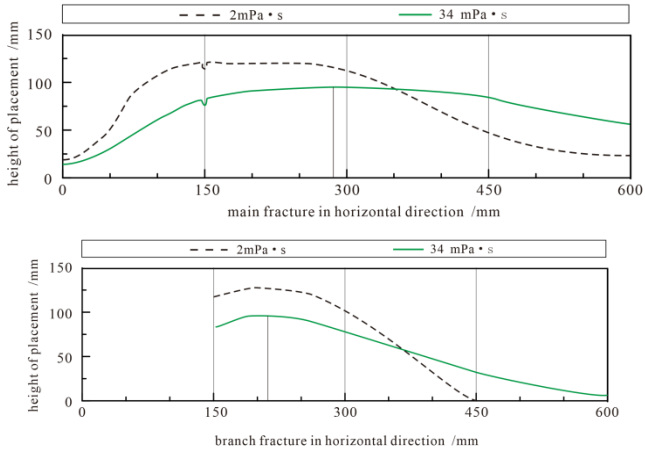

Figure 13: Proppant transport characteristics in the main fracture (left) and branch fractures (right) with different fracturing fluid viscosity

During field operation, the linear gel can appropriately increase the transport capacity, so that the proppant will be transport to the further of the complex fracture, which is beneficial to

increase the length of the proppant fracture, but it will reduce the proppant concentration at the near wellbore fracture. Therefore, the part of the linear gel slug is used to carry sand in the mid-term, and slickwater in the later stage to ensure the length of the proppant complex fracture and the proppant concentration of at the near wellbore fracture, so as to facilitate the flow from the reservoir through the fracture and to the wellbore.

The Influence of Fracture Geometry to Transport

The transport characteristics in the main fracture are shown in Figure 14(left). After the type '1+E' and type 'T' fracture formed branch fractures at 150mm in the horizontal direction, the balanced heights of proppant in the '1+E' and type 'T' main fracture are 116mm and 102mm respectively. After the type 'Double T' fracture formed branch fractures at 150mm and 300mm in the horizontal direction, the first and second balanced heights of proppant in the type 'Double T' main fracture are 89mm and 109mm respectively. After the type 'TF' fracture formed branch fractures at 150mm, 300mm, and 450mm in the horizontal direction, the first, second, and third balanced heights of proppant the type 'TF' main fracture are 77mm, 97mm, 104mm respectively.

The transport characteristics in the branch fractures are shown in Figure 14 (left). The heights of proppant in the ‘T’, ‘Double T’ and ‘TF’ first branch fractures are 116mm, 122mm, and 126mm respectively. The heights of proppant in the ‘Double T’ and ‘TF’ second branch fracture are 98mm and 87mm.The height of the proppant in the 'TF' third branch fracture is 113mm.

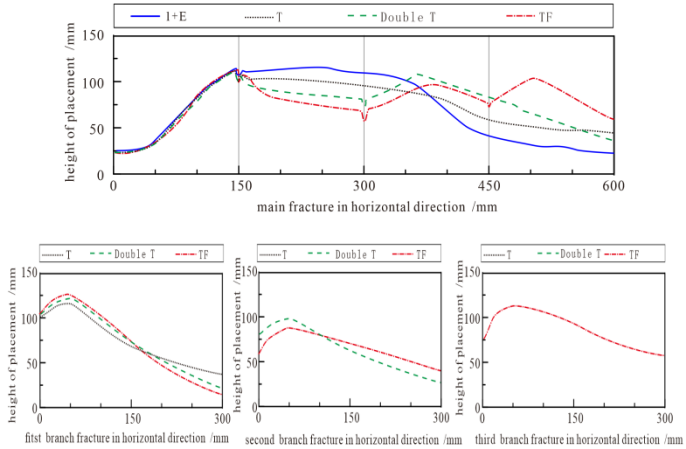

Figure 14: Propant transport characteristics in the main fracture (left) and branch fractures (right) with different fracture geometry

By comparing the transport characteristics of proppants with different fracture geometry in the main fractures and branch fractures, as the fracture complexity gradually increases and the fluid in the fracture being multiple diversed, the closer the diversion nodes, the smaller the fluid flow, the lower the flow velocity in the fractures, and the weaker the carrying and scouring effect of proppant. Therefore, the farther away from the entrance of fractures, the higher balanced heights of proppant.

During the field operation, as the operation proceeds, the complexity of the fracture geometry increases, the fluid pump in the reservoir is diverted step by step, and the flow velocity in the branch fractures gradually decreases, meanwhile the carrying capacity of the proppant and the scouring effect on the proppant dunes decreases. Therefore the more complex the fractures are, the less conducive to transport of proppant. In the mid-term, high-displacement injection should be ensured to compensate the reduction in sand carrying capacity caused by the diversion of complex fractures, and enough proppants should be provided in branch fractures to improve the hydrocarbon production from the well.

