An analysis of influential factors to the development of tight gas sands by multi-stage fractured horizontal wells
---A Case study in Sulige gas field

LuoRuilan[1] XuMei[2] LiuXiaohua[1] Liuhualin[1]

（1. CNPC Research Institute of Exploration and Development—Langfang；2.ZhunDong Oil Production Plant, XinJiang Oil Field, CNPC）

Abstract

With large recourses in the world, tight gas sands have become hotspots to increase reserve and production for many countries in recent years. However, under the current economic and technological conditions, its recoverable reserves and productivity of individual wells are still lower. Staged fracturing horizontal well technology can effectively improve the contact area of production intervals and reservoirs, increase well productivity, and reduce the drilling wells. However, the domestic study on development indicators and production performance of the technology in tight gas sands is limited.

This paper takes Sulige gas field --- the largest gas field in China--- as an example. For geological features in such gas fields, by using methods of numerical well-test simulation and economic evaluation, taking initially absolute open flow (q_{AOF}), cumulative gas production/recovery factor and internal rate of return (IRR) into account, the optimum parameters of the reservoir, drilling, completion wells and stimulations for multi-stage fractured horizontal wells are obtained.

Introduction

Currently, unconventional gas resources, especially the development of tight sandstone gas are highly paid more attention in the world. With vast areas of tight gas exploration, rich in resources in China, it has become an important force in natural gas supply and will continue to be the highlight of reserves and production growth. On proved reserves and technical strength, the exploration and development of tight sandstone gas is the most realistic sense in unconventional gas fields in China [1].

There are large tight gas recourses in the world. However, under the current economic and technological conditions, its recoverable reserves and productivity of individual wells are still lower. It is difficult to develop effectively these kinds of reservoirs in large scale. Staged fracturing horizontal well technology can effectively improve the contact area between well completion and reservoir, which increase well productivity and reduce drilling wells. However, the study on production performance of multi-stage fractured horizontal wells is limited in China.

This paper takes Sulige gas field as an example. Considering the geological features in such gas fields, by using methods of numerical well-test simulation and economic evaluation, taking initially absolute open flow (q_{AOF}), cumulative gas production/recovery factor and internal rate of return (IRR) into account, the optimum parameters of reservoir, drilling, completion wells and stimulations for multi-stage fractured horizontal well are obtained.

Modeling and parameter selection

Parameters of reservoir and gas wells

Sulige gas field is the largest gas field in China. It is typical fluvial tight sandstone gas reservoir, and the effective sand bodies are the isolated lenticular distribution. It is characterized as a fine-grained tight gas with clean to dirty sands of found to be interbedded with thin shale streaks at depth ranging from 2700m to 3400m. Permeability ranges from 0.05md and 1.0md, while porosity values lie between 4% and 14%.

Figure 1and **Figure 2** are the distribution of dynamic reserves and drainage width and length of individual wells in eastern Sulige, separately[2-3].

