A Comparative Study on Wellbore Pressure Transmission of Water and Carbon Dioxide during Fracturing

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Abstract. Hydraulic fracturing is one of the most effective ways for the development of unconventional oil and gas resources, CO₂ has been regarded as an excellent alternative to water as its broad application prospects in unconventional reservoir development and benefit for CO₂ utilization. The wellbore pressure will keep rising before fracture initiation during hydraulic fracturing, and fluid properties have significant influence of wellbore pressure transmission especially for CO₂ fracturing. In this paper, a wellbore pressure transmission model based on the definition of fluid compressibility is established and coupled with wellbore flow model of compressible fluid to calculate the borehole pressurization rate for water-based and CO₂ fracturing. The model has been verified by field data. The results show that the borehole pressurization rate for both water-based and CO₂ fracturing reveal rising trend as pump rate increasing, and borehole pressurization rate of water-based fracturing is 10~20 times that of CO₂ fracturing with same pump rate. Moreover, the borehole pressurization rate increases linearly with pump rate of water-based fracturing, but excessive pump rate might reduce borehole pressurization rate of CO₂ fracturing. The research results can simulate more perceptions for the optimizing design of actual hydraulic fracturing operating.

1. Introduction

With oil and gas consumption rising rapidly in the last few years, the development of unconventional oil and gas reservoir is playing a growing role in the world energy picture. Hydraulic fracturing is one of the most effective ways for the development of unconventional oil and gas resources [1], however, the huge water consumption and severe formation damage limit the application of traditional hydraulic fracturing in the commercial exploration [2]. Carbon dioxide (CO₂) has been regarded as an excellent alternative to water as its characteristics of harmless to the formation and easier to yield a high-connectivity fracture network. Besides, CO₂ fracturing can effectively simulate the development of carbon capture, utilization and storage (CCUS) [3-5], which provide a promising solution to turn the greenhouse gas into treasure.

The energy is transferred from the surface pump by fracturing fluid injecting during hydraulic fracturing, and then powers the fracture initiation and propagation [6, 7]. According to the fracturing
curve from the field test, the inlet pressure of CO₂ fracturing grows more slowly than that of water-based fracturing before fracture initiation, the reason lies in the hysteresis of wellbore pressure transmission caused by the stronger compressibility of CO₂. Furthermore, the physical properties of CO₂ vary with well depth [8, 9] instead of keeping constant as water-based fracturing fluid when flowing downward the wellbore, further affecting the transmission of wellbore pressure. Hence, it is essential to quantize the wellbore pressure transmission of various fracturing fluid to analyse the characteristics of CO₂ and water as fracturing fluids and optimize the operation designs.

In comparison with water-based fracturing fluid, the change of CO₂ physical properties with temperature-pressure conditions is considerable [8, 9], therefore, the pressure transmission is related to CO₂ physical parameters in the wellbore for CO₂ fracturing. Wellbore temperature and pressure coupling calculation model is usually used to deal with this issue. At present, the one-dimensional steady flow governing equations of compressible fluid and quasi-steady heat transfer equation [9, 10] are most widely used in the existing wellbore flow models, which adopt the fundamental laws of thermodynamics to describe the dependence of temperature on pressure variation. The existing researches have revealed that the compressibility of CO₂ might play an important role [11, 12] in predicting the temperature and pressure during wellbore flow, however, the studies on CO₂ wellbore flow still concentrate on coupling calculation of wellbore flow and heat transfer, the existing pressure transmission models for CO₂ fracturing are based on the incompressible assumption. In this study, a pressure transmission model considering fluid compressibility in the wellbore is established, and the pressurization rate is quoted to quantized the speed of wellbore pressure transmission. It should be noted that the wellbore pressure transmission model needs to be coupling with wellbore flow model because of the sensitivity of fluid properties. The model is verified with data from an actually CO₂ fracturing well. In the end, the model is applied to contrastively analyze the pressure growth and transmission mechanisms of water-based fracturing and CO₂ fracturing.

2. The Mathematical Model

The bottom hole pressure grows with wellhead fluid injecting to generate tangential stress till this tangential stress overs the tensile strength of the reservoir rock [13-15]. The volume compressibility coefficient of CO₂ is ten to dozens of times that of water, thus, the wellbore pressurization rate of CO₂ fracturing is much lower than that of water-based fracturing. In addition, the volume compressibility coefficient of CO₂ changes significantly with the temperature-pressure condition instead of keeping constant as water within wellbore temperature and pressure range, consequently, the borehole pressurization rate for CO₂ fracturing needs to be coupling solved.

