Applied Thermal Engineering 132 (2018) 760–768

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Numerical investigation of wellbore temperature and pressure fields in CO_2 fracturing

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HIGHLIGHTS

- A 2D model for wellbore temperature and pressure prediction of CO_2 fracturing is developed.
- Model is validated by the field data from a hydraulic fracturing well and a CO_2 flooding well.
- Effects of pressure work, viscous dissipation and annulus natural convection are analyzed.
- Commingled injection through tubing and casing can effectively reduce the friction.

ARTICLE INFO

Article history:
Received 1 September 2017
Revised 24 December 2017
Accepted 25 December 2017
Available online 27 December 2017

Keywords:
CO_2
Physical properties
Fracturing
Wellbore
Temperature field
Numerical model

ABSTRACT

A 2-D model for wellbore temperature and pressure prediction during CO_2 fracturing is established based on the coupling of fluid flow and heat transfer, while examining CO_2 property changes, annulus natural convection, pressure work, and viscous dissipation. The model is solved by the finite element method and verified with two field cases. A case study of a 2000 m tubing injection well with a tube size of 76 mm is used to analyse heat transfer mechanisms. The simulation results indicate that the pressure work is negligible only when the injection rate is 2.4–3.1 m^3/min, and the viscous dissipation cannot be neglected at high injection rates (>2.8 m^3/min). The CO_2 temperature increased slightly (<0.5 °C) when considering the annulus natural convection, which is negligible for CO_2 fracturing. In addition, for an increase in injection rate from 0.5 to 4 m^3/min, the friction increased by 29.6 MPa. However, tubing-casing synchronised injection can effectively decrease the friction.

1. Introduction

CO_2 fracturing uses pure liquid CO_2 to form fractures in formations for the enhancement of oil and gas production. This technology has the potential for broad applications as it combines CO_2 sequestration, well stimulation, and enhanced oil and gas recovery. During CO_2 fracturing, the temperature of the CO_2 in the wellbore changes owing to the geothermal gradient and other factors, which affects the CO_2 pressure and phase. When the CO_2 reaches the bottom of the hole, it may be in a supercritical state (Fig. 1), in which the physical properties of CO_2 change dramatically with variations in temperature and pressure. Therefore, it is essential to accurately simulate the flow and heat transfer of CO_2 in wellbores to evaluate its fracturing fluid properties, improve its stimulating effects, and optimize treatment designs.

A large amount of progress has been made since Ramey [1] established the first semi-steady state heat transfer model for wellbores in 1962. While many researchers have further developed Ramey's semi-steady model [2–6], development of transient prediction models for wellbore temperature fields has also achieved significant results [7–13]. In addition to these numerical methods, some researchers have also derived analytical models for calculating wellbore temperature fields [14–21]. At present, simulating the wellbore flow and temperature fields using CO_2 as the injection medium is an imperative research issue. The above methods have all been applied to the research of CO_2 injection wellbores. Applying the semi-steady state numerical method, Lu and Connell [22] used a semi-steady thermal conductivity equation and steady continuity and momentum equations to simulate the non-isothermal flow of gas mixtures including CO_2 in a wellbore. Wu [23] optimized the cubic equation of state (EoS) to calculate the properties of gaseous CO_2, and applied it to establish a semi-steady model of wellbore pressure and temperature for the CO_2 flooding process. Wang [24], Dou [25], and Li [26] used more accurate property

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https://doi.org/10.1016/j.applthermaleng.2017.12.095
1359-4311/

Nomenclature

C_p	isobaric heat capacity, J/(kg °C)	$\mathbf{u}$	velocity vector, m/s
g	gravitational acceleration, m/s^2	v_{inj}	injection velocity, m/s
g_G	geothermal gradient, °C/m	t	time, s
$\mathbf{I}$	unit matrix	T	temperature, °C
k	turbulent kinetic energy, J	T_{ini}	initial temperature, °C
p	fluid pressure, Pa	T_{surf}	surface temperature, °C
p_{ini}	initial fluid pressure, Pa	z	well depth, m
p_{bh}	bottom hole pressure, Pa	z_t	total depth of the well, m
p_{net}	hydrostatic pressure, Pa	α_p	coefficient of thermal expansion defined as $-1/\rho(\partial\rho/\partial T)$
p_{wh}	wellhead pressure, Pa	ε	turbulent dissipation rate
p_f	wellbore friction, Pa	ρ	density, kg/m^3
Q	radial heat source, W/m^3	ρ_{ini}	initial density, kg/m^3
Q_{inj}	injection rate, m^3/s	λ	thermal conductivity, W/(m °C)
r_{ti}	inner tubing radius, m	μ	dynamicviscosity, Pa s

