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Optimization design of hydraulic parameters for supercritical CO_2 fracturing in unconventional gas reservoir

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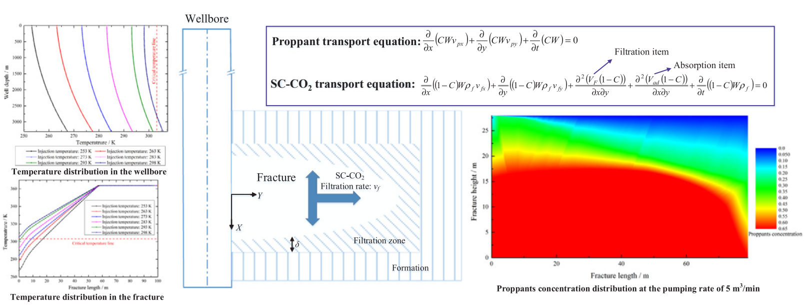
GRAPHICAL ABSTRACT



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ABSTRACT

Unconventional gas reservoirs are characterized by ultra-low permeability. Such ultra-low permeability can significantly affect the geometry of the fractures being created in the reservoir, as well as bring about challenges with regard to how to effectively mitigate formation damage issues during fracturing. Supercritical CO_2 (SC-CO_2) fracturing, as an innovative and promising stimulation method, incurs no formation damage, and is capable of effectively improving the reservoir permeability, preventing near-wellbore formation blockage. Taking the effects of adsorption between CO_2-shale-CH_4 into consideration, a two-phase filtration rate calculation model of SC-CO_2 fracturing in unconventional natural gas reservoirs is proposed. Based on physical property equations of a SC-CO_2 fluid, and considering the internal fluid energy, the change in flow work, and the filtration and adsorption characteristics of SC-CO_2-shale, temperature and pressure field models were built inside the wellbore and fracture of SC-CO_2 fracturing, as was a two-phase flow model of SC-CO_2 fracturing fluid carrying proppant in a fracture under an unsteady state. The calculation results show that the temperature and pressure of the fracturing fluid in the wellbore increase with the depth of the well. The temperature of the SC-CO_2 fluid in the fracture increases with the increase in fracture length, and eventually reaches close to the original formation temperature, whereas the pressure of fluid CO_2 in the fracture decreases with an increase in the fracture length. The hydraulic parameters of SC-CO_2 fracturing are optimized, such as the CO_2 injection temperature, pumping rate, proppant density, and diameter. According to the proppant embankment profile, the method of increasing the proppant concentration in small steps and the optimization of the proppant pumping process satisfy the fracture propping requirements.

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Nomenclature

B	the depth of constant temperature point, m;
C	prefactor related to the capacity of the adsorbent for a specific gas, mmol/g;
C_1	composite compressibility coefficient of the invasion region, Pa^{-1};
C_2	composite compressibility coefficient of the reservoir region, Pa^{-1};
C_f	compressibility coefficient of $SC\text{-}CO_2$, Pa^{-1};
C_J	$SC\text{-}CO_2$ Joule–Thomson coefficient, K/Pa;
C_m	compressibility coefficient of natural gas, Pa^{-1};
C_{pf}	specific heat capacity of $SC\text{-}CO_2$ fracturing fluids, (kg·K);
C_R	rock compressibility coefficient, Pa^{-1};
d_p	proppant diameter, m;
D	pipe diameter, m;
$erf(x)$	the Gauss error function, $erfc(x) = 1 - erf(x)$;
g	gravitational acceleration, m/s^2;
G_{DC}	geothermal gradient, K/m;
H	proppants embankment height at any time in fractures, m;
k	permeability, m^2;
M	Molar mass, g/mol;
p_1	formation pressure in the invasion region, Pa;
p_2	formation pressure of the (undisturbed) reservoir, Pa;
p_b	fracturing fluid pressure at well bottom, Pa;
p_f	pressure of $SC\text{-}CO_2$ fracturing fluid inside the fracture, Pa;
p_i	initial reservoir pressure, Pa;
p_{inj}	fluid injection pressure, MPa;
Q_{inj}	fluid injection rate, kg/s;
Re	Reynolds number, dimensionless;
R_M	radial boundary range of wellbore temperature field, m;
t	time, s;
T	temperature, K;
T_b	fracturing fluid temperature at well bottom, K;
T_{ei}	original reservoir temperature, K;
T_f	land surface temperature, K;
T_{inj}	fluid injection temperature, K;
T_{rw}	rock temperature at x position of fracture face, K;
T_{sur}	formation temperature of constant temperature point, K;
v	fracturing fluid flow rate in fracture, m/s;
v_1	fluid filtration rate in the invasion region, m/s;
v_2	fluid flow rate in the reservoir region, m/s;
v_f	filtration rate of $SC\text{-}CO_2$ fracturing fluids, m/s;
v_t	uniform velocity of proppants settling, m/s
V_{ad}	gas adsorbed on the surface, m^3/ kg;
V_{Total}	total filtration amount, Nm^3;
W	fracture width, m;
x	distance from a certain location to fracture mouth, m;
y	vertical distance from some location to fracture face, m;
y_{max}	maximum fracturing fluid cooling distance vertical to fracture face, m;
z	well depth, m;
α	heat exchange coefficient, $J/(m^2{\cdot}s)$;
β	thermal expansivity, 1/K;
ε	absolute roughness, m;
ρ_f	density of $SC\text{-}CO_2$ fracturing fluid, kg/m^3;
ρ_m	density of natural gas, kg/m^3;
ρ_r	density of reservoir rock, kg/m^3;
ρ_s	proppants density, kg/m^3;
τ	Inverse reduced temperature, dimensionless;
μ	viscosity of the $SC\text{-}CO_2$ fracturing fluids, Pa·s;
η	Reduced density, dimensionless;
η_1	pressure-transmission coefficient of the formation in the fracturing fluid invasion region, m^2/s;
η_2	pressure-transmission coefficient of the formation in the reservoir region, m^2/s;
λ	friction coefficient, dimensionless;
λ_{tc}	thermal conductivity, W/(m·K);
φ	Porosity, dimensionless.