2.1. Pressurization Rate in the Wellbore

A borehole pressurization rate model is developed according to the definition of volume compressibility [6, 16], and a sectioning method is applied because of the nonconstant properties for compressible fluid. The reasonable assumptions are made to simply the calculation as follows: (1) the seepage into the reservoir rock of the fracturing fluid at the bottom hole is neglected; and (2) the deformation of the wellbore caused by fluid injecting is not considered in this study.

On the basis of assumption (2), the volume of the wellbore remains unchanged, denoted as $V_0$, as shown in figure 1. The wellbore is divided into $N$ finite elements, as shown in figure 2, noted the volume of the $i^{th}$ section as $dV_{0}^{i}$, and the pump rate of fracturing fluid is marked as $Q$, unit in m$^3$/min. During a period of time $dt$, a $Q dt$ volume of fracturing fluid is injected into the wellbore, in the meantime, the fluid in the wellbore is compressed, including the in-situ wellbore fluid and injected fluid. Then, based on the definition of compressibility, the volume change can be superimposed by the compression of the in-situ and injected fluid using equation (1), and then we can obtain the formula for borehole pressurization rate, demonstrated as equation (2):

$$dV = Q dt = \left( \beta_m Q dt + \sum_{i=1}^{N} \beta_i dV_{0}^{i} \right) dp$$  \hspace{1cm} (1)
where \( \bar{\rho} \) is the average density of injecting fluid within \( dt \) period, kg/m\(^3\); and \( \beta \) is the volume compressibility, 1/MPa.

\[
C = \frac{dp}{dt} = \frac{Q}{\beta \bar{\rho} Q dt + \sum_{i=1}^{N} \beta_i dV_{0}^{(i)}} = \frac{M / \bar{\rho}}{\rho + \sum_{i=1}^{N} \beta_i dV_{0}^{(i)}}
\]  

(2)

2.2. The Coupling Computation Model of Wellbore Temperature and Pressure

Within temperature and pressure range in the wellbore, the physical properties of water fluctuate little, so water physical parameters are considered as constant in the model. However, for CO\(_2\), physical parameters are functions of temperature and pressure [17], while for CO\(_2\), fluid pressure and temperature are inconstant along the well depth, as a result, physical parameters are coupled with wellbore temperature-pressure when it comes to CO\(_2\) fracturing, which could be solved by the wellbore flow model.

The micro-section of wellbore is shown in figure 2, and three basic hypotheses are proposed for the model in this section: (1) the steady flow and heat transfer of the wellbore flow is considered; (2) the capacity of heat transmission outside the cement conforms Hasan’s Law; and (3) the influences of radiative and longitudinal heat transmission in the wellbore are neglected.

\[
\begin{align*}
\frac{dT}{dz} &= \frac{1}{c_p} \left( \frac{1}{M} \frac{1}{R_f} - \frac{f v^2}{2d_i} + \frac{1}{\rho} \frac{dp}{dz} \right) + J_T \frac{dp}{dz} \\
\frac{dp}{dz} &= \rho g \cos \theta - fv^2 - \frac{\rho v}{2d_i} - \rho v \frac{dv}{dz}
\end{align*}
\]

(3)

where \( c_p \) is the fluid specific heat capacity, J/(kg·K); \( J_T \) is the Joule-Thomson coefficient, K/MPa; \( M \) is the mass flow rate, kg/s; \( T_T \) is the formation temperature, K; \( T \) is wellbore temperature, K; \( R_f \) is the thermal resistance between formation and wellbore fluid; \( \rho \) is fluid density, kg/m\(^3\); \( v \) is the fluid velocity, m/s; \( p \) is the pressure, MPa; \( z \) is well depth, m; \( d_i \) is inner diameter of the injecting pipe, m; \( \theta \) is the deviation angle, rad; \( g \) is the gravity acceleration, m/s\(^2\); and \( f \) is the fluid friction coefficient, dimensionless.

2.3. Physics Properties of CO\(_2\)

Refer to the physical parameters of CO\(_2\), the Span-Wagner equation [18] is applied to compute the thermodynamic properties of CO\(_2\) and the Vesovic model [19, 20] is used for the transfer properties of CO\(_2\). All the aforementioned CO\(_2\) property models are of admitted high precision.
3. Result and Discussion

The wellbore configuration parameters are shown in table 1, and the depth of the gas reservoir is 3250m. The computed results of water-based and CO₂ fracturing are compared with the fracturing curve provided by field tests of the same block, verifying the reliability of the model. And then the pressurization rate under different pump rates of water-based and CO₂ fracturing are analysed.