Sensitivity Analysis of Factors Affecting Proppant Transport Characteristics in Complex Fractures

In order to understand the sensitivity of five factors to proppant transport characteristics in complex fractures, the sensitivity analysis method is applied to analyse , and compare the sensitivities between them.

Sensitivity analysis is a method of analysing system stability in system analysis, Given a system whose system characteristic P is mainly determined by n factors $a=\{a_1, a_2, \ldots, a_n\}$, and $P=f(a_1, a_2, \ldots, a_n)$. In a certain reference state $a^*=\{a_1^*, a_2^*, \ldots, a_n^*\}$, the system characteristic is P^*. Make each factor changes within its own possible range, and analyse the trend and extent of the deviation of the system characteristic P from the reference state P^* caused by the changes of these factors, which is called sensitivity analysis [21].

When analysing the influence of the n parameter a_n on the characteristic P, the other parameters are all referenced, and the sensitivity of the system characteristic P to a_n is expressed as:

$$\psi(a_k) = f(a_1^*, a_2^*, \cdots, a_{k-1}^*, a_k^*, a_{k+1}^*, \cdots, a_n^*)\,\psi(a_k) \tag{2}$$

Where- The sensitivity of the system characteristic P to a_k.

The relative error of the system characteristic P is:

$$\delta_p = |\Delta P| / P \tag{3}$$

Where- ΔP The sensitivity of the system characteristic P to a_k.

The relative error of the parameter a_k is:

$$\delta_{a_k} = |\Delta a_k| / a_k \tag{4}$$

Where- Δa_k *Error of* a_k.

From the formula (4), the sensitivity function curve S_k-a_k of a_k can be drawn. Take $a_k=a_k^*$ to get the sensitivity factor S_k^* of the parameter a_k:

$$S_k^*=S_k(a_k^*)=\left|\left(\frac{d\varphi_k(a_k)}{da_k}\right)_{a_k=a_k^*}\right|\frac{a_k^*}{P^*}\quad k=1,2,...,n \tag{5}$$

S_k^*, k=1, 2, …, n, is a set of dimensionless non-negative real numbers. The larger the value of S_k^*, the more sensitive P is to a_k in the reference state. Through the comparison of S_k^*, the sensitivity of the system characteristics to various factors can be compared and evaluated.

System characteristics, the proppant transport characteristics in complex fractures, are characterized by the ratio of the balance height of proppant to the proppant transport distance in the main and branch fractures. The parameters for sensitivity analysis include proppant performance, displacement, sand concentration, liquid viscosity, fracture geometry.

Observe the proppant transport characteristics in complex fractures, and use curve fitting methods to obtain the sensitivity function, and then calculate the sensitivity factor. Based on the existing experimental results and analysis, the sensitivity values of each parameters is obtained. As shown in Table 3, the sensitivity degree to proppant transport in order is fracture geometry, proppant performance, liquid viscosity, displacement, and proppant concentration.

Table 3: Influencing factors and sensitivity factors of proppant transport characteristics in complex fractures.

Influencing Factors	Proppant Performance	Displacement	Sand Concentration	Liquid Viscosity	Fracture Geometry
Sensitivity Factor	1.19	0.91	0.71	1.07	1.35
Sensitivity Level	Ⅱ	Ⅳ	Ⅴ	Ⅲ	Ⅰ

Conculusions

- Discretise the disordered complex fractures to obtain an orthogonal three-dimensional complex fracture physical model. Developed a complex fracture experimental device, and formed an experimental device to research the transport propant in complex fractures. Highspeed video camera is

used to record the proppant transport characteristics in the complex fracture during the entire experimental process under different conditions.

- Completed experimental research with different factors on proppant transport characteristics in complex fractures. Results shows that, under different conditions(particle size, density, displacement, sand concentration, and liquid viscosity), the same proppant transport at the balance stage of the proppant dune is longer than that in the branch, and proppant dune has a relatively flat slope in the main fracture due to liquid has a stronger scouring effect. With the fracture complexity increasing gradually, and the fluid in fractures is diverted step by step, the later the diverging node, the lower the flow velocity in the fractures and the higher balanced heights of proppant;
- Based on existing experimental results, observe the proppant transport characteristics in complex fractures, and use curve fitting methods to establish the sensitivity function, and then calculate the sensitivity factor of each influencing factors. Results show that, the sensitivity degree to proppant transport in order is fracture geometry, proppant performance, liquid viscosity, displacement, and proppant concentration.The experimental device and research results can provide strong support to optimize the materials into wells and optimize field parameters for unconventional reservoirs multi-staged horizontal well fracturing.

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