Modeling ultrasonic compressional velocity of heavy oil mixed with hydrocarbon solvent

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Summary

The solvent-based recovery methods improve heavy oil production significantly by reducing viscosity of heavy oil. We have measured ultrasonic compressional velocity of heavy oil mixed with hydrocarbon (HC) solvent composed by diluent and propane, and studied their properties experimentally. Based on the measured data, we have built a correlation to describe the solvent effect on ultrasonic compressional velocity of heavy oil at in-situ temperature and pressure conditions. The results of the correlation fit the data well with AARE = 1.898 %.

Introduction

The solvent-based recovery methods improve heavy oil production through significantly reducing viscosity of heavy oil, and thereby increasing heavy oil mobility. Seismic monitoring the performance of the solvent-based injection processes is crucial for designing and optimizing solvent-based processes. Typically toluene, light hydrocarbon (HC) fluid, CO_2, and their combinations are selected as solvents. Therefore, we have been giving efforts to investigate physical properties of heavy oil mixed with toluene (Han and Sun, 2016), and to study density and ultrasonic velocity of heavy oil mixed with light hydrocarbon solvent experimentally (Han and Sun, 2015).

From application viewpoint, we usually build correlations based on the measured data. In this research, we have created a model for acoustic compressional velocity of heavy oil mixed with light hydrocarbon solvent. Although the application of the model is limited by the range of the measured data, we hope that it can be suitable for using in wider situation with a local calibration.

Measured data used for modeling

In order to investigate properties of heavy oil mixed with light hydrocarbon solvent systematically, we have measured ultrasonic compressional velocity of the mixtures of heavy oil with solvent, as well as their single component, heavy oil, diluent, and solvent. The data used for building models were reported (Han and Sun, 2015) and covered in-situ temperature form 8°C (46.4 F) to 90°C (194 F), and pressure from 1 MPa (145 psi) to 48 MPa (7000 psi). The data include the measured ultrasonic compressional velocities of heavy oil, diluent, solvent which is composed by 12 wt.% diluent with 88 wt.% propane, and the heavy oil mixed with the solvent. The data used for this modeling are summarized in Table 1 and 2.

samples	ρ_0 [g/cc]	API	data	
heavy oil	1.0009	10	velocity	RPL measured
diluent	0.6759	78	velocity	RPL measured
propane	0.0018696	75553	velocity	From NIST
Solvent (12 wt.% diluent + 88 wt.% propane)			velocity	RPL made and measured
Five mixtures (Table 2)			velocity	RPL made and measured

Table 1. Summary of data used for modeling.

mixture of three components (Bitumen+Diluent+Propane)							
Volume Fraction				Weight Fraction			
solvent			Bitumen	solvent			Bitumen
Diluent	Propane	D(12%)+P(88%)		Diluent	Propane	D(12%)+P(88%)	
1.29%	9.46%	10.75%	89.25%	0.92%	5.10%	6.02%	93.98%
2.31%	16.91%	19.22%	80.78%	1.72%	9.52%	11.24%	88.76%
3.85%	28.26%	32.11%	67.89%	3.07%	17.04%	20.11%	79.89%
5.25%	38.52%	43.77%	56.23%	4.47%	24.82%	29.29%	70.71%
10.56%	77.44%	88.00%	12.00%	12.15%	67.45%	79.60%	20.40%

Table 2. Volume fraction and weight fraction of the five mixtures of heavy oil with HC solvent at in-situ condition 13°C and 3MPa.

Existed model and method evaluations

Measured data show that the velocity of the heavy oil decreases dramatically with a little HC solvent mixed. The most efficiency happened only by mixing heavy oil with a few percent of solvent within the low temperature range. We need to give a correlation to describe the solvent effect on the heavy oil, especially where solvent works most efficiently. First we use the existing models to match the measured data of heavy oil mixed with HC solvent. We have the conventional oil model in the FLAG program to estimate velocity of conventional oil pretty well. We also have the heavy oil model to estimate the velocity of heavy oil at in-situ temperature and pressure conditions.

First we estimate the density of the mixture at the standard condition, and then use it as a pseudo density which is a crucial input parameter of the existed models. The result of the heavy oil model overestimates the velocity of the mixture. Since solvent components are mainly hydrocarbon fluid, we should apply the conventional oil model, but also obtain overestimated results as shown in Figure 1. The difference occurs mainly in the low temperature range. Usually the conventional oil models are based on in-situ temperature, pressure, and components of conventional oil. But the mixture of heavy oil with solvent has different temperature and pressure properties. Especially the mixtures are not happened naturally during EOR process,

and they are composed by a wide variety of components with different percentage recipes. Therefore, it is necessary to give a new correlation to predict the velocity properties of heavy oil mixed with light hydrocarbon solvent.

