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Study on Numerical Simulation of Steam Huff and Puff Based on Deformable Medium Model

Authors: Tingting Wu, Yawei Hou, Fengyi Zhang, Wankun Xu, Dawei Wang

(Research Institute of Bohai Oilfield, CNOOC Ltd.-Tianjin, Tianjin 300452)

Abstract

Deformable medium model mentioned in this paper is that because of cycling rising and declining of formation pressure during steam huff and puff, the rock which experiencing cycling uploading and unloading appear distorted, which made its compressibility greatly changed. Therefore, the main content of deformable medium model is describing the compressibility change regularity. In traditional study about numerical simulation of steam huff and puff, the rock compressibility is considered constant, which doesn't really reflect the changing of formation energy in the process, and results the predicting of well production and recovery rate are influenced greatly.

In this paper, by using method of theoretical research, experimental analysis and numerical simulation, deformable medium model to simulate the process of steam huff and puff is established on the basis of systematically researching rock deformation mechanism and heavy oil seepage characteristic in deformation medium. History matching, sensitivity analysis and parameter optimization of steam huff and puff on NB oil field are carried out by using the model. Practice indicates that this model can make higher history fitting precision, more reasonable thermal injection parameters and more accurate predict recovery. Comparing with traditional model, the optimized steam injection rate increased 40%, cyclic steam injection volume increased 30%, predict recovery increased 2.3 percentage. Actual development situation proves the model's reliability.

There are abundant heavy oil reserves in Bohai oilfield, which needs steam huff and puff. The results from traditional model may lead decision-making mistakes, such as determining incorrect productivity, predicting low recovery, so that put off development of such oilfields because of no economic benefit. By using the model, it is more effective to fit history data, optimize injection and production parameters, and more precise to make development plan and predict indicators.

Key words: steam huff and puff, deformable medium model, rock compressibility, laboratory experiment, numerical simulation

Introduction

X oilfield is located in the central Bohai Sea. The surface oil viscosity is 2150mPa.s. The steam huff and puff pilot test was started in November 2008, and now it has been put into thermal development totally. But there is a contradiction in history matching. The rock compressibility in application is more than 10~100 times than the actual value; while if the expand compressibility be used, the formation pressure can't be matched.

The process of steam huff and puff is repeated uploading and unloading. The current method takes the rock compressibility as constant during the process of uploading, unloading and reloading. Although it can simplify the simulation process, it can't reflect the rock's changing situation, it also can't make rational analysis for the rock's mechanical property during steam huff and puff, and then it will lower the accuracy of mathematical simulation. In this paper, the deformable medium model which is used in simulating steam huff and puff is built up through deformable mechanism analysis, rock deformable experiment and rock compressibility experiment which simulating the process of steam huff and puff. The model's reliability is validated through X oil field's practical use.

1 Deformable Medium Classification

According to the definition of rock mechanics and mechanical theory, the rock deformation has three forms [1].

(1)Elastic deformation: It is a physical phenomenon that the deformation is generated when rock is under stress, and the deformation is disappeared when stress is removed. The important characteristic is its reversibility.

(2)Plastic deformation: It is a physical phenomenon that the deformation is generated when rock is under stress, but can’t return to normal when stress is removed. It is also called residual deformation or permanent deformation.

(3)Elastic-plastic deformation: It is a transitional type between elastic deformation and plastic deformation. Its physical interpretation is when the formation pressure is recovered, some part returns to original shape because of having elastic; while the other part remains the generated deformation partly or totally. The rock experienced the three stages’ changes in steam huff and puff.

Rock’s deformation characteristic can be illustrated by the relationship diagram of “stress σ and deformation ε” [2] (Fig.1). It can be divided into three areas: (Ⅰ) obeying Hooke′s law area, $\sigma=E\varepsilon$, E is elastic modulus; (Ⅱ) elastic-plastic deformation area; (Ⅲ) plastic deformation area. The deformation in area Ⅰ is reversible, in area Ⅱ is partly reversible, and in area Ⅲ is irreversible.