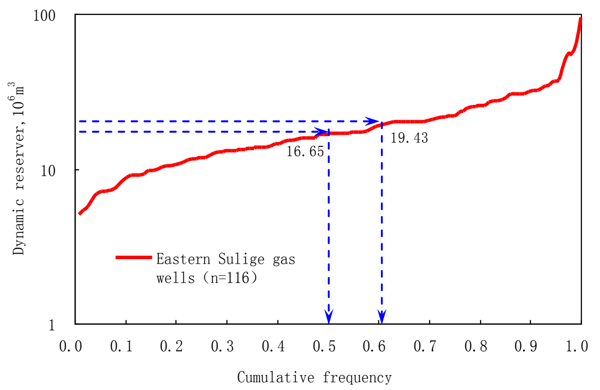

Fig.1 Distribution of dynamic reserves of Eastern Sulige wells

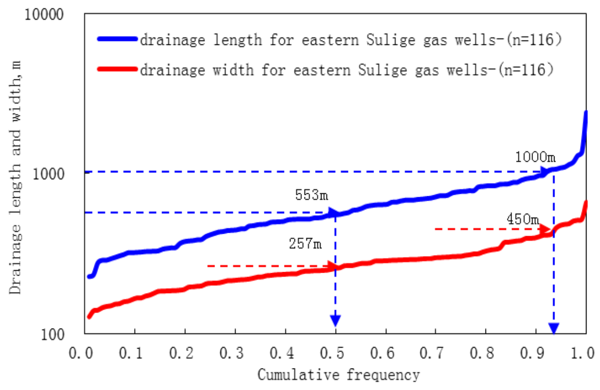

Fig.2 Distribution chart of discharge width in eastern Sulige

Considering geological features and dynamic characteristic in Sulige gas fields[2-6], basic parameters of reservoir and horizontal well are chosen and listed in **Table 1**. A model of multi-stage fractured horizontal well with closed rectangular boundary (600m×1200m) is set up. Considering the poor continuity in fluvial effective tight sandstone, two barriers which are semi-permeable, are added in the model (**Figure 3**).

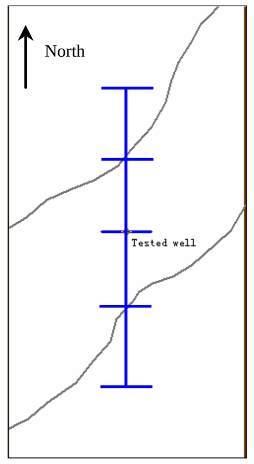

Fig. 3 The model of multi-stage fractured horizontal well

Table1 Basic parameters of reservoir and gas well

Initial formation pressure, MPa	30
Reservoir thickness, m	8
Porosity, %	10
Reservoir effective permeability，md	0.075
Horizontal section length of gas wells，m	800
Fracture half-length，m	60
Psc ，MPa	0.101
Tsc，K	293

Economic parameters

According to the actual drilling and production costs in Sulige gas field, and taking drilling and completion costs of multi-stage fractured horizontal wells in tight gas field in the North American for reference [7], the economic parameters are selected, which shown in **Table 2**.

Table2 Economic parameters

Total cost of fractured vertical wells，M$/Well	1.26
Total cost of fractured horizontal wells，M$/Well（lateral length 800m, completion 5 stages）	3.79
Drilling cost of lateral , $/m	1263
completion, M$/Stage	0.064

Natural gas commodity rate，%	90
Gas prices， $/mcf	4.12
Business tax and surcharges，$/mcf	0.123
Operating costs，$/mcf	0.492
IRR，%	8

Influential factors to development effect of fractured horizontal well

Reservoir thickness-permeability

The different thickness, different permeability, different well types are simulated. Total cases are 5×4×2=40（**Table 3**）.

Table 3 Simulation parameters of reservoir thickness and permeability

h—reservoir thickness，m	4, 10, 15, 25, 40
k--reservoir permeability，md	0.05, 0.075, 0.1, 0.3
Well type	Fractured vertical wells、Fractured horizontal wells（5 stages）

Note: for fractured vertical wells, the fracturing stage is 1

Comparing cumulative gas production, initially absolute open flow (q_{AOF}) and internal rate of return(IRR) (q_{AOF} in gas wells means the average productivity of gas wells in the first month) from different cases, the results are shown as following:①Cumulative gas production and q_{AOF} both increase linearly with kh; ②IRR increases with reservoir thickness, but the growth rate slows down gradually; ③ With permeability increases, IRR of fractured vertical wells will gradually beyond those of the fractured horizontal wells.

Because IRR is associated with both reservoir thickness and permeability, a chart is set up to indicate appropriate range of thickness and permeability, which suitable for different types of wells (**Figure 4)** .In **Figure 4,** the area above the blue curve is suitable for fractured vertical wells, and the area below the blue curve is suitable for multi-stage fractured horizontal wells.

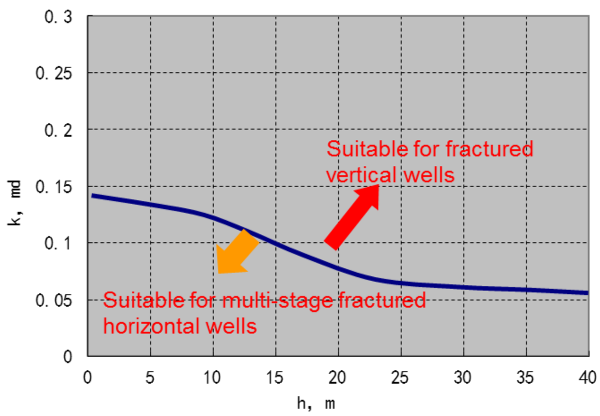

Fig. 4 Chart of thickness and permeability suitable for different type of wells

Compared with fractured vertical wells, multi-stage fractured horizontal wells are more suitable for development of tight reservoirs with thinner thickness and lower permeability (kh <2.0md.m).

