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The flow and heat transfer characteristics of multi-thermal fluid in horizontal wellbore coupled with flow in heavy oil reservoirs

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ABSTRACT

As a new improved oil-recovery technique, multi-thermal fluid injection technology through a horizontal well has been widely used in the development process of heavy oil reservoirs. The flow and heat transfer characteristic of multi-thermal fluid in horizontal wellbore is significantly important for the productivity evaluation and parameters design of the horizontal well. Considering the specific physical properties of multi-thermal fluid, fluid absorption in perforation holes and pressure drop characteristics along the horizontal wellbore, this paper developed the flow and heat transfer model of multi-thermal fluid in perforated horizontal wellbore. In order to evaluate the heating effect of the multi-thermal fluid, a concept of effective heating length of a horizontal well is proposed. Then, a sensitivity analysis process is performed to study the influence of reservoir/fluid parameters and operating parameters on the flowing process of multi-thermal fluid in horizontal wellbore. Simultaneously, using the method of orthogonal numerical test, differential analysis and variance analysis are also conducted. Results show that the flowing process of multi-thermal fluid in horizontal wellbore includes a single-phase flowing process and a gas–liquid two-phase flowing process. The influence of oil viscosity on the flow and heat transfer characteristics of multi-thermal fluid in horizontal wellbore is most significant. Thereafter, the solution of our semi-analytical model is compared against the test results of an actual horizontal well from an oilfield in China. It is shown that the model results are in good agreement with the real test results. This model could be used to calculate and predict the flow and heat transfer characteristics of multi-thermal fluid (or saturated steam) in a perforated horizontal wellbore.

1. Introduction

Multi-thermal fluid is different from conventional steam. It is prepared from the combustion and jetting mechanisms of rocket engine (Liu et al., 2010; Sun et al., 2011). The main components of multi-thermal fluid include nitrogen gas (N_2), carbon dioxide (CO_2) and (superheated) steam. It combines the virtues of both steam and non-condensable gas (Tang et al., 2011; Dong et al., 2014). Therefore, from the composition characteristics of multi-thermal fluid, it is a gas mixture of steam and non-condensable gas, but it is different from the conventional gas mixture of steam and non-condensable gas. In the field, multi-thermal fluid is generally produced from the thermal-fluid-generator (Tang et al., 2011; Li et al., 2012). In comparison with the conventional gas mixture of steam and non-condensable gas, multi-thermal fluid has three different characteristics. Firstly, for the composition characteristics of non-condensable gas, the conventional case is usually pure gas (N_2, CO_2); multi-thermal fluid is the gas mixture of N_2, CO_2, CH_4, and CO, etc. Secondly, for the injection method, the conventional case is usually separate injection of steam and non-condensable gas (tube for steam injection, annulus for non-condensable gas injection); multi-thermal fluid is injected into the reservoir directly. Thirdly, for the heat quantity, compared with the conventional case, multi-thermal fluid has a higher thermal efficiency and heat quantity (Sun et al., 2011; Liu et al., 2012; Dong et al., 2014).

Considering the above three aspects, the stimulation process of multi-thermal fluid has a higher oil recovery in the limited time. In 2010, a pilot test of multi-thermal fluid injection process was conducted in NB35-2S block in Bohai offshore oilfield, CNOOC, Tianjin city, China (Tang et al., 2011; Liu et al., 2011, 2012), as shown in Fig. 1. In that test, about 6 cycles of multi-thermal fluid huff and puff were carried out in four horizontal wells (B14m, B2S, B28h and B29m) of the heavy oil block. The well locations are shown in Fig. 2. During operation, the highest fluid production rate was 178.3 m^3/d, and the highest oil production rate was 126.8 m^3/d.

On account of the obvious advantages of multi-thermal fluid in heavy oil reservoirs, currently this new stimulation technology has