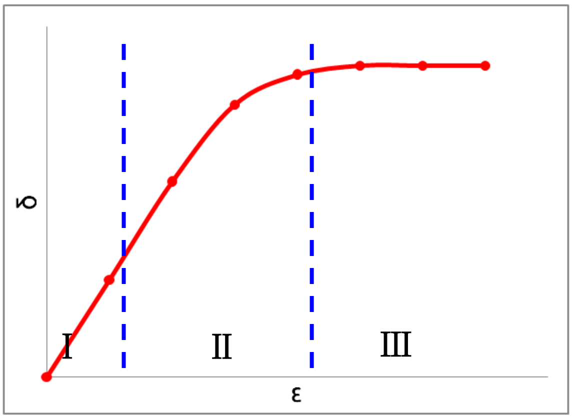
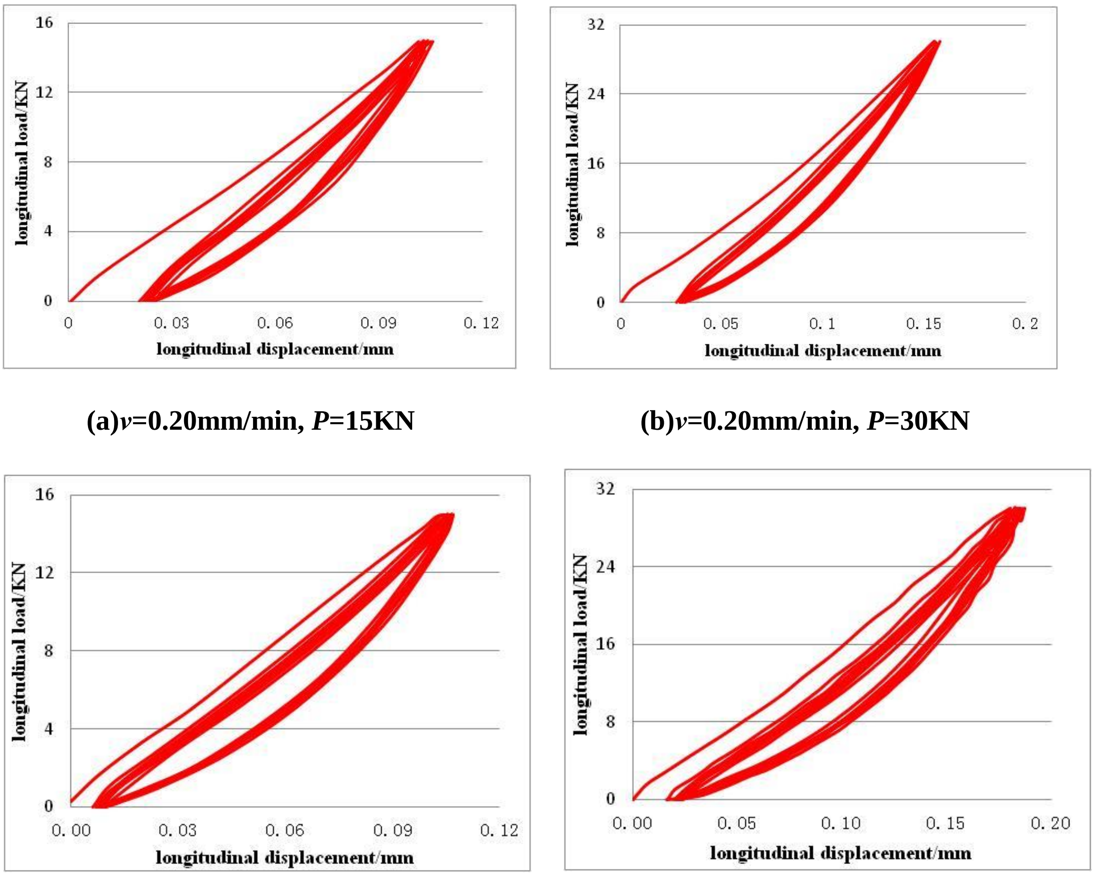


Fig.1 the relationship diagram of “stress σ and deformation ε” for deformable medium

2 Experimental Method

2.1 Rock's Deformation Characteristics Experiment

Deformation characteristic curves are drawn by using two different displacement rates (0.05 and 0.2mm/min) and two different payloads (15 and 30KN) for the rock's deformation characteristics under cycle uploading and unloading during steam huff and puff. The experimental steps[3-10] are as follows: (1) uploading from 0 to *P* under a certain displacement rate, and then unloading to 0 under the same displacement rate; (2) repeating step 1 until finishing 10 times' experiments; (3) changing the rock, and changing displacement rate *v* or payload *P* with repeating step 1 and 2. Fig.2 is the deformation characteristic curves under cycle uploading and unloading.



