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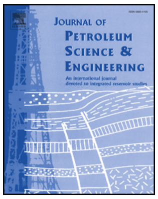

Mechanical performance of casing in in-situ combustion thermal recovery

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ABSTRACT

In-situ combustion is often used to develop heavy oil as it has multiple advantages over alternative thermal methods. However, the wellbore integrity can be compromised if the casing is not properly designed or manufactured. Based on the fundamentals of heat transfer, a mathematical model with multiphysics is built to study the temperature and pressure distributions surrounding the wellbore during in-situ combustion. In laboratory, real casings and coupons with grades of N80, P110, and 3Cr110 were tested under high temperature to study their mechanical performances in the in-situ combustion recovery. From the modeling and laboratory testing results, we propose the casing design and manufacture protocols for thermal recovery of heavy oil. Field applications in Liaohe oil field, Du-66 Block, shows that the mechanical deterioration of P110 and 3Cr110 is less than that of N80 and the mechanical performance stability of 3Cr110 is better than others when the temperature is less than 600°C. When the temperature is above 600°*C* for more than 10 h, the mechanical performance of all casing grades declines quickly. Applying finite element analysis, we recommend a safety factor of 1.1 for designing casing at the temperatures of 250 ˚C,480 ˚C and 485 ˚C. The finding of this study provides fundamentals for the casing design and material selection for in-situ combustion recovery.

1. Introduction

Thermal recovery is often used in enhancing oil recovery, especially for heavy oils which account for 53% of total world reserve. The thermal recovery methods include thermal stimulations, steam flooding, in-situ combustion (ISC), and other variants. The in-situ combustion over steam flooding relies on several advantages of ISC thermal methods. First, ISC has features for being more efficient than alternative thermal methods such steam flooding. The external energy consumed in ISC is mainly used for compressing and injecting air. Literature shows that air ISC requires only about 23–39% of the fuel needed for steam, and even more fuel efficiency by burning oxygen. In steam injection, significant heat losses to the surrounding formation during injection, and heat losses to the overburden and underburden during flooding. ISC can eliminate heat losses to the surrounding since heat is generated in the reservoir.

ISC has also many limitations for operators to overcome in practice, which probably are the main reasons for this early but less popular thermal recovery. As the fire front moves forward, gasses containing CO_2 or H_2S will breakthrough at the producer. These gasses are corrosive to the casing, and flowing with water makes the problem of corrosion even worst. At the same time, air is injected at a high rate which leads to solid particles being displaced to the producer and exacerbates the erosion of casing. Furthermore, the casing strength of casing degrades in the elevated temperature environment. These harsh conditions post tremendous challenges for casing design for in-situ combustion thermal recovery. Other technical challenges and experiences of field practices of ISC were highlighted in literature (Ramey, 1971; Maruyama et al., 1990; Maharaj, 1996).

Improper design of casing can lead to significant casing damage. Wellbore integrity survey in Du-66 Block in Liaohe oil fields show that by the end of 2015. In the production pad of Well Group 92, 28 wells out of 43 wells showed a variety level of casing damage or deformations after they were switched from steam flooding to in-situ combustion. The damage and deformation of casing are mainly located the perforation intervals and regions close to the upper part of perforation zone. The modes of failure are serve deformation and tensile break.

Before 80's most thermal well casing designs were based on Holliday (1969) model which showed that higher strength materials would be needed for thermal wells. However, field practices show that this criteria alone is not sufficient (Han et al., 2016). Lepper (1998) discussed the casing design for thermal fields should account for collapse resistance, tensile stresses, and connection strength for buttress. Hidayat et al. (2016) studied the casing strength degradation in steam

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stimulation process using a three-dimensional finite element analysis on N80 casing and concluded that the casing capability to resist the pressure lowers as the number of thermal cycles increases. However, the authors did not present any laboratory testing on this and other casings. Li (2013) presented the mechanisms of casing failure for thermal recovery wells and recommend to use thicker casing to prevent casing failure. Chen et al. (2017) analyzed the stresses on casing resulted from formation and cement thermal expansion and concluded that the casing deformation could be caused by the different expansion rates of surrounding materials. Nowinka et al. (2008) proposed strain-based design of tubulars for extreme conditions such as high temperature wells in thermal recovery.

To date, there is no standard procedure adopted by the industry for ISC casing design when the temperature is above 180°C except for some proprietary procedures from some operators (Nowinka and Dall'Acqua, 2011). Recently a strain-based design concept coupled with laboratory tests and finite analysis have gain ground in designing casing (Xie, 2008, 2006; Han et al., 2016). This study focuses on ISC casing design by testing the casing strengths under high temperatures using laboratory experiments and numerical simulation with an aim to provide fundamental guideline in casing material selection.

