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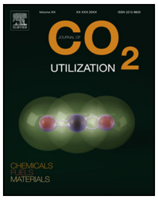

Modification of Ramey's model for carbon dioxide injection in the vicinity of critical point

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ABSTRACT

Temperature profile of the fluid along the depth of injection wells is important for petroleum engineers to design well completions. Knowing the injection fluid temperature at the bottomhole is necessary to study reservoir future performance durinjavascript:void(0)g non-isothermal injection. The common model to estimate fluid temperature as a function of well depth and injection time was developed by Ramey (1962) which is specified for incompressible liquid. This study assessed Ramey's model for carbon dioxide injection around the critical point. It has been found that some assumptions of Ramey are unsuitable for carbon dioxide injection.

In this study, Ramey's model has been modified to improve predictively of its results for carbon dioxide injection case. Comparison of results obtained from the new modified Ramey's model and numerical model revealed that good agreement between them. The difference of temperature at bottom hole for the new modified Ramey's model and numerical model is less than 1.5 °C.

1. Introduction

It has been one of the perennial objectives of the oil industry to increase the oil recovery factor for a given reservoir at the minimum possible cost. This goal has led to the development of numerous improved oil recovery (IOR) techniques [17,16,10]. Carbon dioxide (CO_2) injection is among the more widely applied IOR techniques because of its low cost, useful over a wide range of crude oils, as well as the high displacement efficiency and potential for concomitant environmental benefits through its disposal in the petroleum reservoirs [29,4,14,21,12].

Carbon dioxide is usually injected near its critical point in shallow or offshore wells and it is in form of a compressible fluid there [22,31]. Critical pressure and temperature of CO_2 are 7.38 MPa and 31.1 °C respectively as shown in Fig. 1. [14,21].

An appropriate well completion design requires a knowledge of pressure and temperature profiles along the depth of the well [18,26,24,30,1]. Accurate determination of the downhole pressure and temperature are important to study the performance of hydrocarbon reservoirs [3,5,23,8,9]. Reliable knowledge of bottom-hole pressure is also useful in preventing injection above the pressure than can damage the formation [6,7,2]. While bottomhole gauges can measure pressure and temperature, there is always the potential that over a long period of time downhole gauges may fail. Therefore it would be convenient to be able to calculate the downhole parameters from surface injection parameters [22]. The first theoretical model to estimate fluid temperature as a function of well depth and production time was proposed by [25] and almost all practical methods to calculate the temperature profile in the wellbore return back to Ramey's work [11] and it is used widely in petroleum industry [13].

In the vicinity of the critical point, CO_2 within injection wells is likely to be in a dense state and therefore its weight within the wellbore plays an important role in determining the pressure profile and thus the injection rate. However, the density could vary significantly along the well in response to the variation in temperature [19]. Ramey developed his model for incompressible liquid [25]. Therefore, Ramey's model for the calculation of temperatures profile during liquid CO_2 injection near the critical point would be assessed in this study.

2. Description of Ramey's model

Ramey derived the total energy equation for steady-state single-phase fluid flow for shown system in Fig. 2 as:

$$dh - gdz + udu = dq \tag{1}$$

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Nomenclature

a	Geothermal gradient (°C/m)
A_r	Coefficient (m)
b	Surface geothermal temperature (°C)
C_j	Joule Thomson coefficient (°C/Pa)
CO_2	Carbon dioxide
C_p	Specific heat of the fluid at constant pressure (J/(kg.°C))
e	Internal energy per unit mass (J/kg)
f(t)	Dimensionless temperature defined by Ramey
g	Acceleration of gravity (m/s^2)
h	Enthalpy per unit mass (J/kg)
IOR	Improve oil recovery
k_e	Thermal conductivity of the earth (W/(m.°C))
$\dot{m}_f$	Injection fluid mass flow rate (kg/s)
NIST	National Institute of Standards and Technology
P	Pressure (Pa)
q	Heat flow rate between the formation and wellbore per unit mass (J/kg)
r_{tubo}	External radius of the tubing (m)
T	Temperature (°C)
T_{cemo}	Temperature at outer surface of the cement (°C)
T_e	Temperature of earth (°C)
T_f	Fluid temperature in the tubing (°C)
T_{inj}	Injection fluid temperature at surface (°C)
u	Velocity (m/s)
U_{to}	Overall heat transfer coefficient ($W/(m^2.°C)$)
v	Specific volume (m^3/kg)
z	Length (m)
ρ_f	Density of the injection fluid (kg/m^3)

h = Enthalpy per unit mass (J/kg)

g = Acceleration of gravity (m/s^2)

z = Length (m)

u = Velocity (m/s)

q = Heat flow rate between the formation and wellbore per unit mass (J/kg)

by definition, enthalpy is given by [15]:

$$dh = de + d(Pv) \tag{2}$$

e = Internal energy per unit mass (J/kg)

P = Pressure (Pa)

v = Specific volume (m^3/kg)

Ramey developed his model for an incompressible liquid. For an incompressible liquid, (2) is simplified as:

$$dh = C_p dT + v dP \tag{3}$$

C_p = Specific heat of the fluid at constant pressure (J/(kg. °C))

T = Temperature (°C)

By combining (1) and (3):

$$C_P dT + v dP - g dz + u du = dq \tag{4}$$

Ramey assumed the following assumptions:

- Kinetic energy term is zero:

$$u du = 0 \tag{5}$$

- dP term equals to change in the fluid head by neglecting friction and kinetic energy change terms in pressure gradient calculations since:

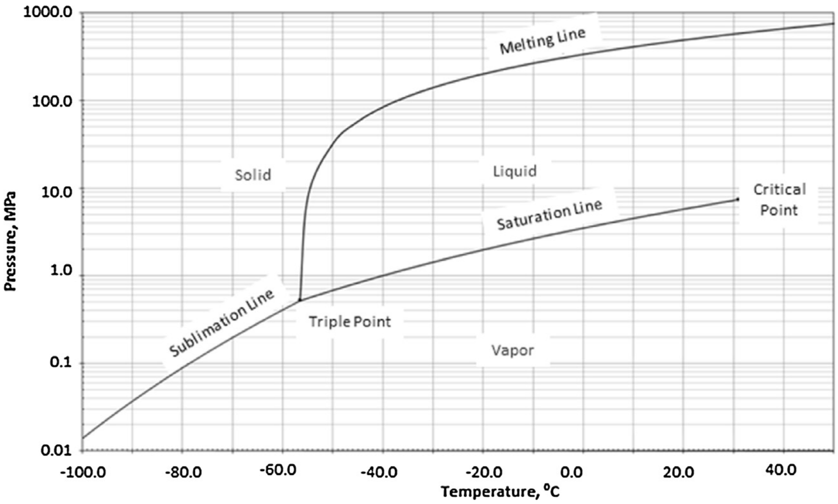

Fig. 1. Temperature- pressure diagram of CO_2.