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Phase state control model of supercritical CO_2 fracturing by temperature control

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ABSTRACT

A phase state control model of supercritical CO_2 (SC-CO_2) fracturing by temperature control has been developed on the basis of CO_2 physical properties, fluid filtration characteristics, internal energy, and flow work variation in the fractures. A considerable amount of analysis focuses on the effects of the CO_2 injection temperature and pressure, geothermal gradient, pumping rate of CO_2 fracturing fluid temperature, pressure field, and phase behavior in the wellbore and fractures. In this study, the phase control method of the fractures during SC-CO_2 fracturing in addition to its chart is obtained. The results indicate that the temperature of the SC-CO_2 fracturing model in the wellbore and fracture is less than that when not considering the flow work model at the same location. During the process of fluid flow, a transition occurs from the liquid to supercritical state in the wellbore or fractures. The phase transformation point differs in the fractures such that a lower injection temperature relates to a high pumping rate, lower geothermal gradient and closer location of transformation point to the end of fractures. Thus, to obtain the optimal stimulation effect of the supercritical CO_2 fracturing, the phase behavior of CO_2 should be controlled according to the reservoir conditions through surface equipment by optimizing the injection temperature, pressure, and pumping rate of the fracturing fluid.

1. Introduction

Unconventional natural gas reservoirs are generally characterized by low porosity, low permeability, and low pore throat radius. The resistance of gas flow is significantly greater than that of conventional reservoirs, and the physical properties degrade with increasing burial depth [1]. Therefore, fracturing has been widely used for improving oil and gas production indices in unconventional reservoir development, with the ultimate aim of improving single-well production and achieving a stable production period.

SC-CO_2 fluid refers to a CO_2 fluid at a particular state above the critical temperature (304.1 K) and critical pressure (7.38 MPa) [2]. The SC-CO_2 is featured with high density, low viscosity, zero surface tension and high diffusion coefficient. It also has good heat transfer and mass transfer performance. The SC-CO_2 fracturing technology has many advantages comparing traditional hydraulic fracturing [3,4]. (1) No harm to the reservoir and be able to prevent clay from swelling in sensitive formations. (2) Can reduce the viscosity. The SC-CO_2 is gasified quickly and dissolved into the crude oil at formation temperature, which can greatly reduce the viscosity of crude oil. (3) Improve the reservoir permeability and reduce fluid flow resistance. (4) Quickly and completely flowing back after fracturing. Compared with the liquid CO_2 fracturing or other fluids, SC-CO_2 has strong liquidity which can flow into the micro fractures of formation with its zero surface tension properties. Meanwhile, it shows up a lower threshold pressure which can greatly reduce pumping pressure [5,6]. In consequence, SC-CO_2 fracturing is a promising fracturing technology. The critical temperature and pressure can be reached in the wellbore by controlling the fracturing parameters, which makes the CO_2 in supercritical state.

In the early years of shale gas development, many countries such as the United States and Canada conducted a large number of experiments to explore CO_2 fracturing technology in shale gas fields with favorable results. The U.S. Department of Energy conducted a pilot test of CO_2 fracturing in tight shale gas reservoirs; the production was five times that of fracturing with N_2 foam [7]. A high yield was also obtained in a tight gas reservoir in south Texas, U.S.A., by using CO_2 fracturing [8]. Moreover, by using CO_2 fracturing, the national energy company of Canada achieved a significant increase in yield in the southern Alberta tight gas reservoir compared with conventional fracturing [9]. The statistics of CO_2 fracturing applications in the field are listed in Appendix A.