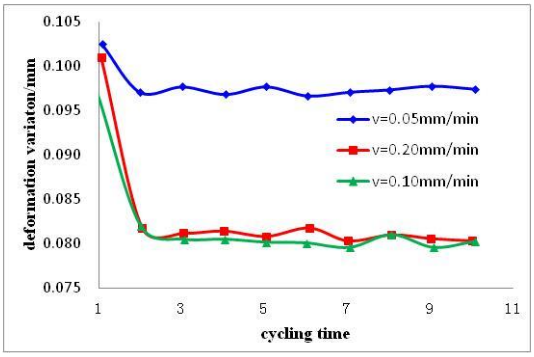
(a)*v*=0.20mm/min, *P*=15KN **(b)*v*=0.20mm/min, *P*=30KN**

(c)v=0.05mm/min, P=15KN **(d)v=0.05mm/min, P=30KN**

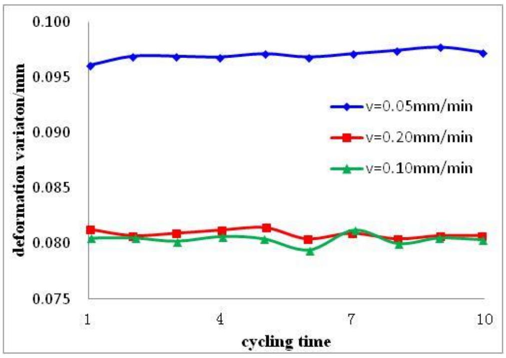
Fig.2 rock's deformation curves under different displacement rates *v* and different payloads *P*

It is can be seen from Fig.2 that the rock's uploading curve and unloading curve don't coincide under cycle loading, and will form a closed plastic hysteretic loop. The hysteretic loop area has great change only from the first time to the second one, while the area is basically the same from the second time to the tenth time. That is the plastic hysteretic loop won’t generate obvious change with increasing cycling times from the second time. Therefore, the residual deformation is basically unchanged from the second cycling for steam huff and puff.

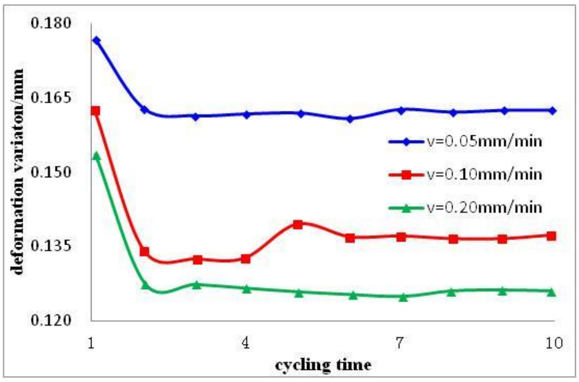
The relationship between deformation variation and cycling times is drawn in order to quantitatively analyzing the rock’s deformation rule under different displacement rates and different payloads. It is can be seen from Fig.3 that in uploading stage, the deformation has great change for the first cycling. But it is basically the same from the second cycling, which further confirms that rock generate obvious plastic deformation for only the first cycling in steam huff and puff.