However, when the value of kh is lower than 0.1md.m, the IRR of both vertical fractured wells and multi-stage fractured horizontal wells are negative at current gas price in China (4.12$/mcf) (**Figure 5)**. It is not economical to develop tight gas reservoir with kh<0.1 md.m at current gas price. In **Figure 5,** fracturing stage 1 presents fractured vertical well, and the others present multi-stage fractured horizontal wells. It is shown that IRR of multi-stage horizontal wells increases quickly when fracturing stages increase from 2 to 6, and when the fracturing stage is more than 6, the growth rates gradually reduce. When gas price is higher than 5.37$/mcf, the IRR of multi-stage fractured horizontal wells with fracturing stage 4~10 is positive.

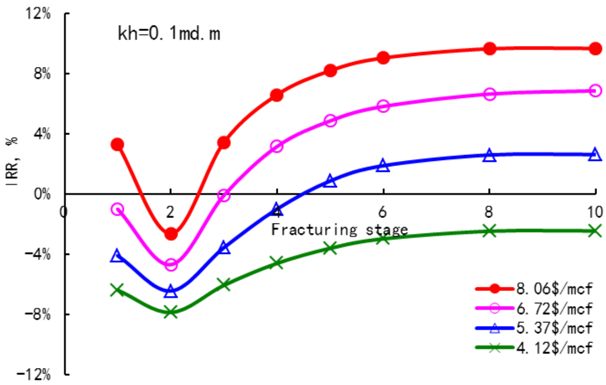

Fig. 5 Relationship of gas price and IRR for different type wells

Anisotropy of vertical and horizontal permeability

Taking four different K_h / K_v value and two type wells into account. K_h presents horizontal permeability of reservoir, and K_v presents vertical permeability of reservoir. Total cases are 4 × 2 = 8 (**Table 4**).

Table 4 Simulation parameters of K_h/K_v

K_h/K_v,	0.001, 0.01, 0.1, 1.0
Well type	Multi-stage fractured horizontal wells, Conventional horizontal wells

Note: fracturing stage of multi-stage fractured horizontal wells is 5; conventional horizontal wells are not fractured.

The evaluation results are shown as following:①Kv/Kh has little effect on development effect of fractured horizontal wells, but has great impact on those of conventional horizontal wells; ②When there exist vertical interlayers, the horizontal wells must be fractured in order to obtain better development effect (**Figure 6** to **Figure 7**).

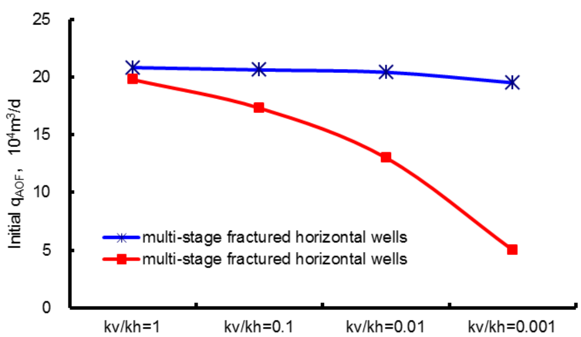

Fig. 6 Relationship of Kh/Kv and initial q_{AOF}

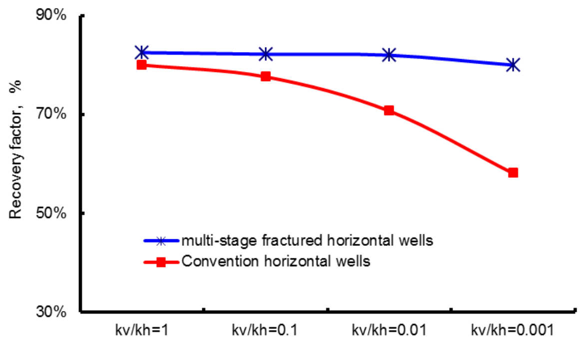

Fig. 7 Relationship of Kh/Kv and recovery factors

Lateral length of horizontal wells

Taking six different lateral length in range of 300m to 1000m, and two-type wells into account, total programs are 6×2=12(Table 5).