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Nomenclature

C_{pf}	specific heat capacity of fracturing fluid, J/(kg·K)
C_{pw}	specific heat capacity of formation fluid, J/(kg·K)
C_{pr}	specific heat capacity of rock, J/(kg·K)
C_R	rock compressibility, Pa^{-1}
C_1	formation compressibility in fluid-invaded area, Pa^{-1}
C_2	compressibility coefficient of oil–gas reservoirs, Pa^{-1}
C_f	compressibility of SC-CO_2, Pa^{-1}
C_{JT}	Joule-Thomson Coefficient, K/MPa
d_{ti}	internal diameter of tubing, m
E_H	specific enthalpy of CO_2, J/kg
f	coefficient of friction resistance, dimensionless
F	fluid filtration rate of SC-CO_2, m/s
G_{DC}	geothermal gradient, K/m
H	fracture height, m
k	permeability, m^2
k_f	fracturing fluid thermal conductivity, J/(m·K)
k_w	formation fluid thermal conductivity, J/(m·K)
k_r	rock thermal conductivity, J/(m·K)
Q_{inj}	injection rate, kg/s
r_0	wellbore radius, m
r_h	outer radius of cement sheath, m
S	saturation of formation fluid, dimensionless
p	pressure, Pa
p_1	formation pressure in fluid-invaded zone
p_2	formation pressure, Pa
p_i	initial formation pressure, Pa
p_f	pressure of supercritical CO_2 in the fracture, Pa
p_b	pressure of fluid at the bottom of well, Pa
p_{ei}	original reservoir pressure, Pa
T	temperature of CO_2 fluid, K
T_0, p_0	temperature and pressure of triple point, K, MPa
T_f	average temperature of fluid in the fracture at y location, K
T_{sur}	temperature of formation at constant temperature point, K
T_{inj}	fluid injection temperature, K
T_{rw}	temperature of rock at fracture wall in y location, K
T_b	temperature of fluid at the bottom of well, K
T_e	temperature of formation at certain depth, K
t	time, s
u	fluid velocity, m/s
V	fluid volume, m^3
W	fracture width, m
α	heat transfer coefficient, J/(m^2·s)
z	well depth, m
ρ_f	fracturing fluid density, kg/m^3
ρ_w	formation fluid density, kg/m^3
ρ_r	rock density, kg/m^3
η_1	pressure conductivity coefficient of formation in fluid invaded zone, m^2/s
η_2	pressure conductivity coefficient of oil-gas reservoirs, m^2/s
φ	porosity, dimensionless
μ	fluid viscosity, Pa·s
μ_1	viscosity of CO_2, Pa·s
μ_2	viscosity of reservoir fluid, Pa·s
θ	angle between wellbore and horizontal plane, °
λ_{wb}	heat transfer coefficient between fluid and formation in wellbore, J/(m·s·K)
T_{wb}	temperature at the interface between wellbore and formation, K
δ	formation thermal diffusivity, m^2/s
ΔE	enthalpy difference, kJ/m^3
erf(x)	gauss error function: $\mathrm{erfc}(x) = 1 - \mathrm{erf}(x)$

The fracture temperature field of the SC-CO_2 fracture affects the physical properties of the fracture fluid and the law of fracture propagation. It is difficult to fully calculate the fracture temperature field for SC-CO_2 fracturing by using the conventional method mainly because for the following reasons. The phase and thermophysical parameters of CO_2 in the fracture are dependent on temperature and pressure, and each parameter needs to be calculated by using a coupling algorithm. In addition, the CO_2 filtration rate is far more than that for conventional fracturing fluid, and a filter cake rarely forms [10]. Further, CO_2 in porous media seepage has an obvious throttling effect [11]; the high filtration characteristics and throttling effect significantly influence the temperature field in the fracture.

The phase control of CO_2 fracturing fluids in the fractures are mainly subject to temperature and pressure fields in the wellbore and fractures, which are determined through coupling calculation. In conventional fracturing, heat conduction, convection, and radiation are considered for calculating the temperature and pressure fields according to the heat transfer law. The temperature field model for heat exchange between liquids and the wellbore or formation is deduced through the finite difference method [12]. Moreover, the dimensionless heat transfer coefficient and Joule-Thomson effect are used to improve the computational accuracy of the temperature and pressure fields in the wellbore [13,14]. In the fracture and near-fracture areas, heat conduction and convection in the formation and heat convection along the direction of the fractures are studied for calculating the temperature field in the fractures [15]. However, this method disregards the temperature gradient in vertical fractures, and the treatment for leak-off is unreasonable. A numerical solution proposed by Kamphuis–Davies–Roodhart (K–D–R) [16] for determining the fracture temperature field considers fractures, the fluid loss zone, and reservoir temperature distribution; therefore this algorithm is ideal. In recent years, application of gas and foam, along with other unconventional fracturing fluid has been greatly developed for use in oil and gas reservoirs, particular in tight reservoir. Analysis on the flowing laws of CO_2 emulsion and CO_2 foam in the fracture combined with laboratory experiments and field examples have been conducted [17–20]. However, research on the temperature and pressure distribution of SC-CO_2 fracturing fluid in fractures requires further improvement.

In this work, based on physical property equation of CO_2, the phase state control model of CO_2 by temperature control has been established in view of CO_2 internal energy, variations of flow work and filtration properties. The effects of injection temperature, injection pressure, pumping rate and different geothermal gradient on CO_2 phase distribution in the wellbore and fractures can be obtained. Accordingly, the phase control method is proposed to provide theoretical basis for SC-CO_2 fracturing.

2. Phase control model

Owing to the CO_2 fluid properties, phase changes occur during fracturing as a result of temperature and pressure variation. CO_2 fluids present three types of phase state: gas, liquid, and supercritical state. The SC-CO_2 fracturing fluid exhibits double properties of