Ultrasonic P-wave velocity and density of heavy oil – toluene mixture

De-hua Han and Min Sun, RPL, University of Houston*

Summary

The P-wave velocity and density properties of heavy oil - toluene mixture were measured and analyzed for the range of temperatures from 22°C (71.6°F) to 90°C (194°F), and pressures from 3.45 MPa (500psi) to 48.27 MPa (7000psi). P-wave velocities and densities of the mixture decrease with increasing toluene's fraction, increasing temperature, and decreasing pressure. Based on the measured data, preliminary models have been developed.

Introduction

Huge potential of heavy oil resources is important now, and even more important in the near future. However, producing and transporting heavy oil remains a major engineering challenge. Currently, thermal recovery technique, such as Steam Assistant Gravity Drainage (SAGD) has been commonly used for underground heavy oil production. However, the thermal technology is almost prohibited for heavy oil reservoirs in a deep depth (especially on offshore) due to the challenge in economic and environmental difficulty. We may have to find alternative way to produce high viscosity oil in deep depth.

Low-viscosity solvent is a potential alternative to reduce heavy oil viscosity, and an additional benefit of which is reusable. Recently combinations of thermal and solvent miscible methods are proposed for a pre-heated reservoir (Pathak et al., 2010). In order to evaluate efficiency of the technology, we need to know how solvent fraction affects seismic properties of heavy oil mixture at in-situ temperature and pressure conditions. We carried a preliminary study with toluene as solvent. This paper describes our experimental design, measured data and empirical modeling on velocity, density and viscosity of heavy oil- toluene mixture.

Sample preparation and experimental design

Sample preparation

We used a general heavy oil sample with density of $\rho_0 = 0.971 g/cc$ (API = 14.27), and toluene with density of $\rho_0 = 0.871 g/cc$ (API = 30.96) (Laboratory grade with purity > 99.7%). Since toluene is miscible with heavy oil, ten samples of heavy oil-toluene mixture were prepared by volume percentage as shown in the following table.

	Volume percentage									
Heavy oil	100	95	90	85	80	75	70	65	60	0
toluene	0	5	10	15	20	25	30	35	40	100

Experimental design

a. Ultrasonic P-wave velocity and density were measured in following temperature and pressure ranges:

$22°C \leq T \leq 90°C$ ($71.6° F \leq T \leq 194° F$)

$3.45 MPa \leq P \leq 48.27 MPa$ ($500psi \leq P \leq 7000psi$)

Three mixture samples with toluene fraction of 5%, 20% and 35% were measured.

b. Density was measured on ten samples at the room condition. Density at the standard condition was calculated from the measured data.

c. P-wave velocity of the heavy oil was measured at the pressure 0.1MPa and temperature from -40°C to 100°C.

Experimental results and discussions

Toluene has a lower velocity, density, and viscosity compared with those of the heavy oil. In general, the toluene fraction causes decreases of velocity, density and viscosity of the heavy oil-toluene mixture.

Velocity and density of heavy oil and toluene

First, we measured ultrasonic velocity of the heavy oil at room pressure with temperature ranged from negative -40ºC to 100ºC as shown in Figure 1. The measured data show a near linear trend at high temperature, in which heavy oil is in the liquid phase, and then gradually deviates from the linear trend with decreasing temperature lower than 50ºC, in which heavy oil transits into quasi-solid trend. The FLAG program is used to estimate density and compressional velocity of heavy oil as a function of temperature and

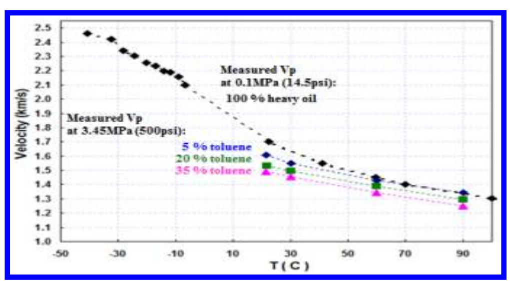

Figure 1. Measured velocities vs. temperature for the heavy oil at 0.1 MPa and mixtures at 3.45 MPa.

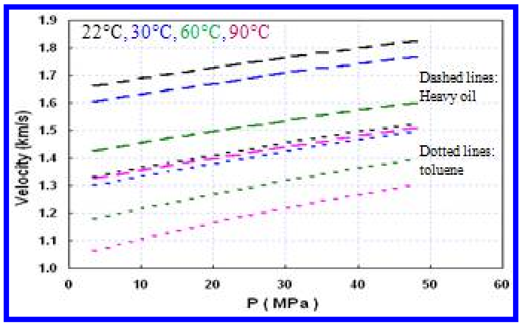

Figure 2. Velocities of heavy oil and toluene.

pressure. Density and velocity of toluene are calculated using NIST program as shown in Figure 2 for their velocity.

