Pressure and Temperature Effect on Heavy Oil Sands Properties

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Summary

Heavy oil sands generally have quite large porosities, and their properties are quite temperature-dependent, since temperature has great influence on heavy oil properties. Moreover, pressure also has great influence on heavy oil sand properties, since pressure can cause the grain contact to change.

Our work in this paper demonstrates that at high porosity, the sand grains are suspended in heavy oil; and at low porosity, heavy oil may work as cement in oil sands. Besides, the pressure effect on sand properties is simulated with theoretical models. In the end, we used Gassmann equation to calculate the heavy oil sand velocities change with temperature. We compared the simulation results under different situation, and analyzed the results.

Introduction

As one kind of unconventional resource, heavy oil has enormous amount. Although the heavy oil reservoir production has lasted for many years, it is still not clear how the heavy oil sand properties are related to pressure and temperature. The main reason is due to the complex properties of heavy oil.

Heavy oil sands generally have very high porosities, which are even beyond the critical porosity (37%). Figure 1 shows the statistics of Canada and Alaska heavy oil sands porosities. It can be seen that most of the samples' porosities are larger than critical porosity. We conclude that so high porosity would cause the sand grains to suspend in heavy oil.

Due to high porosity, pressure would have large effect on heavy oil sands properties. Because pressure increase can cause the porosity to decrease, and further lead to more grain contact, which would increase the bulk modulus greatly. It is of great importance to study the pressure effect on heavy oil sands, especially in production stage. Because the production of oil would cause the reservoir pressure to reduce, which can lead to the formation of foamy oil and even repacking of sands (Fereidoon et al., 2008).

Heavy oil viscosity is highly temperature-dependent. As temperature increases, heavy oil viscosity drops sharply. According to Han (2006), as temperature increases, heavy oil can be classified as three stages: glass solid stage, quasi-solid stage, and liquid stage. When temperature is low, heavy oil viscosity is very high (above 10^{15}cp), and it is like solid, so is called the glass solid stage; when temperature is high, heavy oil viscosity is very low (below 10^3cp), just like common fluid, so is called the liquid stage; in between the glass solid stage and liquid stage is the quasi-solid stage, because in this stage, the heavy oil is like a visco-elastic fluid, its viscosity is not so high as solid, and not so low, since it can support the shear modulus. In figure 2, we show the typical different viscosities of heavy oil in different temperature ranges.

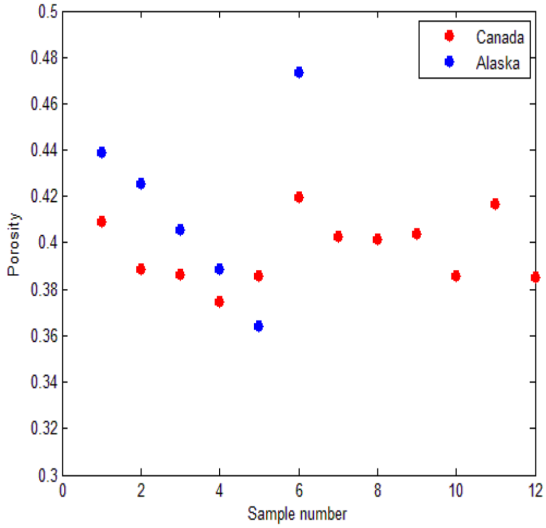

Figure 1. Statistics of heavy oil sand porosities.

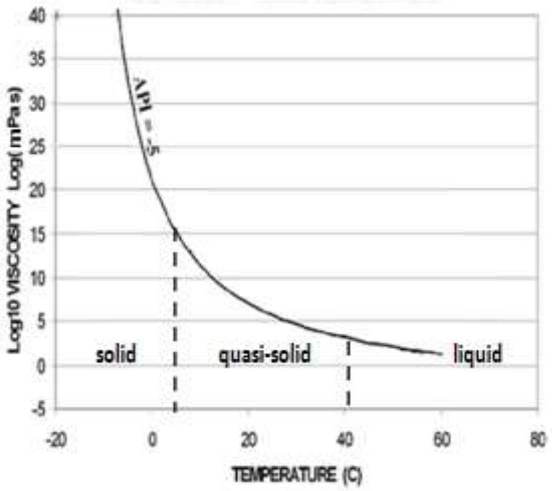

Figure 2. Viscosity of heavy oil in phase transition (M. Batzle, et al., 2006).

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Rock Physics Modeling of Heavy Oil Sands

Before doing rock physics modeling, we need some basic assumptions about heavy oil sands. Since heavy oil sands are generally of high porosities, it is reasonable to assume that for those sands with porosity larger than critical porosity (37%), the quartz grains are suspended in heavy oil. Moreover, we assume the quartz grains are oil-wetted, rather than water-wetted.