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Nomenclature

C_1, C_2	coefficient
d	pipe diameter, m
E	liquid holdup, decimal
F_i	F function
f	friction factor, decimal
g	acceleration due to gravity, m/s^2
G_i (i=N_2, CO_2, H_2O)	mass flux rate of component i, kg/s
H_i (i=m, CO_2, N_2, S, W)	enthalpy of component i, J/kg
$H_l(\theta)$	liquid holdup with the dip angle θ, decimal
k_s	effective permeability of multi-thermal fluid, 10^{-3} μm^2.
l	length of well micro-control element, m
M_i (i=N_2, CO_2, H_2O)	molecular weight, kg/mol
n	perforation hole
p	fluid pressure, MPa
p_s	saturated vapor pressure, MPa
Q	heat flux rate, W
q_{vs}	total fluid injection volume, m^3
Re_g, Re_{lg}	Reynold's number
R_i	heating radius, m
r_{ci}, r_{co}	inner and outer radii of case, m
t	injection time
T	fluid temperature, °C
U	heat transfer coefficient, W/(m °C)
v	fluid velocity, m/s
W	frictional power losses, W
x	saturated steam quality, decimal
y	component fraction, decimal
z	well depth, m
Z_m	compressibility factor

Greek symbols

β	constant, 0.7546
Ω_a, Ω_b	constant
ε	relative roughness
θ	dip angle of wellbore, deg
λ	heat transfer coefficient, W/(m °C)
ρ	fluid density, kg/m^3
τ_f	friction stress
τ_D	non-dimensional time

Subscripts

ci	critical state of component i
g	gas
l	liquid
m	gas mixture
ri	corresponding state of component i
W	water
S	steam

also been introduced into Shengli oilfield, SINOPEC, Dongying city and Liaohe oilfield, CNPC, Panjin city, in China, as shown in Fig. 1. The successful operation of the multi-thermal fluid stimulation process tremendously proved the feasibility and effectiveness of multi-thermal fluid in heavy oil reservoirs. Compared with the conventional steam stimulation process, the productivity of the multi-thermal fluid stimulation process is enhanced by about 1.5–3.0 times.

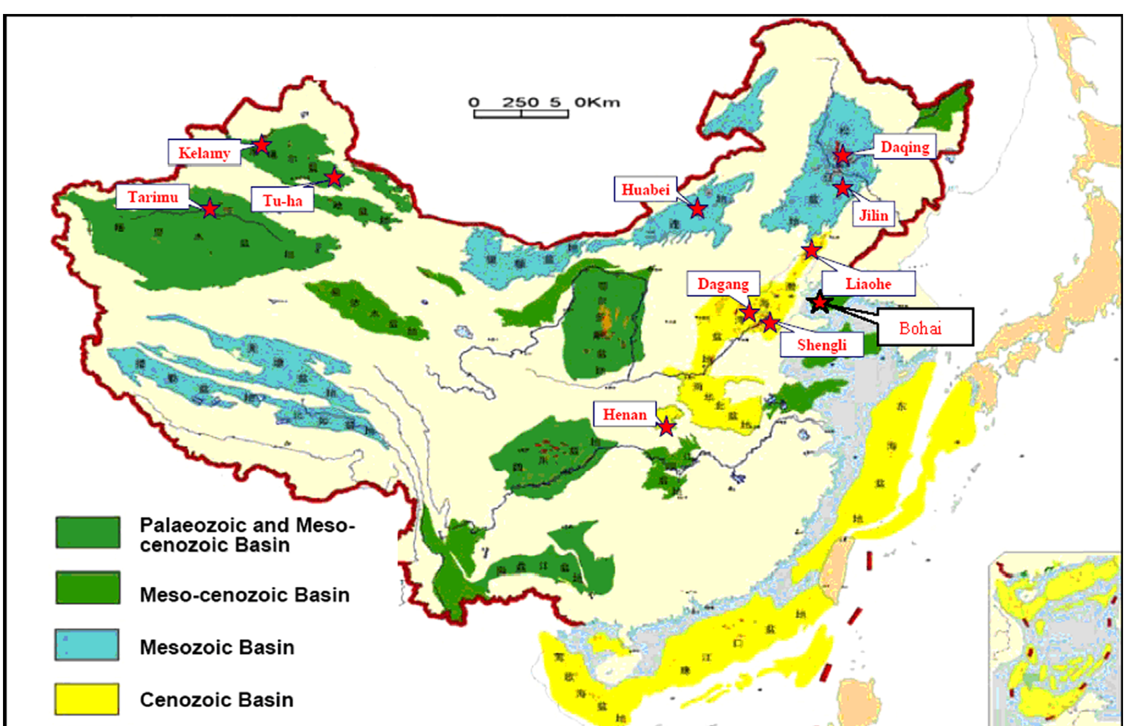

Fig. 1. Heavy oil fields' location in China (Shiyi et al., 2005).

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