Empirical Modeling of the Saturated Shear Modulus in Heavy Oil Saturated Rocks

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Summary

We present an empirical model which estimates the saturated shear modulus of heavy oil saturated rocks. The inputs to the model are porosity, oil saturation, dry shear modulus and apparent shear modulus of the heavy oil. The first two inputs are available through common petrophysical analyses and the rest can be determined through our empirical relationships and procedures. Model parameters have been deterimend by utilizing a well log data set of an athabascan heavy oil play and the validity of the model is verified with ultrasonic lab measurements. Several applications of the model in seismic monitoring of heavy oil reservoirs will be presented.

Introduction

Rock Physicists explain the effects of conventional fluids on seismic velocities of saturated reservoir rocks using bulk modulus and density. Heavy oils, unlike conventional fluids, are viscoelastic materials. They exhibit shear rigidity, which depends on their density, temperature and the frequency dispersion of the measurements. As a result, in heavy oil saturated rocks at cold temperatures, saturated shear modulus is higher than the dry shear modulus and consequently, observed P- and S-wave velocities are higher than Gassmann's predicted velocities.

Researchers have been trying to model the rock physics response of heavy oil deposits for decades (Makarynska et al., 2010; Gurevich et al., 2008; Han et al., 2008). Despite recent advancements (Ciz et al., 2009; Kato et al., 2008), proposed models and methodologies are still complicated or inaccurate such that their practical utilization has become restricted.

Theory and/or Method

Appropriate modeling of the saturated shear modulus (μ_{sat}) can greatly enhance the accuracy of quantitative interpretation of spatial fluid saturation and temperature distribution within the reservoir through hot production. Using a well log data set of an Athabasca heavy oil play and measured viscosities of core samples, we estimate fluid viscosity, oil shear modulus (μ_a) and API gravity logs by training a neural network with available well logs. We also estimate the dry shear modulus (μ_{dry}) of heavy oil saturated rocks using a neural network approach after modeling the pressure variations in the reservoir. We compare the results with Hertz-Mindlin theory. After estimating μ_a and μ_{dry}, we use oil saturation (S_o) and porosity ($\varnothing$) logs available through standard petrophysical techniques to build our mathematical model of μ_{sat}.

Conclusions

We proposed an empirical model to calculate μ_{sat} from μ_a, S_o, ϕ and μ_{dry}. The model shows good agreement with literature data from (Yuan et al., (2014); Kato et al., (2008); Wang and Nur (1990); Doan, et al., (2010); Bauer et al., (2011) as can be seen in Figure 1 and explains how presence of heavy oil at very small saturations as a thin coating film can significantly increase the moduli. The model can also predict the behavior of the μ_{sat} as a function of temperature. Figure 2 shows the modeled variations of the μ_{sat} for a rock sample with μ_{dry} = 0.8 GPa at two different porosity and three different API values. We derived an equation for the critical state of input parameters with regards to the model. The condition of minimum porosity ensures that the predicted μ_{sat} values remain in the Hashin-Shtrikman bounds. The model can explain the effect of API, temperature and frequency through μ_a.

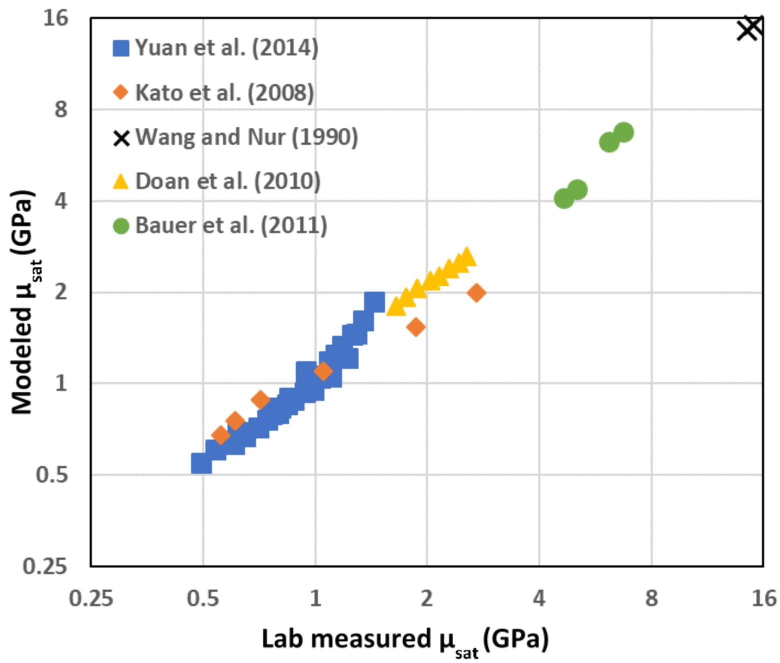

Figure 1 Compares the results of our modeled saturated shear modulus with available data from 5 different sources. Apparent shear modulus of the heavy oil in plotted points is larger than 5×10^{-3} GPa.