1. Introduction

In the 21st century, the world's economic development entered a new stage, with a significantly increasing demand for gas resources around the world, and a huge contradiction of an insufficient gas production capacity. As a result, unconventional gas resources have gradually attracted attentions from researchers [1–3]. However, unconventional gas resources are difficult to produce because they are generally characterized by low porosity, low permeability, low pressure, and a tight rock formation [4]. Through integrating the horizontal well drilling technology and fracturing technology, a historical breakthrough in shale gas production technology was achieved in the development of Barnett Shale of the Fort Worth Basin in Texas, greatly reducing the production cost of a single well [5–8]. Therefore, the fracturing is mainly used for improving the hydrocarbon zone during the development of unconventional gas reservoirs to improve the gas productivity index, significantly increasing the single well production and the duration of stable production. The United States has formed several fracturing treatments and stimulation measures for shale gas reservoirs, such as horizontal well + multiple stage fracturing, water fracturing, synchronous fracturing, and multiple fracturing. However, through site operation, it has been found that conventional hydraulic fracturing can cause severe damage to a low permeable shale reservoir, lead to serious secondary pollution and affect the treatment of fracturing stimulation measures, which are concretely involved in the following ways [9–13]:

(1) formation damage is caused by polymer in an additive water-based fracturing fluid;
(2) an unsuitable drainage velocity easily damages the formation; and
(3) water-sensitivity reservoir is easily damaged.

$SC\text{-}CO_2$ has special phase behaviors, namely, high density, low surface tension, high diffusion coefficient, strong dissolution ability, and good heat transfer characteristics. Compared with liquid CO_2 fracturing, a zero surface tension property (strong flow capability) can allow $SC\text{-}CO_2$ to enter the micro-cracks of a formation that liquid CO_2 or other fracturing fluids cannot. Preliminary studies have shown that the innovative use of these basic features of $SC\text{-}CO_2$ is expected to properly address reservoir contamination problems during the fracturing process [14–20].

The purpose of fracturing is to create fractures with high conductivity connecting the strata and wellbore to change the seepage mode of the reservoir fluid and maximize the hydrocarbon production index of the formation. Fracturing parameter optimization is an important step to improve the fracturing effect of unconventional gas reservoirs. It can produce high conductivity fractures, and allow the development of an efficient production capacity. A $SC\text{-}CO_2$ fracturing fluid has low viscosity and high permeable diffusion capability within the formation, and can enter the pores and micro fractures in the reservoir, such that the micro fractures can be communicated, a micro fracture network is formed, and the oil and gas recovery rate can be improved. At the same time, however, when the viscosity of $SC\text{-}CO_2$ is low and the diffusion capability is high, the $SC\text{-}CO_2$ fracturing fluid in an unconventional gas reservoir will achieve a high filtration rate. The fracture width is narrow, and the sand carrying capacity is weak, which