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Rock physics modelling of acoustic velocities for heavy oil sand

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ABSTRACT

The rock physics models for the acoustic velocities of the heavy oil sand with different oil distributions are proposed in this paper. The heavy oil distributions are classified into three primary types, based on which the corresponding acoustic velocity models are given. For the first type, the heavy oil is detached from the sand grains, for which the Hertz-Mindlin- Hashin-Shtrikman (HMHS) model can be used. In the second type, a continuous matrix is formed by the heavy oil and the sand grains float inside the matrix. The Hashin- Shtrikman (HS) lower bound gives good estimation results under this condition. For the third type, the heavy oil cements the sand grains at the grain contacts. The modified Contact Cement Theory (CCT) can describe this cementation effect well. To validate the proposed models, we analyzed the heavy oil sand data from Xinjiang Oil Field of China. The heavy oil distribution is obtained and the corresponding model is selected to estimate the acoustic velocities. The results show that it can predict the measured data well. Furthermore, we also compare the responses of the acoustic velocities for the heavy oil sand with different oil distributions. It reveals that different heavy oil distribution results in different acoustic velocities responses. The heavy oil distribution can thus be obtained by matching the measured data with the results estimated by the models. The model that match the data best implies the primary oil distribution. Many properties of the sand can then be estimated from the heavy oil distribution, such as the strength and permeability of the sand.

1. Introduction

The heavy oil sand is an important type of hydrocarbon reservoirs, which contributes a large amount of the world's reserves of oil and gas. Different from the oils in the conventional reservoirs, the heavy oils often exhibit the property of high viscosity. This results in the difficulties of using the conventional technologies to produce the heavy oil. In order to enhance the heavy oil production, a variety of methods have been proposed (Speight, 2013). These methods focus on lowering the viscosity of the heavy oil through the injection of the chemical solvents or the heat. Among them, thermal recovery has been proved to be the most efficient method. During the thermal recovery, monitoring the physical property changes of heavy oil sands is of great importance to the improvement of the recovery efficiency. For this purpose, the geophysical methods, such as 4D seismic technology and sonic well logging, are usually applied (Gurevich et al., 2007). The analysis of the acquired seismic or logging data provides the information needed for the operation of thermal recovery. However, most current analyses are based on the qualitative analysis and the information contained in the data are not fully extracted, which is due to the complex properties of the heavy oil sand. Hence, it is essential to carry out the quantitative analysis of the acquired seismic and logging data. To this end, building the rock physics models which connect the measured geophysical parameters with the physical properties of the heavy oil sand is necessary. In order to do so, it is most important to establish the relationship between the fundamental geophysical parameter, i.e., the acoustic velocities, with the physical properties of the heavy oil sand.

The properties of the heavy oil are controlled by the temperature (Han et al., 2006). Depending on the different properties of the heavy oil at varying temperatures, the acoustic velocities of the heavy oil sand also changes. At low temperature, the heavy oil behaves like the elastic solid. Under this condition, the effective elastic properties of the heavy oil sand are dominated by the heavy oil distributions (Han et al., 2007). Then it transfers to the quasi-solid phase with the increasing temperature. At this phase, the heavy oil exhibits the viscoelastic properties. It means that it behaves like the fluid in the low frequencies, but almost like the elastic solid in the high frequencies. In this case, the acoustic velocities of the heavy oil sand are frequency dependent and the intrinsic energy dissipations can be observed (Wolf et al., 2006; Han et al., 2008). The heavy oil distribution also plays an important role on the acoustic velocities. When the temperature continues to increase, the heavy oil will transfer to the fluid phase for which Gassmann equations (Gassmann, 1951) can be applied to

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estimate its effects on the acoustic velocities of the heavy oil sand.

Up until now, a number of rock physics models have been proposed for the elastic properties and acoustic velocities of the heavy oil sand in the low and intermediate temperatures. Marion and Nur (1991) and Das and Batzle (2008) applied the Hashin-Shtrikman (HS) lower bounds and the averaging methods to predict elastic moduli for the heavy oil sand, whose results agree with the experimental data well. Gurevich et al. (2007, 2008) combined the HS bounds with the Coherent Potential Approximation (CPA) theory to obtain an estimation of the elastic properties of the heavy oil sand. They match their results with the experimental data, which shows qualitative agreement. This theory was then further developed by Makarynska et al. (2010). Other researchers utilized the de la Cruz-Spanos theory (Eastwood, 1993) and the generalized Biot theory (Tsiklauri and Beresnev, 2003) to calculate the acoustic velocities of the heavy oil sand. All these models do not consider any specific heavy oil distribution, the heavy oil sand is treated as the general isotropic medium. These models may be applied well when several types of heavy oil distributions co-exist which results in the averaged values of the elastic moduli for the heavy oil sand. However, as pointed out by Han et al. (2007), the heavy oil usually has specific distributions which play a vital role on the elastic properties of the heavy oil sand. Hence, acoustic velocity models for the heavy oil sand should be built based on the heavy oil distribution.