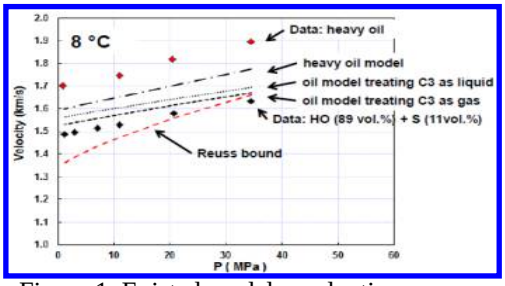

Figure 1. Existed models evaluation.

Creating a new velocity model for heavy oil mixed with HC solvent

Methodology for designing new model

Following the ideal fluid principle, we basically assume that the properties of the mixture are the ideal fluid combination of properties of each single component, with a local correlation or local calibration expressed as,

$$P_m = \sum f_i P_i + \Delta P_{cor} \quad (1)$$

Where

P_m is the properties of the mixture;

f_i is volume fractions of each single component, and

$$\sum f_i = 1$$

P_i is the properties of each single component;

ΔP_{cor} is a local correlation to describe the relations of physical property among single components.

We have used the methodology to model the velocity and density of the miscible mixtures of conventional oil with carbon dioxide (CO_2) (Han and Sun, 2013), the velocity and density of water (H_2O) with dissolved methane (CH_4) and CO_2 (Han and Sun, 2013), and the velocity and density of heavy oil mixed with toluene (Han and Sun, 2016). In this research we use the method to model the velocity properties of heavy oil mixed with solvent. At the first step we need to know volume fraction, and velocity properties of each single component.

Volume fraction

Generally we use the volume fraction of each single component with their physical properties at the same condition. However, the volume fraction is a function of temperature, pressure, and component at in-situ condition, especially for heavy oil mixed with solvent. Similar to GOR (gas and oil ratio at the standard condition) used in conventional oil, we use the volume fractions of each component at the standard condition, 15.6°C and 0.1 MPa. When we conducted the experimental measurement, the mixed samples were made by the weight fraction at room temperature with pressure first, and then calculated the volume fractions at the standard condition from the weight fraction as shown in the Table 3.

mixture of three components (Bitumen+Diluent+Propane)							
Volume Fraction				Weight Fraction			
solvent			Bitumen	solvent			Bitumen
Diluent	Propane	D(12%)+P(88%)		Diluent	Propane	D(12%)+P(88%)	
1.29%	9.58%	10.87%	89.13%	0.92%	5.10%	6.02%	93.98%
2.31%	17.11%	19.41%	80.59%	1.72%	9.52%	11.24%	88.76%
3.85%	28.53%	32.38%	67.62%	3.07%	17.04%	20.11%	79.89%
5.24%	38.84%	44.08%	55.92%	4.47%	24.82%	29.29%	70.71%
10.47%	77.66%	88.13%	11.87%	12.15%	67.45%	79.60%	20.40%

Table 3. The volume fractions at the standard condition (15.6°C and 0.1 MPa).

Velocity properties and models of the components

Heavy oil

The compressional velocity of the heavy oil is estimated by FLAG/VHO program with the following local calibration (Figure 2).

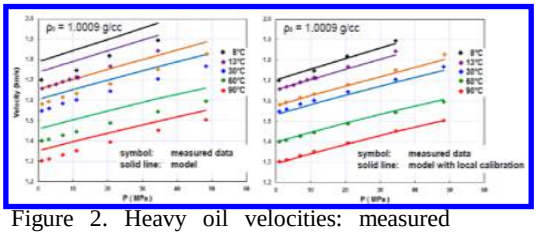

Figure 2. Heavy oil velocities: measured data with the result of the model.

The pseudo density, ρ_{HO_pseudo}, is used instead of ρ_0,

$$\rho_{HO\_pseudo} = \rho_0 - \Delta\rho_T \quad (2)$$

where

$$\rho_0 = 1.0009\ g/cc$$

$$\Delta\rho_T = \begin{cases} 4.48 \times 10^{-4} T + 1.9576 \times 10^{-2} & T \le T_l \\ -0.041 & T > T_l \end{cases} \quad (3)$$

T_l is the liquid point temperature of the heavy oil estimated via FLAG/VHO program.

Diluent

The FLAG/Poil program can be used to calculate velocity of the diluent with its $\rho_0 = 0.67593\ g/cc$ (Figure 3). A temperature adjustment is used for density estimate with

$$\rho_{d\_pseudo} = \rho_0 - \Delta\rho_T \quad (4)$$

where $\Delta\rho_T = 0.00029T + 0.00246$ (5)

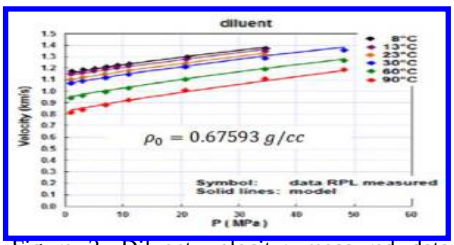

Figure 3. Diluent velocity: measured data with the result of the model.