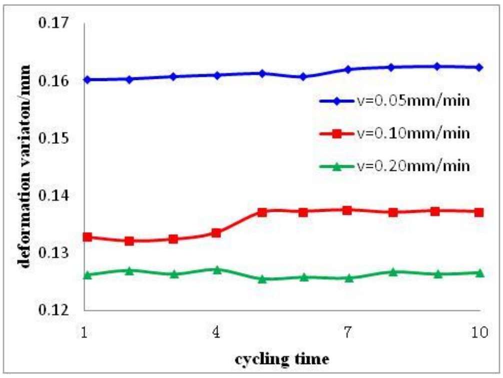
(a) *P*=15KN in uploading stage



(b) *P*=15KN in unloading stage



(c) P=30KN in uploading stage



(d) P=30KN in unloading stage

Fig.3 the relationship between deformation variation and cycling times

2.2 Rock Compressibility Experiment

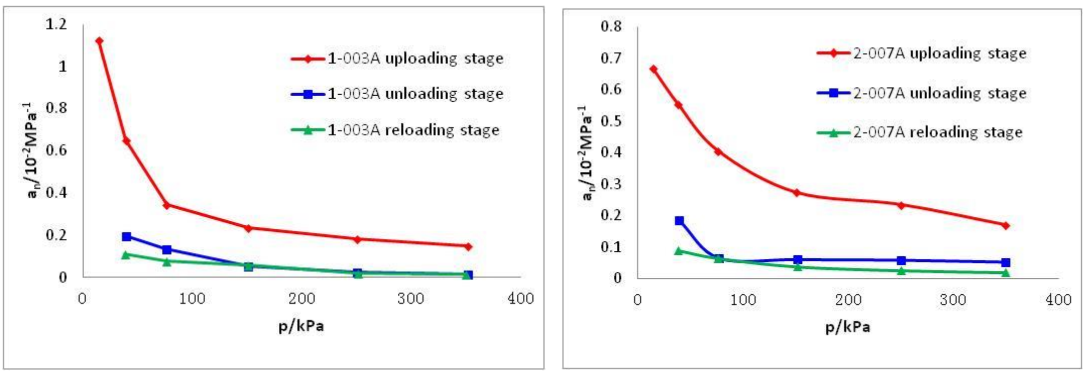
The rock compressibility experiment simulates the actual process of steam huff and puff for this time, which is increasing pore pressure to simulate injecting steam firstly; and then decreasing pore pressure to simulate oil production. It is obtained from rock’s deformation characteristics experiment that the deformation has great change for the first cycling in uploading stage, but it is basically the same from the second cycling. Therefore, there are only

three processes need to be simulated which are uploading, unloading and reloading. The rock's net valid overlying pressure is:
0.4→0.3→0.2→0.1→0→0.1→0.2→0.3→0.4→0.3→0.2→0.1→0MPa.

a_0, a_1 and a_2 are used to describe the rock compressibility in uploading, unloading and reloading stages. The compressibility's changing situation in different stages is obtained through calculation as Tab.1. The relationship between compressibility and pressure in three stages for rock 1-003A is showed as Fig.4 (a). The compressibility decreases with increasing net effective overlying pressure in different uploading stages. The compressibility curve of a_0 uploading stage is on the top and also the steepest, which shows that a_0 is far more than a_1 and a_2. The compressibility in uploading stage is no different than reloading stage. Fig.4 (b) has the same conclusion.

Tab.1 physical property of rock sample

Number	Depth m	Diameter cm	Length cm	Porosity %
1-003A	942.72	2.482	4.513	29.06
2-007A	968.55	2.216	4.044	38.79



(a) rock sample 1-003A **(b) rock sample 2-007A**

Fig.4 a_n-p curve

3 Deformable Medium Model

3.1 Deformable Medium Description

The results in Fig.4 show that the rock compressibility has large difference in different stages. It is greatly increased in uploading stage. While in unloading and reloading stages, there is no big change, and the compressibility is greatly reduced. The deformable medium model is established on the basis. The rock compressibility in the first cycle is analyzed by stages as Fig.5. In steam injecting stage, the net effective overlying pressure decreases and the porosity slowly increases with increasing pore pressure, and rock experiences elastic swelling; the porosity greatly increases with increasing pore pressure, and rock experiences plastic swelling. In producing stage, the net effective overlying pressure increases and the porosity slowly decreases with decreasing pore pressure, and rock experiences elastic compaction; the porosity greatly decreases with decreasing pore pressure, and rock experiences re-compaction[11]. The rock compressibility after the first cycle borrows the value in producing stage, because of later compressibility basically unchanged.