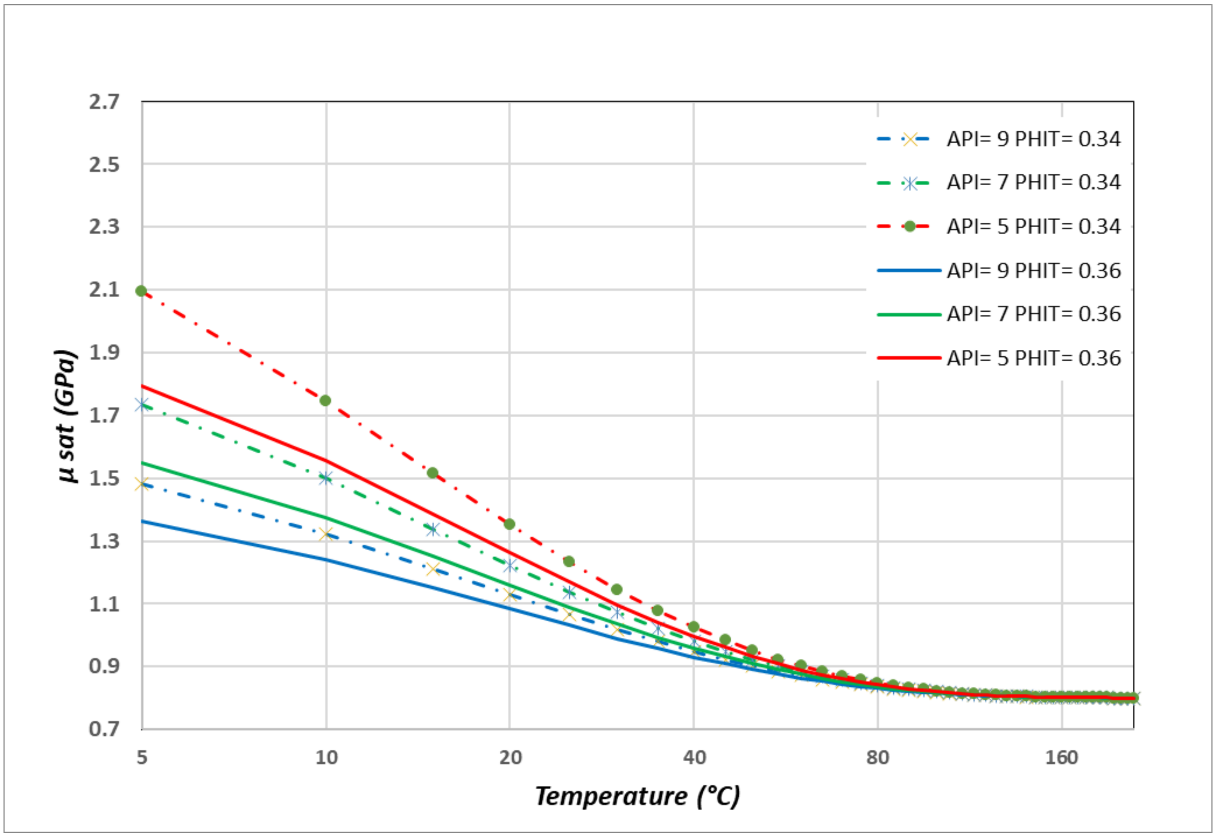

Figure 2 Shows temperature effect on the saturated shear modulus of a heavy oil saturated rock at sonic frequencies (f = 12500 Hz) with three different API values (i.e., 5, 7 and 9 degrees) where μ_{dry} = 0.8 GPa. Dashed lines are corresponding to ϕ = 0.34 while the solid lines represent ϕ = 0.36. A constant μ_{dry} assumption implies that the pore pressure remains constant through heating. S_o =1 and does change however, since $\mu_a \approx 0$ for $T > 50$ °C, replacement of oil at $T > 50$ °C does not make a change in the graphs.

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