Table 1. Wellbore configuration data.

| Content         | Surface casing     | Technical casing  | Tubing        |
|-----------------|--------------------|--------------------|---------------|
| Diameter×Depth  | Φ244.5 mm×525.62 m | Φ139.7 mm×3386.55 m| Φ60.32 mm×3252 m |

3.1. Model Verification

As can be seen in figures 3 and 4, the bottom hole pressure of water-based fracturing grows faster than that of CO₂ fracturing, which verifies our statement of the relationship between fluid compressibility and wellbore pressure transmission.

![Figure 3](image-url). The time-varying curve of bottom hole pressure during water-based fracturing before fracture initiation.

![Figure 4](image-url). The time-varying curve of bottom hole pressure during CO₂ fracturing before fracture initiation.

For water-based fracturing, the fracture initiation occurs within 1min injecting with a pump rate of around 0.2m³/min, while for CO₂ fracturing, the fracture initiation occurs at about 5min with an approximately injecting pump rate of 0.5 m³/min. The tendency of calculated bottom hole pressure for both water-based and CO₂ fracturing are nearly in accordance with measured values according to figures 3 and 4, which indicates the dependability of the computation of borehole pressurization rate.

3.2. The Relationship between Injecting Pump Rate and Borehole Pressurization Rate

According to equation (2), the pump rate of fracturing fluid has a considerable implication on the wellbore pressurization. Therefore, the pressurization rate of water-based fracturing and CO₂ fracturing under different pump rates are researched, the results are shown in figures 5 and 6. Noted that the inlet temperature-pressure condition will also affect borehole pressurization rate of CO₂ fracturing, and the initial conditions consistent with CO₂ fracturing field test in Section 3.1 are set in this computing sample, to be specific, the inlet parameters are $T_0=258K$, $p_0=6MPa$. While for water-based fracturing, the initial injection pressure is same as atmospheric pressure. Figures 5 and 6 demonstrate the curves of borehole pressurization varying with the injecting pump rate for water-based fracturing and CO₂ fracturing.

![Figure 5](image-url). The time-varying curve of calculated borehole pressurization rate for water-based fracturing.

![Figure 6](image-url). The time-varying curve of calculated borehole pressurization rate for CO₂ fracturing.

It can be observed from figure 5 that the borehole pressurization of water-based fracturing increases linearly with pump rate, which could also be concluded according to equation (2). As the physical parameters ($β$ and $ρ$) of water are constant under different temperature-pressure conditions, borehole pressurization rate of water-based fracturing is independent with flowing temperature-pressure conditions.

Comparing figure 6 and figure 5, it can be concluded that the borehole pressurization rate of CO₂ fracturing is far below that of water-based fracturing. It first rises and then reduces as CO₂ pump rate
growing, as shown in figure 6. The reason lies in that CO$_2$ physical properties are significantly depending on temperature-pressure conditions. And under excessive pump rate, the high friction loss would lead to less pressure increment along well depth, which will affect CO$_2$ physical parameters ($\beta$ and $\rho$) and make the borehole pressurization decrease.

In general, the borehole pressurization rate for both water-based fracturing and CO$_2$ fracturing increase with injecting pump rate, and borehole pressurization rate of water-based fracturing is 10~20 times that of CO$_2$ fracturing with same injecting pump rate. In addition, wellbore temperature-pressure conditions have little effect on the borehole pressurization rate of water-based fracturing, but have a significant effect on CO$_2$ fracturing. Excessive pump rate might actually reduce the borehole pressurization rate of CO$_2$ fracturing. Furthermore, the pressure drop resulting from friction loss will increase as pump rate growing for both water-based fracturing and CO$_2$ fracturing, so the injecting pumping rate during fracturing operation needs to be optimized to get a better fracture initiation effect.

![Figure 5](image5.png)  
**Figure 5.** Curve of borehole pressurization over injecting pump rate of water-based fracturing.  

![Figure 6](image6.png)  
**Figure 6.** Curve of borehole pressurization over injecting pump rate of CO$_2$ fracturing.

4. Conclusions
The wellbore pressure will continue to increase before fracture initiation during hydraulic fracturing. And the properties of fracturing fluid have significant influence of wellbore pressure transmission. In this paper, we establish a new wellbore pressure transmission model on the grounds of fluid compressibility definition and solved the model considering the characteristics of water and CO$_2$ as fracturing fluid. Finally, the conclusions of this study are summarized as follows:

1. For water-based fracturing, the borehole pressurization of water-based fracturing increases linearly with pump rate and is independent with flowing temperature-pressure conditions.
2. For CO$_2$ fracturing, the borehole pressurization rate first rises and then reduces as CO$_2$ pump rate growing, excessive pump rate might reduce borehole pressurization rate.
3. The borehole pressurization rate of water-based fracturing is 10~20 times that of CO$_2$ fracturing with same injecting pump rate.

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