The evaluation results are shown as following: (**Figure 8~ Figure 10**);①both initial q_{AOF} and recovery factor increase with the lateral length of horizontal wells, but the growth rates gradually derease. Lateral length has more impact on the development effect of conventional horizontal wells; ②For multi-stage fractured horizontal wells, optimal development effect can be obtained when the lateral length is in the range of 600m to 800m.

Table 5 Simulation parameters of lateral length

lateral length，m	300, 400, 500, 600, 800, 1000
Well type	Multi-stage fractured horizontal wells, Conventional horizontal wells

Note: fracturing stage of multi-stage fractured horizontal wells is 5; conventional horizontal wells is not fractured

Dynamic information of gas wells should be considered to determine the optimal lateral length of horizontal wells.The production performance analysis of multi-stage fractured horizontal wells in Suligas field shows that when lateral length is lower than 700m (reservoir drilling rate 55%~65%), the dynamic reserves of these wells is much less than those of wells with lateral length of 800m to 1200m (**Figure 11** and **Table 6**).

Table 6 Lateral length of Sulige multi-stage fractured horizontal wells

Well No.	S3X-15-XH	S3X-18-XH	S3X-7-XH	S3X-8-XH
lateral length,m	382.5	1050	1200	471.8
reservoir lateral length，m	248	915.3	578.8	269.2