Figure 3 displays the velocity simulation result with different porosities. At low porosity, considering that the heavy oil viscosity is very high, we use Dvorkin's cement model with contact scheme2, which assumes the sand grains are covered by oil film on the surface (Dvorkin and Nur, 1996); at high porosity, the Hashin-Strikman lower bound (Hashin and Strikman, 1963) is used to do modeling, provided that the sand grains are suspended in heavy oil.

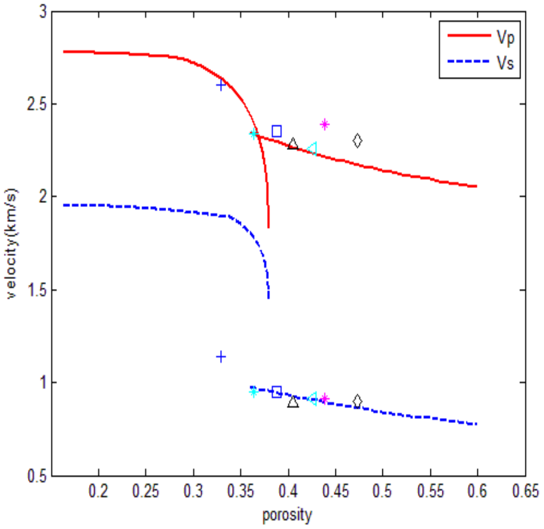

Figure 3. Heavy oil sand velocity versus porosity. When porosity is below critical porosity 37%, the cement model is used to model it; when porosity is above critical porosity, the Hashin-Strikman lower bound is used for modelimg.

It can be seen in figure 3 that at high porosity (porosity above 37%), the Hashin-Strikman lower bound fits both the Vp and Vs well with the measured data; and at low porosity (porosity below 37%), the cement model fits well with Vp, but not fits the Vs. Moreover, figure 3 also indicates that when porosity decreases from 38% to 36%, there is a sharp increase of velocity. This is because the sand grains transit from suspension state to grain contact state, causing the bulk modulus to increases drastically.

Pressure effect

Pressure effect on heavy oil sands properties is mainly due to the grain contact change caused by pressure variation. When differential pressure is low, there are fewer grain contact, therefore the sands' bulk modulus is smaller. Because heavy oil sands porosities are usually very high, we use the unconsolidated sand model (Norris and Johnson, 1997) to simulate them. Figure 4 shows the sands velocity variation with differential pressure, and figure 5 shows the porosity change due to the increasing pressure.

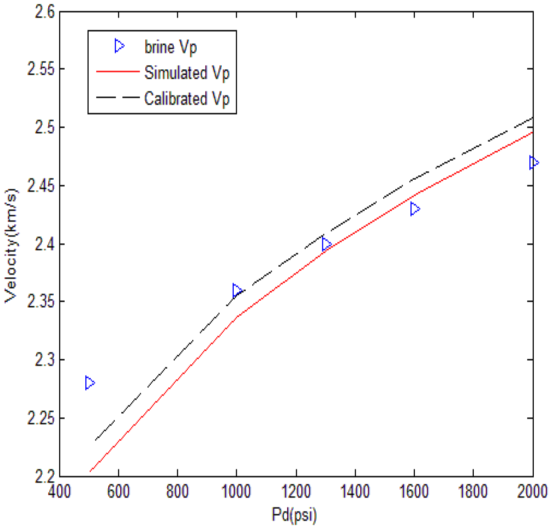

Figure 4. Oil sand P-wave velocity versus differential pressure. The blue triangular is the measured brine-saturated sands P-wave velocity, the red curve is the simulated result with unconsolidated sand model, and the red dashed line is the calibrated Vp.

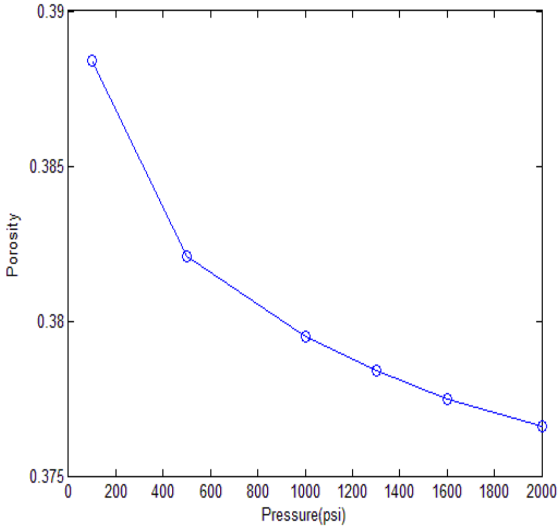

Figure 5. Porosity change with pressure.