2. Mathematical model for in-situ combustion

In the process of in-situ combustion recovery, usually air is injected at an injection well and oil is being produced from a producer as shown in Fig. 1. If the air injection pressure and temperature at the bottom hole of the injection well are P_w and T_w, and at far distance ($r = r_\infty$) and the temperature and pressure are T_0 and P_0, respectively; we can set up a mathematical model with the following assumptions:

a) Initial water and oil saturations are constant;
b) Overburden and underburden formations are impermeable to oil or water
c) Heat losses to overburden and underburden are neglected.
d) Water and oil are immiscible in the reservoir conditions
e) Darcy's flow for oil and water
f) Other than viscosity, fluid and rock thermal properties are constant with temperature except for viscosity

The general governing equation for thermal energy balance in a cylindrical coordinates is given by Eqn. (1) (Bird et al., 2004):

$$\rho c\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\cdot\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \theta}\left(\lambda\frac{\partial T}{\partial \theta}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + q \tag{1}$$

Where λ is the heat conductivity of rock,W/(m.K); ρ is density,kg/m^3; c is the specific heat capacity of rock, [J/(kg · K)],q is heat flux,W/m^2.

For Eqn. (1), since we are mainly interested in highest temperature in the region near by the injection well bore, the heat conduction terms in θ and z directions can be neglected. Therefore, in the r-direction, Eqn. (1) is written as follows:

$$\rho c\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\cdot\frac{\partial T}{\partial r}\right) + q \tag{2}$$

Other than the combustion of coke in the combustion location, we assume there is no other chemical reactions. For mass balance, for the region nearby well bore, if we assume one –direction flow surrounding the well, the mass balance equations for oil and water in cylindrical coordinates are as follows (Ahmed, 2006):

$$\frac{\partial(\phi\rho_o S_o)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\rho_o k_o k}{\mu_o}\frac{r\partial P}{\partial r}\right) \tag{3}$$

$$\frac{\partial(\phi\rho_w(1-S_o))}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\rho_w k_w k}{\mu_w}\cdot\frac{r\partial P}{\partial r}\right) \tag{4}$$

whereρ_o and ρ_w are density of oil and water, respectively,kg/m^3; $k$is permeability, m^2; P is pressure,Pa; $\phi$is porosity; $S_O$is oil saturation; $\mu_o$and $\mu_w$are oil and water saturations, respectively,Pa.s ; k_o, $k_w$are relative permeability of oil and water, respectively. Given that we are only interested in the near well bore region of the injector, we assume there are oil and liquid water as small gas may exist but in solution form. The generated steam as the result of in-situ solution is also not considered as the steam region can quickly move further into formation and condensate to liquid water.

The above three equations can be solved implicitly as the viscosity is a function of temperature, and the relative permeability is a function of saturations of oil and water. Based on the measurement of relative permeability from the Liaohe Du-66 block, the empirical correlation between saturation and relatives are shown in Eqn. (5).

$$\begin{cases} k_o = 99.95\cdot e^{(-(1-S_o)/0.06968)} - 0.01749 \\ k_w = 0.00684\cdot e^{((1-S_o)/0.137)} - 0.07708 \end{cases} \tag{5}$$

Matching the experimental data with the Bergman Equation for heavy oil (Bergman and Sutton, 2009), The temperature and viscosity relationship for this field is given by Eqn. (6).

$$\log[\log(\mu_o + 0.6)] = 9.1138 - 3.5635\log(273.15 + T) \tag{6}$$

Where T is temperature is °C, ad viscosity is in cp. Fig. 2 gives the viscosity and temperature relationship based on the equation Eqn. (6). On this figure, oil viscosities are 0.58 mPa s and 0.68 mPa s at temperatures of 600°C and 400°C, respectively. These two temperatures are highlighted because they are the region boundary temperature of in-situ combustion study in this paper. Fig. 2 shows that the viscosity

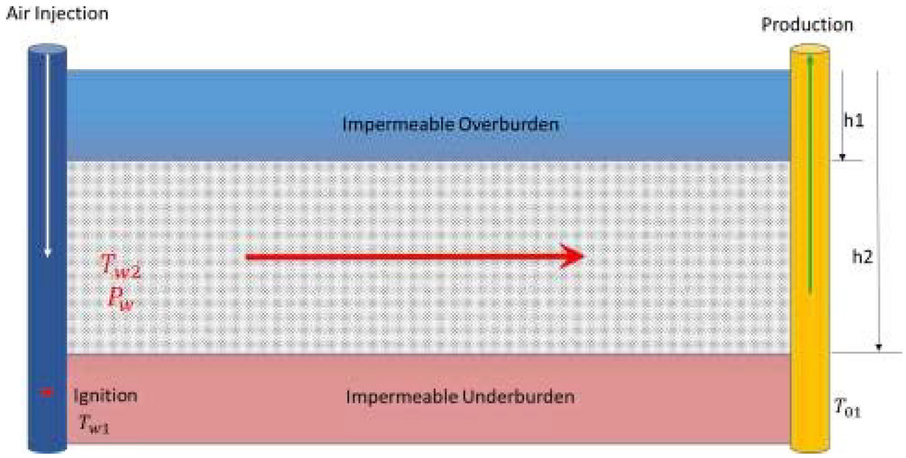

Fig. 1. Model diagram of in-situ combustion from an injection well a production well.