Velocity of the heavy oil – toluene mixture

Figure 3 shows measured velocity data at different pressure and temperature conditions on three mixture samples with 5%, 20% and 35% of toluene fraction, respectively. Dash lines are estimated velocities of the heavy oil using the FLAG program. Compared with modeled heavy oil velocities, measured data of the mixtures show following features:

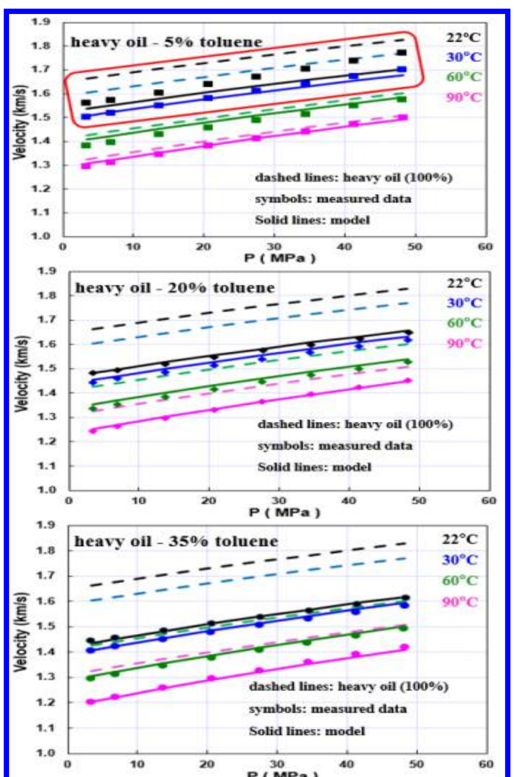

Figure 3. Measured velocity data with model predicted result: 5%, 20%, and 35% toluene.

1. Velocities of the mixtures show similar trend as that of heavy oil to increase linearly with increasing pressure. However, velocity data measured on the sample with 5% toluene at room temperature of 22ºC show higher gradient with pressure (Figure 3). It can be interpreted as that viscosity of the mixture increases with increasing pressure to cause the phase of the mixture moving further from the liquid phase. This suggests that at room temperature the mixture with 5% toluene is in quasi-solid state with dispersed high velocities as shown in the red cycle.

2. We also need pay attention to the temperature effect on phase transition for the heavy oil-toluene mixture. For the mixture with 5% toluene at low temperature of 22-30-60ºC range, velocity data also show abnormally large temperature effect to reduce velocity, similar as those of heavy oil. This suggests that this sample is in quasi-solid phase at low temperature. However, the mixture with toluene fraction higher than 20% appears to locate in the liquid phase with a near linear velocity trend versus temperature as shown in Figure 3.

3. Measured velocity data also reveal that toluene fraction shows gradually reduced effect to decrease velocities of the mixture from those of heavy oil. Data suggest that large effect on velocity at low temperature with small amount of toluene is caused by both that heavy oil is in the quasi-solid state, and the mixture with small amount of toluene can reduce viscosity significantly to push transition of the mixture to the liquid phase. Again, the mixture with a toluene fraction of more than 20% appears to locate in the liquid phase, and velocity reduction with increasing toluene fraction tends to be reduced.

Density of the heavy oil – toluene mixture

The density of heavy oil - toluene mixture (10 samples) measured at room condition is presented in figure 4. In comparison with the values estimated by the model of the ideal liquid principle, the density of the mixture is higher than the model predicted, which suggests that the volume of the mixture is reduced from that before mixing. We can assume that the reduced volume after mixing is due to part of solvent saturated within the matrix of heavy oil. Indeed, with increasing toluene fraction, density tends to be incrementally higher than that of ideal liquid, which suggests more toluene saturated within heavy oil matrix. This trend ends up to ~20% of toluene fraction. Then, the density trend appears to point to the toluene density. Addition of toluene into the saturated mixture seems to follow the ideal liquid principle.

Figure 5 shows measured density data. Generally densities of the mixture samples decrease with additional toluene fraction, and still maintain trends of the pressure and temperature effect.