Only a few models have considered the influences of heavy oil distributions. One such model was proposed by Leurer and Dvorkin (2000, 2006) for the heavy oil distributed at sand grain contacts, which acts as the viscoelastic cement in the heavy oil sand resulting in the frequency-dependent acoustic velocities and attenuations. To build the acoustic velocity models for the heavy oil sand, more heavy oil distribution types need to be taken into account. As the elastic properties of the heavy oil sand will both depend on the heavy oil distributions and frequency in the intermediate temperature, it is reasonable to establish the acoustic velocity models for the heavy oil sand in the low temperature first. Under this condition, the influences of the heavy oil distribution can be investigated conveniently without the effects of the frequencies. The acoustic velocity models for the heavy oil sand at the intermediate temperature can be developed in the future by incorporating the influences of the frequencies.

As observed by Han et al. (2007) in the experiments, the heavy oil in the low temperature has three primary distributions in the heavy oil sand (Fig. 1): a) the sands are water wet which makes the heavy oil detached from the pore walls, the heavy oil thus becomes part of the fluid. In this case, the heavy oil can only support the pore pressure, its influences on the acoustic velocities can be modelled in the similar way as the fluids. b) The heavy oil saturation is high enough that it forms the matrix, the sand grains thus float inside the matrix. c) The heavy oil has a relatively low saturation degree and accumulates at the grain contacts. The sands are cemented by the heavy oil which significantly increases the acoustic velocities of the heavy oil sand. The last two types of heavy oil distributions often occur for the oil wet sands. Depending on the different heavy oil distribution, different acoustic velocity model for the heavy oil sand should be built.

In this paper, we proposed the corresponding acoustic velocity model for the heavy oil sand under each specific heavy oil distribution in the low temperature (Fig. 1). Then the heavy oil sands from Xinjiang Oil Field of China are studied, the proper acoustic velocity model is selected based on its heavy oil distribution. Furthermore, the estimation results for other oil distributions are also given and analyzed based on the corresponding models. Finally, the potential applications of the acoustic velocity models are discussed.

2. Acoustic velocity models under different type of heavy oil distribution

The heavy oil in the low temperature behaves like an elastic solid. Therefore, the heavy oil sand under this condition also has the elastic properties, its compressional and shear wave velocities can thus be calculated from its moduli (bulk and shear moduli) and density as follows:

$$V_p = \sqrt{\frac{K_{eff} + 4/3G_{eff}}{\rho}}, \tag{1}$$

$$V_s = \sqrt{\frac{G_{eff}}{\rho}}, \tag{2}$$

where V_p and V_s are the compressional and shear wave velocities, respectively; K_{eff} and G_{eff} is the effective bulk and shear moduli of the heavy oil sand, respectively; ρ is the density of the heavy oil sand.

Thus, the bulk and shear moduli are needed to calculate the acoustic velocities of the heavy oil sand. Most current models, such as K-T model (Kuster and Toksoz, 1974), Self-Consistent theory (SC) (Berryman, 1980), and Differential Effective Medium (DEM) model (Berryman, 1992), are proposed for the consolidated sandstone. For the heavy oil sand in the low temperature, it is usually unconsolidated with very low acoustic velocities which can be easily overestimated by these models. Therefore, the models for the unconsolidated sandstones are required to estimate its acoustic velocities. To this end, some models have been developed, which mainly include Hertz-Mindlin (HM) model (Mindlin, 1949), Contact Cement Theory (CCT) (Dvorkin et al., 1994), and Hertz-Mindlin- Hashin-Shtrikman (HMHS) model (Dvorkin and Nur, 1996). Such models estimate the moduli of the sandstone from the

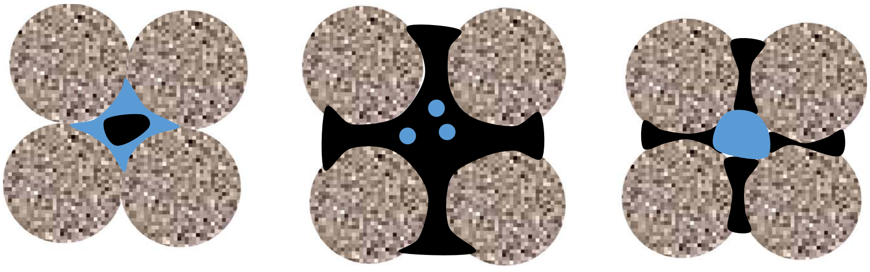
(a) (b) (c)

Fig. 1. Three types of oil distributions. (a) Heavy oil is part of the pore fluid. (b) Heavy oil forms the continuous matrix. (c) Heavy oil cements the sand grains. Note that the blue part represents formation water and the black part stands for the heavy oil. For Type a, the sand grains are usually water wet. For the other two types, the sand grains are normally oil wet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)