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Pressure transmission in the tubing of supercritical carbon dioxide fracturing

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ABSTRACT

The hydrostatic pressure state at bottom hole is directly correlated with the reservoir stimulation results, and a mathematical model was proposed to investigate the pressure transmission in the tubing in order to calculate the hydrostatic pressure state at bottom hole for supercritical carbon dioxide fracturing. The closed model fully coupled the pressure transmission, heat transfer and compressibility of carbon dioxide, and then the wellbore flow field is presented based on field application. The results show that, the pressure increases in a linear method after hypothermic liquid carbon dioxide is injected into the tubing. In the jet nozzles at bottom hole, the pressure drops abruptly by 6.55 MPa. The increasing trend of temperature slows down gradually as well depth increases, and it dominates the changing trend of both density and viscosity of carbon dioxide. The density, viscosity and conductivity all decreases with increasing depth, while the changing trend of conductivity is dominated by the increasing pressure. As the well depth increases, the capacity firstly increases because of larger temperature increase and then it gradually begins to decrease because of larger influence of pressure increase. The pressure transmission is directly related to density profile and viscosity profile, and the heat transfer is mainly dominated by the temperature difference between carbon dioxide in the tubing and formation rock. The pressure transmission is highly coupled with changing temperature and properties of carbon dioxide. The results facilitate to lay theoretical foundation for manual control of supercritical carbon dioxide fracturing.

1. Introduction

In the exploitation of shale gas resource, multi-stage hydraulic fracturing is essential for obtaining economical enhanced recovery (EOR) [1–3], which has achieved wide application and also met some limitations on the other side. Both scholars and engineers recognized that, fracturing with water-based working fluid would not only consume huge amount of water and could also induce potential damages to both formation and the environment [4,5], hence the feasibility of non-aqueous fracturing fluids (including carbon dioxide [6],liquefied petroleum gas [7], nitrogen [8]) is now drawing more interest. Due to its low viscosity, carbon dioxide fracturing could facilitate to induce complex fractures in stimulated reservoirs [9,10,21], which is also highly related to the effective pressure transmission in the tubing (dominated by the low viscosity and high density of supercritical carbon dioxide). The recovery could also get enhanced further because of prioritized adsorption of carbon dioxide than methane in shale body [11], geological storage of greenhouse gas is another favourable result. Carbon dioxide could also effectively dissolve heavy oil components in pay zone [12], and benefit to increase permeability. Thus, fracturing with carbon dioxide is believed to have promising future, especially suitable for depleted reservoirs and unconventional reservoirs [13].

The fracture propagation is powered by hydraulic pressure at bottom hole [14], which is supplied from pumps at surface and transferred through tubing by the fracturing fluid. Compared to uncompressible fracturing fluid, how the pressure energy is transmitted by carbon dioxide through the tubing is still in fuzzy. The pressure transmission method is essential for better control of the pressure state at fracture entrance, which influences the fracture propagation significantly. The pressure transmission in the tubing is highly related to the density and viscosity of carbon dioxide, and the properties of carbon dioxide would also change significantly with varying pressure and temperature downhole [15,16]. The above-mentioned coupling method would intensify the complexity of quantitative calculation of the pressure transmission. Span-Wagner model [15] and Fenghour-Wakeham model [16] are widely used to calculate the properties of carbon dioxide with best accuracy. Ni et al. [17] have proposed a mathematical model to calculate wellbore flow and heat transfer. Based on pipe-flow

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Nomenclature

ρ	Density, kg/m^3
v	Flow velocity vector, m/s
v_i	the component of v on i axis, m/s
T	Temperature, K
c_p	Isobaric heat capacity, J/(kg K)
h	Specific enthalpy, J/kg
k	Thermal conductivity, W/(m k)
δ	Reduced density, dimensionless
τ	Inverse reduced temperature, dimensionless
M	Molecular weight, kg/mol
R	Universal gas constant, $R = 8.314\ \mathrm{Pa\ m^3\ K^{-1}\ mol^{-1}}$
P	Pressure, Pa
η_0	Zero-density viscosity, μPa s
$\Delta\eta$	Excess viscosity, μPa s
T^*	T/251.196 K, dimensionless
λ_0	Thermal conductivity, W/(m K)
Q_{rc}	Heat transferred from rock to casing, J
Q_{cw}	Heat transferred from casing to water in the annulus, J
Q_{wp}	Heat transferred from water in the annulus to carbon dioxide in the tubing, J
λ_c	Thermal conductivity of casing, W/(m K)
r_r	Diameter of formation rock, m
r_c	Diameter of casing, m
l	Length of finite unit, m
T_r	Temperature of formation rock, K
T_c	Temperature of casing, K
T_w	Temperature of water in the annulus, K
T_p	Temperature of carbon dioxide in the tubing, K
$\hat{h}$	Convective heat transfer coefficient between the inner wall of the tubing and carbon dioxide in the tubing, W/(m^2 K)
λ_p	Thermal conductivity coefficient of tubing, W/(m K)
λ_w	Thermal conductivity coefficient of water, W/(m K)
r_i	Inner diameter of tubing, m
r_o	Outer diameter of tubing, m
m	Mass flow rate, kg/s
m_u	Mass, kg
λ	Flow friction coefficient of carbon dioxide in pipe or annulus, dimensionless
d	Equivalent diameter, m
g	Gravity, m/s^2
A	Section area of the jet, m^3
P_1	Pressure of the jet inlet, Pa
P_2	Pressure of the jet outlet, Pa
T_1	Temperature of the jet inlet, K
R_s	Specific gas constant, $R_s = 0.1889$ kJ/(kg K)
ΔT_j	Temperature drop of the jet
ΔP_j	Pressure drop of the jet
s_{ij}	the symmetric part of local speed gradient tensor, dimensionless
F_i	Mass force component on i axis, m/s^2
p	Stress, Pa
δ_{ij}	Kronecker delta
P_t	Target pressure at bottom hole, Pa