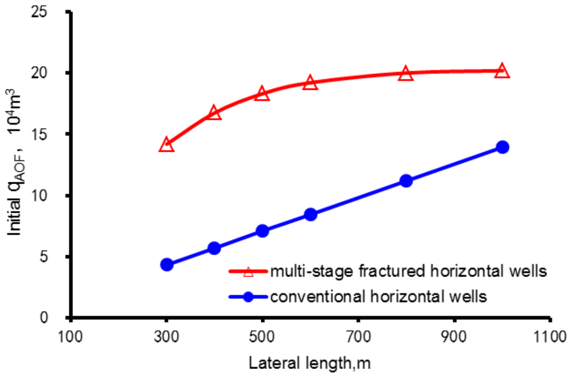

Fig. 8 Relationship of lateral length and initial q_{AOF}

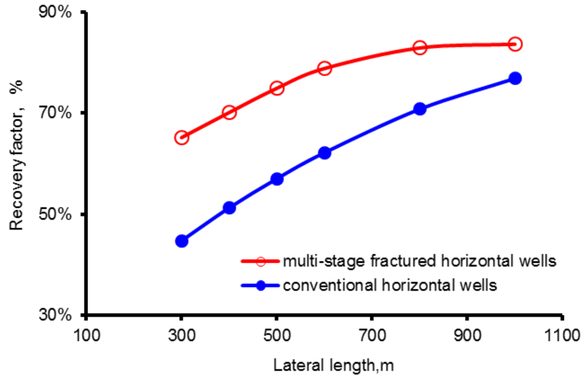

Fig. 9 Relationship of lateral length and recovery factors

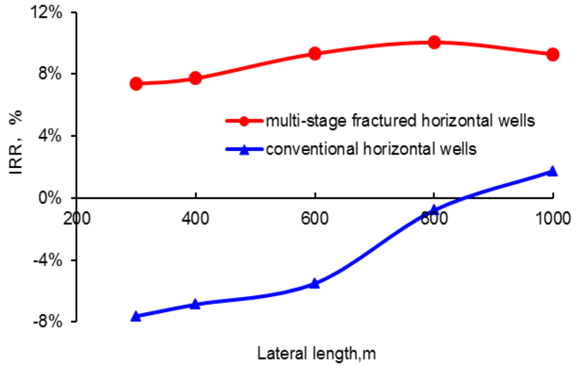

Fig. 10 Relationship of lateral length and IRR

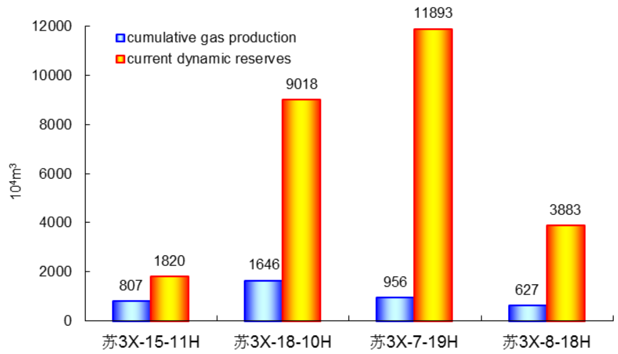

Fig.11 Dynamic reserves of Sulige fractured horizontal wells

According to the geologic statistics of dimension of single sand body, and results of well interference testing, most length of effective sand body is less than 900m in Sulige gas field. Considering the results of theoretical calculations, reservoir drilling rate and drilling rig capacity, the proposed length of the horizontal section in Sulige gas wells is within the range of 800m to 1200m.

Fracturing stages

Eight different fracturing stages with nine different permeability (0.01md~1.0md) are stimulated. Taking the two-type wells (the fractured horizontal wells and the fractured vertical wells) into account, and total cases are 8×9=72 (**Figure** 12~14).

Table 7 Simulation parameters of fracturing stages

Fracturing stages	1, 2, 3, 4, 5, 6, 8, 10
Formation permeability，md	0.01, 0.03, 0.05, 0.075, 0.1, 0.15, 0.3, 0.5, 1.0

By analyzing data in **Figure 12** to **Figure 14**, it is found that the reasonable fractured stages in horizontal wells are closely related to the formation permeability. The lower the formation permeability is, the more stages need to be fractured. And therefore a reasonable fracture spacing Chart is determined according to the reservoir permeability, shown in **Figure 15**. With this chart, the reasonable fractured stages of horizontal wells can be determined.

In fact, reservoir conditions in Sulige gas field is more complex than the modling of this paper. There exists many tight barriers and the scales of effective sand bodies are limited. So when determining the reasonable fracture spacing in gas wells, the well logging imformatoin and drilling imformatoin need to be carefully considered.