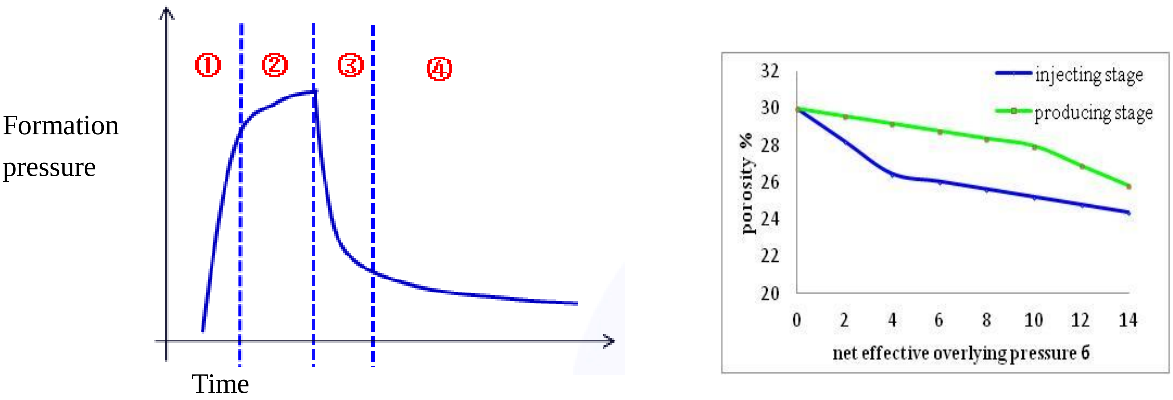


Fig.5 changes of formation pressure and rock quality in steam huff and puff

3.2 Deformable Medium Model

With uploading, unloading and reloading, rock experiences swelling, compaction and re-swelling. So the porosity under pressure (p) is given as formula (1)

$$\phi = \phi_r \exp[c(p - p_r)] \qquad (1)$$

Where φ_r is the porosity under reference pressure P_r; φ is the porosity under any pressure point; c is rock compressibility, and its unit is 1/kPa.

3.3 Fluid-solid Coupling Model

Because of porosity changes leading to permeability changes, the permeability's changing is given as formula (2)

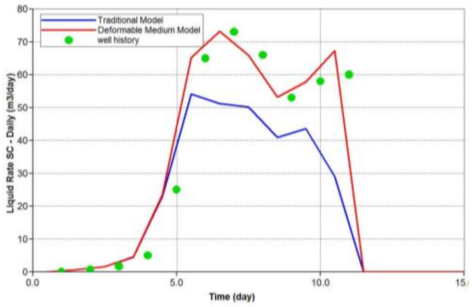
$$K(p) = Ko * \exp[kmul * (por(p) - poro)/(1 - poro)] \qquad (2)$$

Where *Ko* and *poro* are initial permeability and porosity; Kmul is permeability multiple factor.

4 Site Application

The rock compressibility of X oilfield in steam injecting stage is $1.35*10^{-2}MPa^{-1}$ by laboratory experiment, and it is $0.45*10^{-2}MPa^{-1}$ in producing stage. The rock compressibility value is $0.45*10^{-2}MPa^{-1}$ from the second cycle, because of it basically unchanged from then on.

As you can see in Fig.6 and Fig.7, the fitting precision of injecting rate and production which is calculated by deformable medium model is high. Recovery efficiency is forecasted 16.1%, which is closer to the actual compared to previous 13.5%. The reliability of the model is validated.



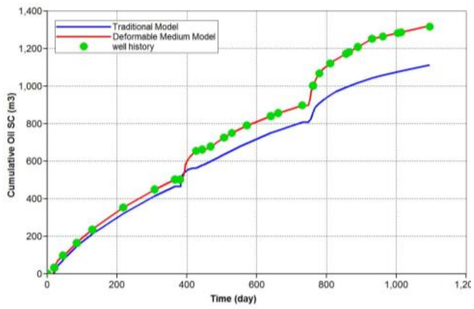


Fig.6 contrast curve of daily injecting **Fig.7 contrast curve of cumulative oil production**

5 Conclusion

(1) The deformable medium model is established for simulating the process of steam huff and puff. It conquers the limits of traditional geomechanics model, and simplifies the description of rock quality during cycles by laboratory experiments.

(2) The elastic/plastic deformation and fluid-solid coupling are both considered in the model, which can truly reflect the changes of rock characteristic during steam huff and puff.

(3) By using the model, the parameters of production during steam huff and puff can be optimized more precisely, the development plan can be made and the indicators can be forecasted more reasonably.

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