Propane

The velocity data of propane are calculated using NIST program. At the standard condition, propane is in its vapor phase. But it changes to its liquid phase by only increasing pressure to 0.7MPa. Since our model targets on the mixture at in-situ conditions, where it shows liquid behavior, we extend its liquid trend to the standard condition to get its pseudo density (Figure 4),

$$\rho_{C3\_pseudo} = 0.50593\ g/cc$$

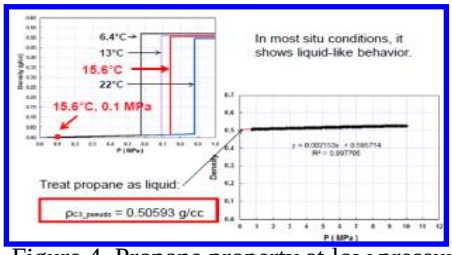

Figure 4. Propane property at low pressure.

In the liquid phase, we give a model mainly for liquid part of propane as shown in the equation 6. The data from NIST and values estimated by the model are shown in Figure 5.

$$V_p = a_1 + a_2T + a_3P + a_4P^2 + a_5TP^{a_6} \quad (6)$$

Where

i	1	2	3	4	5	6
a_i	0.89544	-0.02068	0.01093	-0.00006	0.0126	0.08277

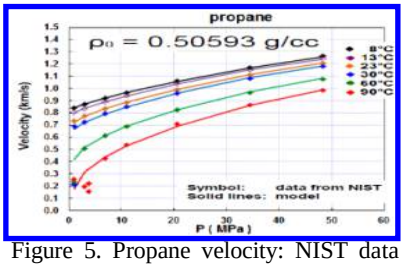

Figure 5. Propane velocity: NIST data with the result of the model.

Development of the velocity model for the heavy oil mixed with HC solvent

$$V_p = V_{p_0} + \Delta V_{p_f} + \Delta V_{p_{TP}} \quad (7)$$

where

$$V_{p_0} = f_{HO}V_{HO} + f_dV_d + f_{C3}V_{C3} \quad (8)$$

$$\Delta V_{p_f} = \frac{0.245 f_{HO}}{f_{HO}-1.00001}(1 - f_{HO} - f_{d_1})(f_{d_1}V_d - f_{HO}V_{HO}) \quad (9)$$

$$f_{d_1} = \frac{f_d(f_d+f_{C3})}{\frac{V_{d_0}}{V_{C3_0}}f_{C3}+f_d+0.00001} \quad (10)$$

$$\Delta V_{p_{TP}} = -\frac{f_{HO}-1}{f_{HO}-1.00001}(a_1 + a_2T + a_3T^2 + a_4T^3 + a_5P + a_6P^2 + a_7TP^{a_8}) \quad (11)$$

i	a_i	i	a_i
1	$1.55538079 \times 10^{-1}$	5	1.695016×10^{-3}
2	$-4.3146774 \times 10^{-2}$	6	-1.4354×10^{-5}
3	1.16048×10^{-4}	7	3.5691718×10^{-2}
4	-6.12×10^{-7}	8	-2.28×10^{-3}

In the velocity model (Figure 6), V_{p_0} is the ideal combination of the velocity of each component, and it covers the main features of the velocity of the heavy oil mixed with HC solvent.

ΔV_{p_f} is the additional property occurred by solvent fractions.

$\Delta V_{p_{TP}}$ also describes solvent effect on the heavy oil. Since the slop of the velocity estimated by the model is almost the same as the measured data, pressure effect is almost matched. It seems that $\Delta V_{p_{TP}}$is dominated by temperature effect. However, because heavy oil viscosity is a function of temperature, the temperature effect actually describes that injected solvent decreases viscosity of heavy oil dramatically in the lower temperature condition. This view is also supported by the fact that solvent effect feeds out with temperature increasing. The viscosity of the pure heavy oil is estimated by the viscosity model of FLAG/VHO (Figure 7). f_{d1} increases propane effect by the initial ratio of diluent velocity (V_{d0}) with propane velocity (V_{C30}) at the standard condition.

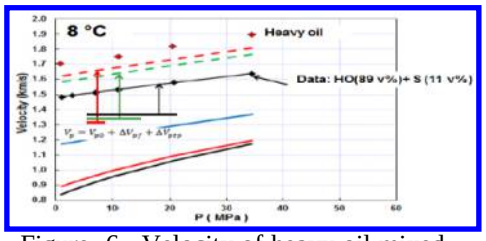

Figure 6. Velocity of heavy oil mixed with HC solvent: model development.