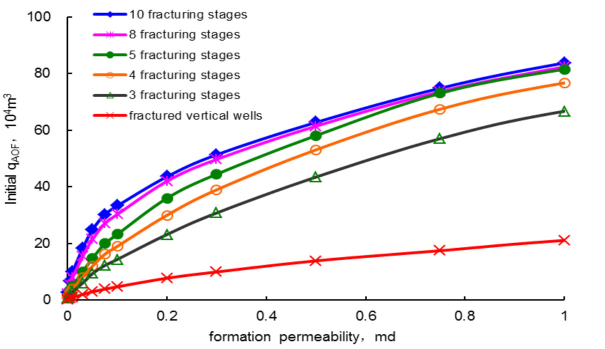

Fig. 12 Effect of Fracturing stages on qAOF

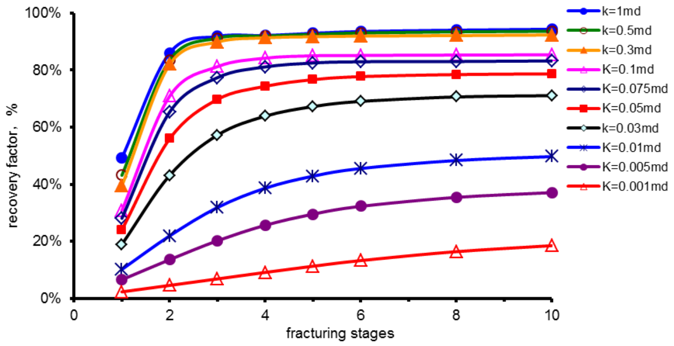

Fig.13 Effect of Fracturing stages on Recovery

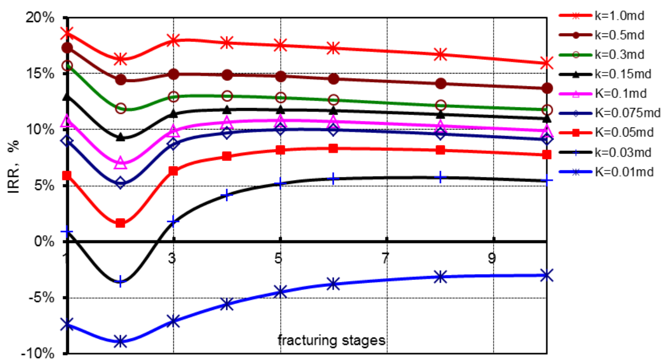

Fig.14 Effect of Fracturing stages on IRR

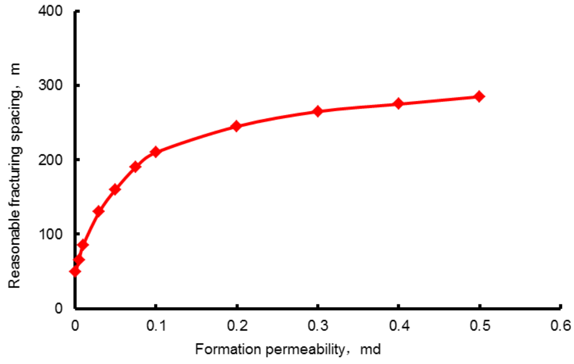

Fig.15 Reasonable fracture spacing of fractured horizontal wells

Fracture half -length

Nine different fracture half-length(20m～240m) with four different permeability(0.03md~0.1md) are stimulated, and total cases are 9×4=36 (**Figure 16~ Figure 18**).