experiment of carbon dioxide, Wang et al. [18] have proposed friction coefficient model vs Reynolds number. The preliminary results lay feasibility for this study to some extent.

According to actual engineer conditions, this study proposes a mathematical model to illustrate the pressure transmission method in the tubing during carbon dioxide fracturing. The model fully couples the hydraulics, flow friction, wellbore heat transfer and properties of carbon dioxide. Finally, the flow field in the tubing is presented and analysed aiming to form theoretical foundation for pressure control at down hole.

2. Mathematical models

In field application, tubing would be implied to locate jet nozzles and transport liquid carbon dioxide from surface to down hole. Hypothermic liquid carbon dioxide would inevitably endotherm from formation, and it finally changes into supercritical state at certain depth. By influencing the properties of carbon dioxide, the pressure transmission and heat transfer is coupled. At bottom hole, the fracture would propagate at certain pressure, and then new flow path emerges to allow carbon dioxide to flow out. The geometry model is presented in Fig. 1.

Experimental study [19] shows that, the geothermal reaction between carbon dioxide and formation rock do not have significant impact on temperature, which is therefor beyond the consideration when calculating temperature profile in this study.

2.1. Governing equations

By influencing the properties of carbon dioxide, the pressure transmission and heat transfer is coupled in the flow field. As a finite volume method, Eulerian method is most widely used for modelling the compressible flow [20], which assumes that the pressure and temperature is constant in every flow field element. Eulerian method is mainly composed of continuity equation, momentum equation and energy equation.

The simplified continuity equation for compressible flow can be

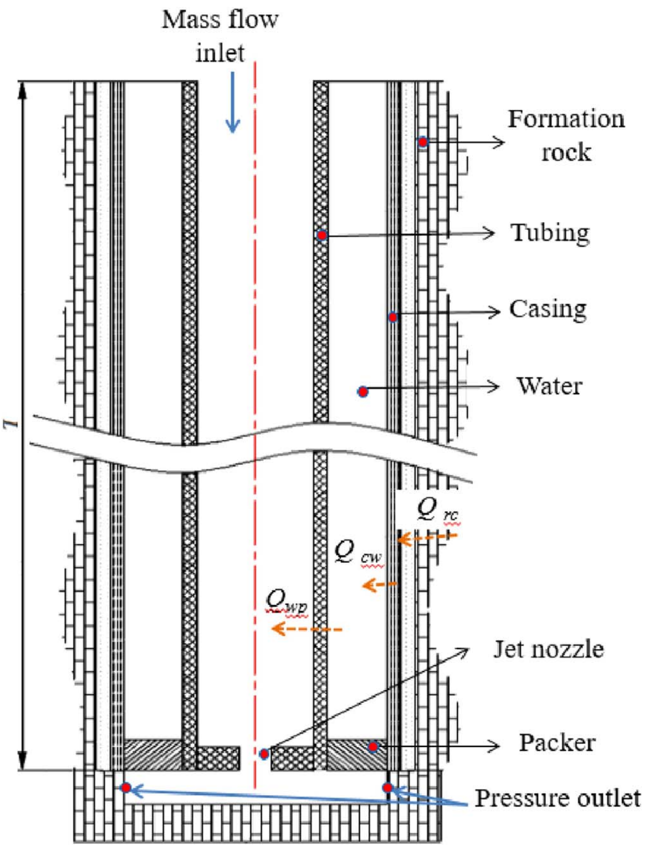

Fig. 1. Physical model of the flow field.