In figure 4, it is obvious that as differential pressure increases, the Vp increases. Because the differential pressure increase causes the sands bulk modulus to increase, thus increase the velocity. Moreover, it can be seen that the result predicted by unconsolidated sand model matches the data well overall. However, at low pressure, the misfit is big. This is because in modeling, we use the constant coordinate number 6.084, which is calculated with Makse's model (Makse et al., 2004). But actually, the grain contact would vary with changing pressure. As figure 5 displays, at low pressure, the porosity is bigger, and there is less grain contact, whereas at high pressure, porosity is smaller, with more grain contact. The black dashed line is the calibrated calculation, in which the grain contact variation is considered. It can be seen the calibrated curve fits the data better, and the error between this calibration and the measured data is 0.0051, while the error between original calculation and measured data is 0.0073.

Temperature effect

Temperature has a great influence on heavy oil sand properties, mainly because heavy oil properties are temperature-dependent. Heavy oil viscosities decrease a lot with increasing temperature.

Figure 6 displays the velocities of four heavy oil sand samples from Alaska, and figure 7 shows the corresponding Vp/Vs ratio variation with changing temperature.

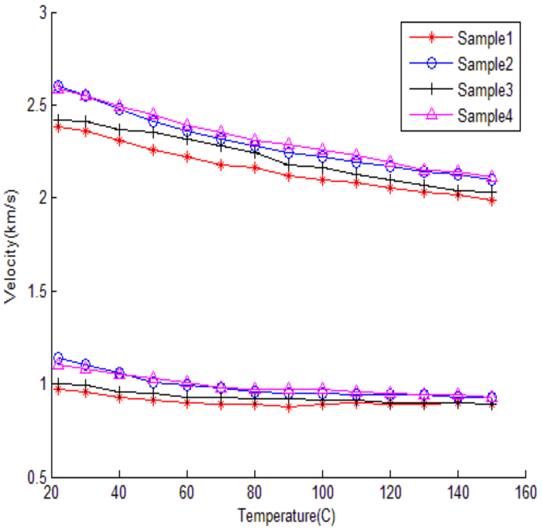

Figure 6. Heavy oil sand velocites versus temperature.

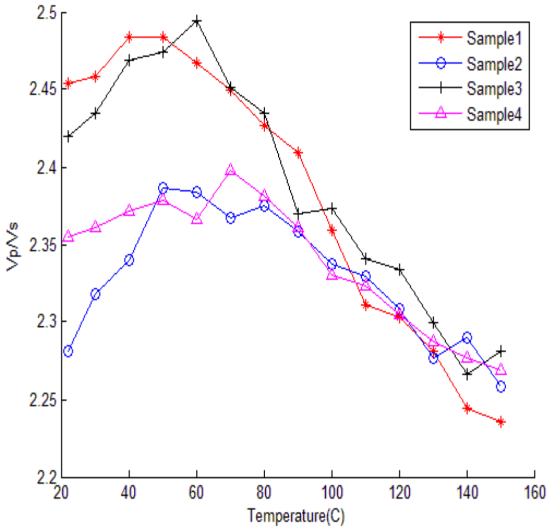

Figure 7. Heavy oil sand Vp/Vs ratio versus temperature.

As we can see from figure 6, there is a transition temperature point between about 60C^0 and 80C^0. Before this point-liquid point (Han et al., 2006), Vp and Vs decrease with increasing temperature at a large gradient, and after this point, they decrease at a smaller gradient, especially for Vs, which almost keeps constant. The Vp/Vs ratio in figure 7 gives a more clear indication, since Vp/Vs ratio reaches a peak near this point.

When temperature is below liquid point, both Vp and Vs decrease with increasing temperature, but Vp has a larger gradient. So the Vp/Vs increases with temperature. Above liquid point, heavy oil is liquid stage, and it is only pore fluid. Thus, the oil sand Vs keeps constant – the shear modulus is the frame modulus, which doesn't change with temperature. For Vp, the oil bulk modulus will continue to decrease with increasing temperature, although at a smaller rate. Therefore, the Vp/Vs will decrease with temperature, and Vp/Vs reaches the peak near liquid point. This sensitiveness property of Vp/Vs may suggest it as a temperature indicator.

Figure 8 displays the measured heavy oil sand velocities with different temperatures, and Gassmann calculations under different assumptions. The parameters for measurement and calculation are: differential pressure 25bar, quartz grains bulk modulus 35GPa, shear bulk 44Gpa, water bulk modulus 2.2GPa, density 1.0g/cm^3, air bulk modulus 1.31*10^{-4}GPa, density 1.19*10^{-3}g/cm^3. Here we simply assume heavy oil has similar properties as water. This may not be necessarily the truth, and the heavy oil density and bulk modulus may exceed that of water.