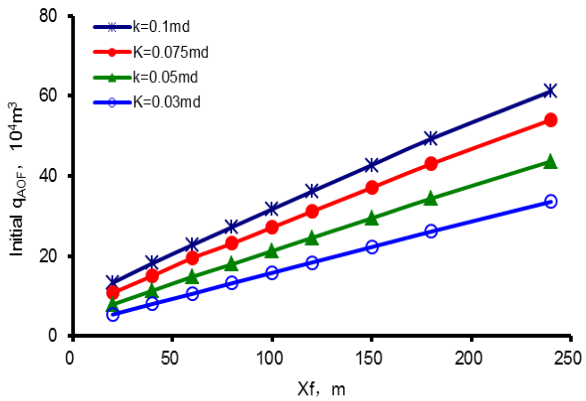

Fig.16 Effect of Fracture half-length on qAOF

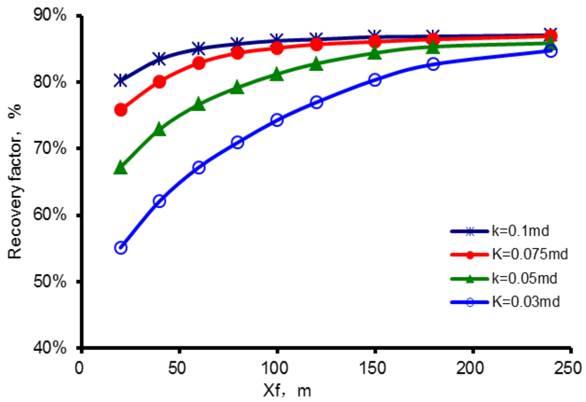

Fig.17 Effect of Fracture half-length on Recovery

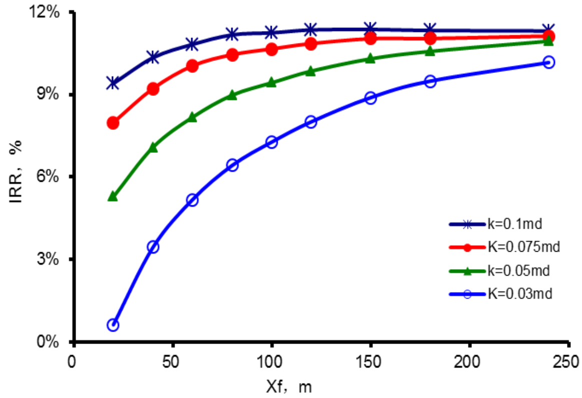

Fig.18 Effect of Fracture half-length on IRR

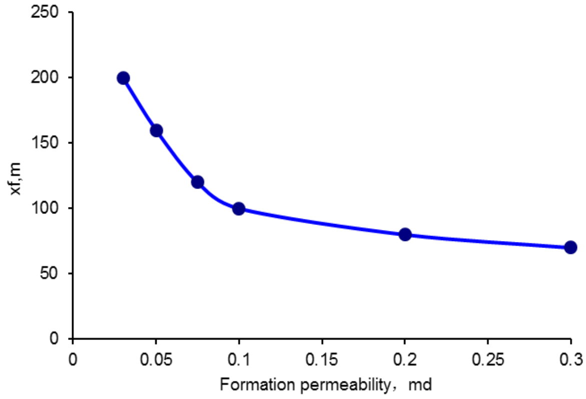

Fig.19 Reasonable Fracture half-length Chart for fractured horizontal wells

Table 8 simulation parameters of fracture half-length

Fracture half-length xf，m	1, 2, 3, 4, 5, 6, 8, 10
Formation permeability，md	0.03, 0.05, 0.075, 0.1

From **Figure16** to **Figure18**, the q_{AOF} increases linearly with fracture half length, and the recovery and IRR increase slowly with the increasement of fracture half-length. The best value of fracture half-length is closely related to formation permeability, and the lower formation permeability is, the longer the required fracture half-length is. According to above analysis, a reasonable fracture half-length chart is established, shown in **Figure 19**.

Fracture conductivity

Eight different fracture conductivity (1md.m～500md.m) with two different permeability(0.03md~0.1md) are stimulated. Total cases are 8×2=16 (Fig.19-21). The caculation conclues that when fracture conductivity is about 50md.m（FCD=10）, the best development effect will be obtained. So when fracturing technique is used in the horizontal wells in tight gas resevoir, it is not necessary to get high fracture conductivity.

Table 9 Simulation parameters of fracture conductivity

Fracture conductivity Fc，md.m	1, 2, 5, 10, 20, 50, 200, 500
Formation permeability，md	0.03, 0.075