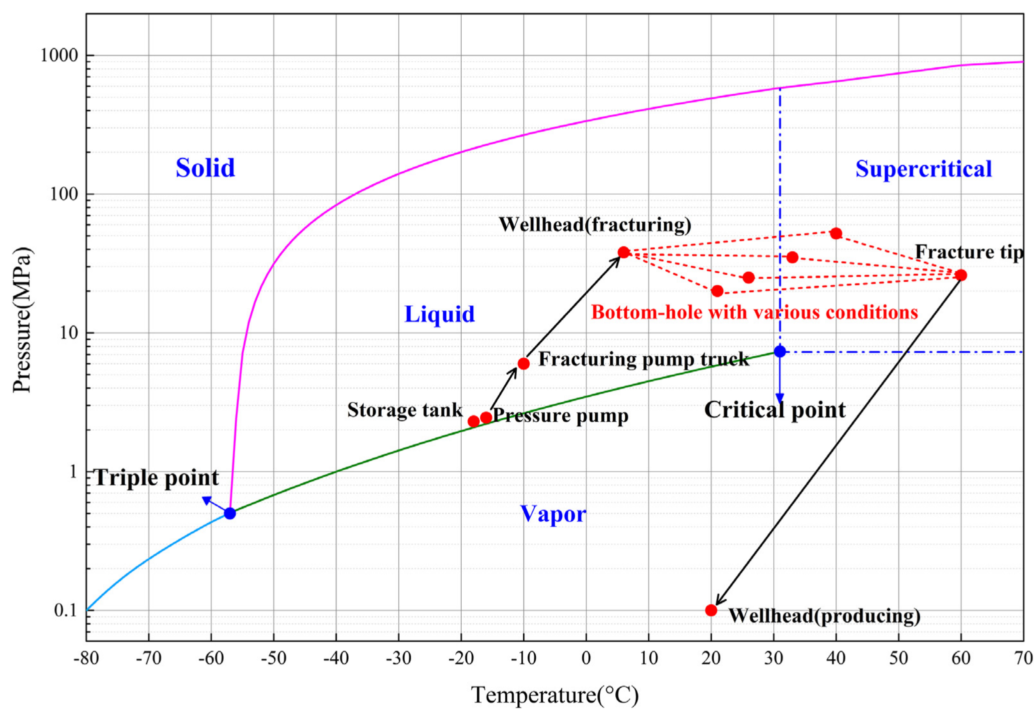

Fig. 1. Variations in CO_2 temperature, pressure, and phase during CO_2 fracturing.

calculation models (the Span-Wagner (S-W) EoS, Vesovic model, and Fenghour model) to modify Wu's model for more precise predictions. Although semi-steady models perform well for slowly injecting processes such as CO_2 flooding and CO_2 sequestration, they are not suitable for rapidly injecting processes (like fracturing) owing to their assumption of a steady state in the fluid governing equations [9]. Applying the transient numerical method, Lu [27] developed a transient wellbore temperature prediction model for CO_2 fracturing by coupling CO_2 property models, a steady momentum equation, and Eickmeier's model [10]. Pan [28] developed a wellbore simulation that describes the transient non-isothermal flow of CO_2-brine mixtures, which used the drift-flux model to calculate the momentum equations while the wellbore heat transfer was handled semi-analytically. Hu [29] established a coupled wellbore and reservoir model to simulate the non-isothermal flow of CO_2 in the wellbore and reservoir and studied CO_2 leakage through wellbores. Lu and Connell [30] studied the transient behaviour of CO_2 flow in injection wells during geological storage, and the model accounted for phase transitions. Guo [31,32] considered the friction heat source, volume force work, and the Joule-Thomson effect in using the transient momentum equation to develop a full transient simulation to predict a CO_2 wellbore temperature field. Transient models can simulate the fracturing process precisely, but these models have not yet considered or analysed the effects of pressure work or viscous dissipation, which can significantly influence CO_2 fracturing. Applying analytical methods, Singhe [33] extended Hagoort's model [18] by accounting for the Joule-Thomson effect and verified the solution with data from Ketzin, Germany. However, this analytical solution is based on Ramey's semi-steady model, which means it is not suitable for applying to the fracturing process. In addition, all of these models are one-dimensional in their simulations of the wellbore