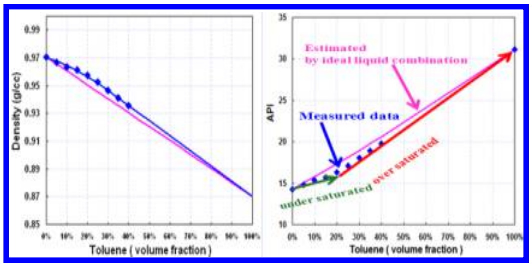

Figure 4. Densities at the standard condition based on measured data at room condition.

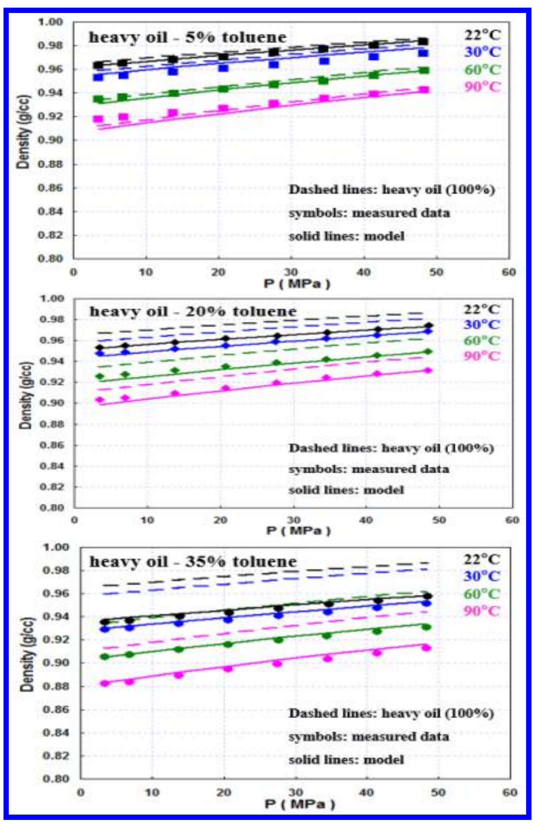

Figure 5. Measured density data with model predicted result: 5%, 20%, and 35% toluene.

Viscosity of the heavy oil – toluene mixture

The viscosity of heavy oil can be estimated by the viscosity model Vis-2011, which is used in the FLAG/VHO program (Liu, et al., 2011). For viscosity of toluene, we use Santos model (Santos, et al., 2006),

$$\ln(\eta^*) = -5.2203 + \frac{8.964}{T^*} + \frac{5.834}{(T^*)^2} + \frac{2.089}{(T^*)^3} \quad (1)$$

Where $\eta^* = \dfrac{\eta(T)}{\eta(298.15)}$ (2)

$$\eta(298.15) = 554.2 \pm 3.3 \mu Pas \quad (3)$$

$$T^* = \frac{T}{298.15}. \quad (4)$$

Due to dramatically low viscosity of toluene (about ~4 order of magnitude) from that of the heavy oil (Figure 6), even small fraction of toluene can greatly reduce the viscosity of the mixture as velocity data indicated in Figure 3. Since we defined the liquid point of heavy oil as a temperature where viscosity of heavy oil equals to 10^3 cP, our data suggest that the mixture with 20% toluene or more, has viscosity less than 10^3 cP. We need a further measurement of the mixture's viscosity directly.

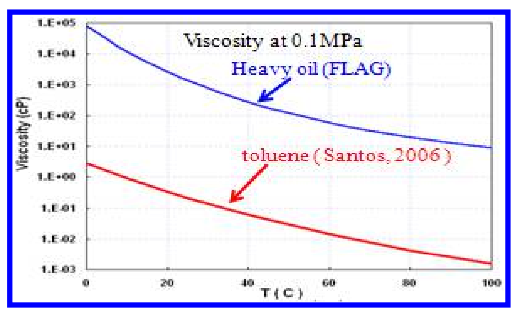

Figure 6. Estimated viscosities.

Model design for heavy oil - solvent mixture

For heavy oil in liquid phase, we have the conventional oil model in the FLAG program to estimate its velocity and density. As shown in measured data, the mixture may be in the quasi-solid phase to cause velocity dispersion. For application purpose, we focus on modeling properties of the heavy oil- solvent mixture in the liquid phase first. This may be the most important phase for the formation with solvent invasion. The transition zone bounded with heavy oil may contain less solvent, which may stay in the quasi-solid phase. But they tend to be thin and less important for seismic monitoring. In addition, their property can still be estimated with the heavy oil model in the FLAG program if needed. Therefore, our approach to model the heavy oil-solvent mixture will based on the conventional oil model in the FLAG program. As mentioned earlier, the toluene behavior is similar as conventional oil, if we can use the oil model to predict the solvent's properties, we may be able to reveal a correlation to describe properties of heavy oil-solvent mixture.