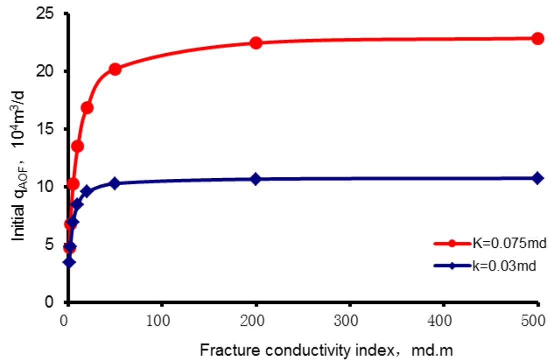

Fig.20 Effect of Fracture conductivity on q_{AOF}

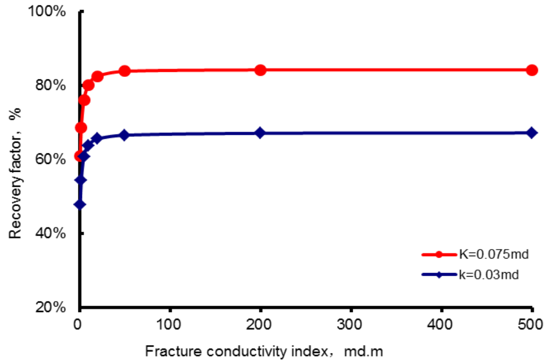

Fig.21 Effect of Fracture conductivity on Recovery

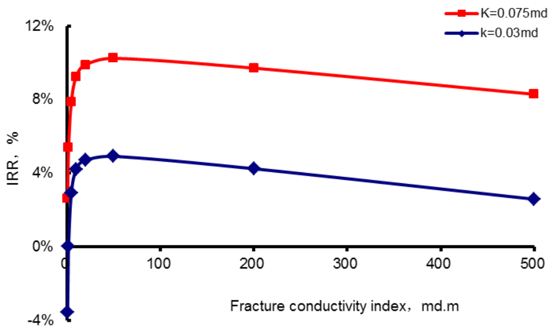

Fig.22 Effect of Fracture conductivity on IRR

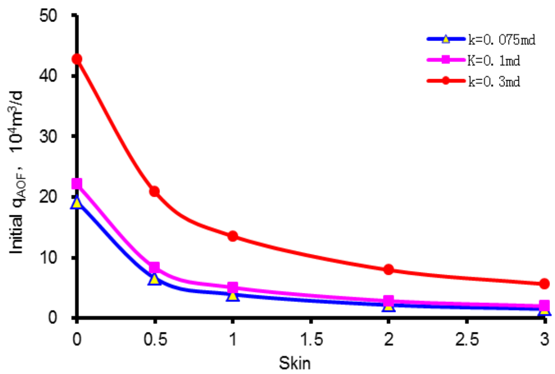

Fig.23 Effect of skin on t q_{AOF}

Skin

Five different skin values (0～3.0) with three different permeability(0.075md、0.1md、0.3 md) are stimulated, and total cases are 5×3=15 (**Figure 23 to Figure 25**).Comparing with vertical wells, the drilling time of horizontal wells will be longer, and the contact area between drilling(complection) fluid and resevoir will be larger. So, under the same reservoir and drilling conditions, the formation damage of horizontal wells is generally much more serious than that of vertical wells. Figure 23 - Figure 25 show that skin values have great impact on the gas development effect. And the lower the formation permeability is, the greater the influence is. For unconventional gas reservoirs, high quality of drilling and completion are needed. Many factors will affect the skin values of gas wells, such as the proppant strength, colloidal damage, clay damage, fracture geometry, proppant, the stress, fracturing fluid flowback and the like[8].

Table 10 Simulation parameters of skin values

Skin	0, 0.5, 1.0, 2.0, 3.0
Formation permeability，md	0.075, 0.1, 0.3

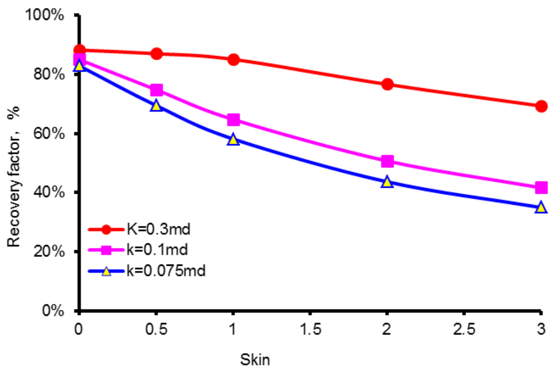

Fig.24 Effect of Skin on Recovery

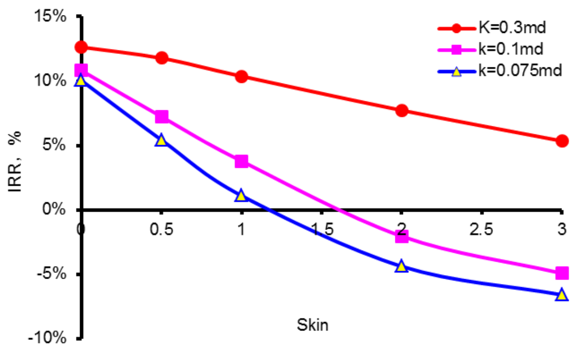

Fig.25 Effect of Skin on IRR

Conclusions

By using methods of numerical well-test simulation and economic evaluation, taking initially absolute open flow (q_{AOF}), cumulative gas production/recovery factor and internal rate of return (IRR) into account, the optimum parameters of reservoir, drilling and fracturing for multi-stage fractured horizontal well are obtained.

① Compared with fractured vertical wells, multi-stage fractured horizontal wells are more suitable for developing the reservoirs with thinner thickness, lower effective permeability (kh<2.0md.m). However, when kh is less than 0.1md.m and gas price is less than 4.12$/mcf (the current natural gas price of Sulige gas field), it is not economical to develop such kind of reservoirs neither with multi-stage fractured horizontal wells nor fractured vertical wells.

② For Sulige gas field, the suitable parameters of multi-stage fractured horizontal wells are horizontal length 800m to 1200m, fracturing stages 4 to 6, fracture half-length 80m to 150m, and fracture conductivity 50md.m (FCD=10).

③ Skin values have a great impact on gas development effect, the lower the formation permeability is, and the greater the influence is. For unconventional gas reservoir, high qualities of drilling and completion are most important.

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