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However, we still use that values which give us a plausible trend of the Gassmann calculation.

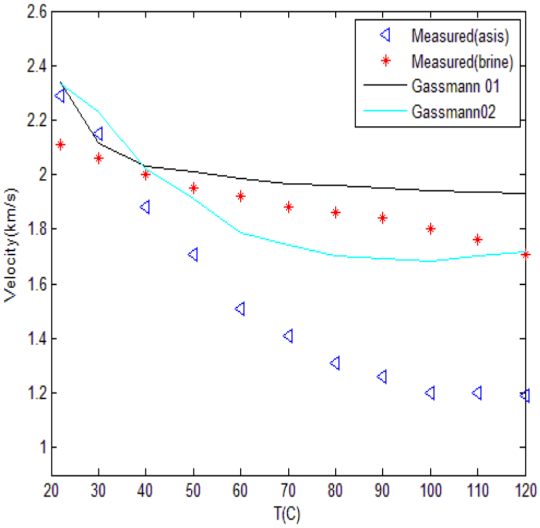

Figure 8. Heavy oil sand velocities versus temperature. The blue triangular is the measured data under asis contidion; the red asterisk is the measured data with brine saturated oil sands; the black curve is the Gassmann calcultion under the assumption that heavy oil is part of frame matrix, not pore fluid; the cyan curve is the Gassmann calculation under the assumption that heavy oil is totally pore fluid.

It can be seen in figure 8 that when temperature is low (below about 38C^o), the measured asis Vp is higher than brine saturated sand Vp. Because when temperature is low, heavy oil viscosity is high, and it works as cement, cementing the sand grains together, so the oil sand bulk modulus is high, and thus Vp is high. The saturation of water, although increases the bulk modulus, only make a little contribution, since the bulk modulus is already very high; on the other side, the saturation of water makes more contribution to the density increase. Therefore, the brine Vp is lower than asis Vp. When temperature is above 38C^o, heavy oil viscosity is low, it is in liquid state, and works as pore fluid, thus the sand bulk modulus decreases. Under such condition, the saturation of water increases both the bulk modulus and density, but makes more contribution to the bulk modulus increase. Therefore,the brine Vp is higher than asis Vp.

The black curve is Gassmann calculation assuming the heavy oil as cement matrix, while the cyan curve assuming the heavy oi as pore fluid. It is obvious that black curve is close to measured data at low temperature, and goes farther as temperature increases, and the cyan curve is opposite,it goes closer as temperature increases. We think this is because when temperature is low, the heavy oil is in solid state, and it does work as cement matrix, just as the assumption for black curve, therefore the black curve is close to measured data, and cyan curve doesn't match well; when temperature is high, the heavy oil is in liquid state, as the assumption for cyan curve, so the cyan curve fits well and black curve doesn't. However, in mediate temperature range, neither black curve nor cyan curve can match the measured data. Because in this temperature range, heavy oil is in quasi-solid state, and it could be part of matrix and part of pore fluid, so assuming heavy oil as pure solid or pure liquid can not work well here.

Conclusions

At high porosity, sand grains are suspended in heavy oil, as described by Hashin-Strikman lower bound, and at low porosity, the cement model gives us an insight into the situation (although the Vs doesn't fit).

However, the true story is much more complex, far beyond our assumptions. First of all, it is quite possible that the sand grains are not perfect spheres as assumed in Hashin-Strikman bound. Besides, the sands may have grain contact even at high porosity, since they are not necessarily sphere. Thirdly, the heavy oil sand grains may not be oil-wetted, if so, the Dvorkin's cement model is not appropriate for modeling.

Grain contact is a very important factor affecting the bulk modulus, which links sand properties with the pressure. Although our calculation shows some meaningful result, it is based on theoretical model. We hope to do more measurement to justify that.

Vp/Vs ratio has peak values near liquid point, and this is not an individual case, it can be explained theoretically. We believe it can be an effective temperature indicator, if combined with other factors.

Gassmann calculations indicate that the heavy oil works as cement matrix at low temperature, and works as pore fluid at high temperature. But, in mediate temperature range, it is still not clear how heavy oil reacts with sand grains. We are even not sure whether the complex property is due to the heavy oil or the reaction between heavy oil and sand grains. More work need to be done about this range.

In the end, it should be pointed out that in real production, neither temperature nor pressure would affect oil sands properties alone, they usually couple together to cause influence. We feel that our work is just a starting point, and much more work needs to be done in the future.

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