Basically, we assume that properties of the mixture is kind of average property of heavy oil and solvent component with a correlation expressed as,

$$F = f(f_{v\_HO}, P_{HO}, f_{v\_solvent}, P_{solvent}, C_{HO\_solvent}) \quad (5)$$

Where f_{v_HO} and $f_{v\_solvent}$ are volume fractions of heavy oil and solvent respectively, and $f_{v\_HO} + f_{v\_solvent} = 1$; P_{HO} is properties of heavy oil; $P_{solvent}$ is properties of solvent; and $C_{HO\_solvent}$ is a correlation to describe physical property relations between heavy oil and solvent.

Velocity model for heavy oil - toluene mixture

$$V = f_{v\_HO}V_{HO} + f_{v\_toluene}V_{toluene} + C_{HO\_toluene} \quad (6)$$

Where, *V* is velocity of heavy oil-toluene mixture.

V_{HO} is oil velocity estimated with FLAG.

$V_{toluene}$ is toluene velocity, which can also be obtained using FLAG with an effective density, ρ_0 = 0.79598 g/cc.

We have empirically determined the correlation parameter as

$$C_{HO\_toluene} = -0.1 f_{v\_toluene} f_{v\_HO} V_{HO}. \quad (7)$$

The model is basically a volume average one with a linear additive as correlation. In this model we select the proportional heavy oil velocity as the correlation. The measured data with the estimated results of the model are presented in Figure 3. The model results match the measured data well, except for the 5% toluene at the room temperature 22°C. The model underestimates velocity at that condition, because the temperature is below the liquid point, and the mixture with 5% toluene is in quasi-solid phase with dispersed velocity.

Density model for heavy oil-toluene mixture

Based on the measured data at room condition, the density of heavy oil-toluene mixture at the standard condition can be expressed as,

$$\rho_0 = f_{v\_HO}\rho_{HO\_0} + f_{v\_toluene}\rho_{toluene\_0} + C_{HO\_toluene\_0}. \quad (8)$$

Where ρ_0 is density of the mixture; ρ_{HO_0} is density of heavy oil; $\rho_{toluene}$ is the density of toluene; and a density correlation,

$$C_{HO_{toluene_0}} = a_1 f^4_{v_{toluene}} + a_2 f^3_{v_{toluene}} + a_3 f^2_{v_{toluene}} + a_4 f_{v\_toluene} + a_5 \quad (9)$$

The values of coefficients in Equation (9) are:

i	a_i	i	a_i
1	-0.0831	4	0.0628
2	0.2132	5	-0.0005
3	-0.1932		

Density of the mixture can be obtained by using FLAG program with ρ_0 as input. Figure 5 shows that predicted results by FLAG match measured data.

Conclusion

1. Velocities and densities of heavy oil + toluene with 5%, 20% and 35% volume fraction were measured within the designed range of $22°C \le T \le 90°C$ ($71.6°F \le T \le 194°F$) and $3.45\ MPa \le P \le 48.27\ MPa$ ($500psi \le P \le 7000psi$). Added toluene decreases velocities and densities of heavy oil greatly.

2. Viscosities of the mixture were analyzed by models. Added toluene dramatically decrease viscosity of heavy oil and increase its flowability.

3. The preliminary models are proposed for predicting velocity and density of heavy oil - toluene mixture. The predicted results are matched with the measured data, but more data are needed to refine the models for different heavy oil.

Acknowledgements

This research has been supported by the "Fluids/DHI" consortium, which is collaborated between University of Houston and Colorado School of Mines, and sponsored by oil industries all over the world. We appreciate our sponsors for providing the samples.

EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Liu, J., D. Han, and M. Sun, 2011, Models of heavy oil — Review and development: Presented at the 2011 Annual meeting of Fluids, DHI.

Pathak, V., and T. Babadagli, 2010, Hot solvent injection for heavy oil/bitumen recovery: An experimental investigation: CSUG/SPE.

Santos, F. J. V., C. A. Nieto de Castroa, J. H. Dymond, N. K. Dalaouti, M. J. Assael, and A. Nagashima, 2006, Standard reference data for the viscosity of toluene: Journal of Physical and Chemical Reference Data, **35**, 1–8.