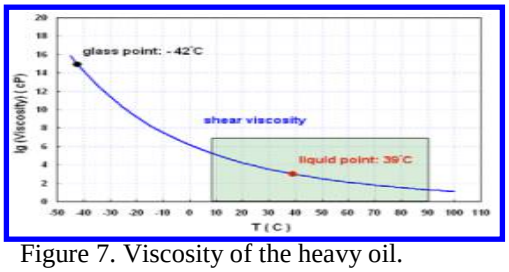

Figure 7. Viscosity of the heavy oil.

Result and discussion

1. Within the measured data ranges of temperature from 8°C to 90°C, and pressure from 1Mpa to 48 MPa, the estimated results of the model can match the measured data well as shown in Figure 8.
2. Seismically, the solvent effect on heavy oil velocity can be predicted by application of HN model bedded in FLAG/VHO as shown in Figure 9. The only 11 vol.% solvent mixed with heavy oil greatly decreases the velocity dispersions of the heavy oil. The dispersion is caused by viscosity of the heavy oil.
3. The validity of the models is analyzed using the Average Absolute Relative Error (AARE),

$$AARE = \frac{100}{N}\sum_{i=1}^{N}\left|\left(V_{i\_predicted} - V_{i\_measured}\right)/V_{i\_measured}\right| \qquad (12)$$

where N is the number of measured points, $V_{i\_calculated}$ is the calculated velocity by the models, and $V_{i\_measured}$ is the measured value. For the velocity model, AARE = 1.898 %.
4. The model can be used to predict velocity properties of the heavy oil mixed with different percentages of the solvent (Figure 10).
5. Since we use diluent and propane as a single component to model instead of using solvent, the models may also suitable for different combination of diluent and propane, with local calibration.
6. Asphaltene is generally insoluble in normal alkanes such as propane, n-heptane, n-pentane, etc. With the injection of light hydrocarbon solvent, asphaltene precipitation may take place with certain temperature, pressure, components of solvent, and even the percentages of solvent. Although we test phase behavior via velocity and density measurement, and to make sure we keep the samples in a single liquid phase during the experimental measurement (Han and Sun, 2015), we still need to understand physical and chemical properties of asphaltene.

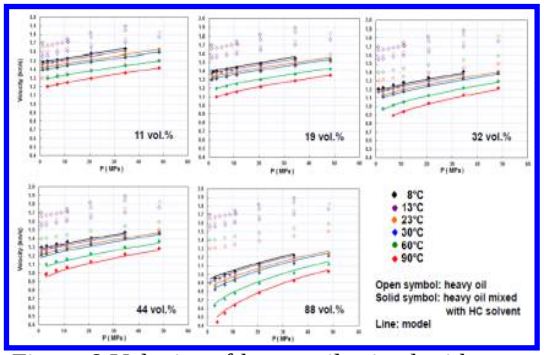

Figure 8.Velocity of heavy oil mixed with HC solvent: measured data with the result of the model for different percentages of solvent.

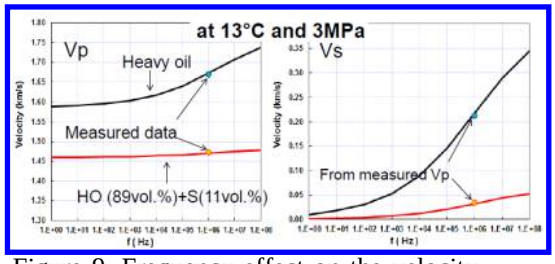

Figure 9. Frequency effect on the velocity of heavy oil mixed with HC solvent.

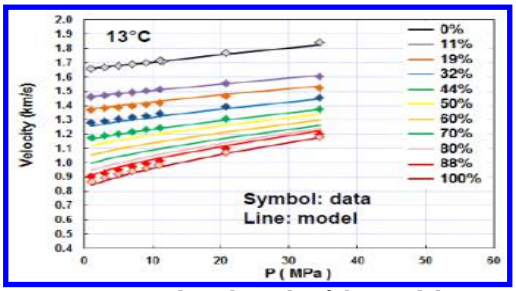

Figure 10. Predicted result of the model.

Conclusions

We have built the correlations for ultrasonic compressional velocity of light hydrocarbon liquid (diluent and propane), which can be used for predicting the velocity properties of the single component, and also be used for further liquid combination research.
Based on the measured data and the models of each single component, we have built the correlation of heavy oil mixed with light hydrocarbon solvent. The results of the correlation fit the data well with AARE = 1.898 %.

Acknowledgements

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EDITED REFERENCES

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