

## Cold, Hot, or Dilute: Modeling the Viscosity of Heavy Oil for *In Situ* Processes

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### Summary

Two methods (the Expanded Fluid model and the Modified Walther correlation) used for fitting and predicting the viscosity of heavy oil and solvents were assessed on a dataset including the viscosity and density of mixtures of bitumen and ethane, propane, butane, pentane, heptane, and carbon dioxide. Both correlations were adapted to determine crude oil viscosity based on C30+ GC assays. The methods provided order-of-magnitude viscosity estimates with no tuning and fit crude oil viscosity data to within 30% after tuning to a single dead oil experimental data point. The correlations also predicted the diluted bitumen viscosities to within 30% at temperatures from 20 to 180°C and pressures up to 10 MPa.

### Introduction

*In situ* processes for heavy oil recovery include cold production, thermal methods, solvent-based processes, and solvent assisted steam processes. These processes encompass a broad range of temperatures, pressures, and compositions in the reservoir and at the surface. Since viscosity reduction is arguably the most important goal in any heavy oil process, it is critical to develop a viscosity model that is suitable for this broad range of conditions.

The viscosity models which extend to the full phase diagram including liquid and vapour regions are corresponding states methods (Pedersen and Fredenslund, 1987), Friction Theory (Quiñones-Cisneros, 2001), and the Expanded Fluid (EF) model (Yarranton and Satyro, 2009). The Expanded Fluid correlation was developed specifically to include heavy oil viscosities. This presentation demonstrates how to use this correlation for a variety of heavy oil process conditions. The simpler modified Walther correlation (Yarranton et al., 2012), which only applies in the liquid state, is also examined.

### Method

#### EF Model

This model (Yarranton and Satyro, 2009) relates viscosity to the density of the fluid as follows:

$$\mu - \mu_o = 0.165(\exp(c_2\beta) - 1) \quad (1)$$

$$\beta = \frac{1}{\exp\left\{\left(\frac{\rho_s^*}{\rho}\right)^{0.65} - 1\right\} - 1} \quad (2)$$

where  $\mu$  is the viscosity of the fluid (mPa.s),  $\mu_o$  is the dilute gas viscosity,  $\rho$  is the fluid density,  $\rho_s^*$  is the density of the fluid in the compressed state and  $c_2$  is a fitting parameter specific for each fluid. The

compressed state of the fluid is, by definition, a hypothetical state of the fluid beyond which the fluid cannot be compressed without incurring a solid-liquid phase transition. It is assumed that the viscosity of the fluid approaches infinity as the fluid density approaches the compressed state density. The compressed state density is a function of pressure as follows:

$$\rho_s^* = \frac{\rho_s^o}{\exp(-c_3 P)} \quad (3)$$

where  $\rho_s^o$  is the compressed state density in vacuum,  $c_3$  is a fitting constant in  $\text{kPa}^{-1}$ , and  $P$  is pressure in  $\text{kPa}$ .

The model has three temperature independent parameters for each fluid:  $c_2$ ,  $c_3$  and  $\rho_s^o$ . The inputs to the model are the measured fluid density, pressure, and the dilute gas viscosity. Note, the effect of temperature on viscosity is introduced through the density and the dilute gas viscosity both of which are temperature dependent. The model is only valid for Newtonian fluids.

The EF model treats a mixture as a single-fluid. The fluid-specific parameters of the mixture are calculated with following mixing rules (Motahhari et al., 2012):

$$\rho_{s,mix}^o = \left( \sum_{i=1}^{nc} \sum_{j=1}^{nc} \frac{w_i w_j}{2} \left( \frac{1}{\rho_{s,i}^o} + \frac{1}{\rho_{s,j}^o} \right) (1 - \beta_{ij}) \right)^{-1} \quad (4)$$

$$\frac{c_{2,mix}}{\rho_{s,mix}^o} = \sum_{i=1}^{nc} \sum_{j=1}^{nc} \frac{w_i w_j}{2} \left( \frac{c_{2,i}}{\rho_{s,i}^o} + \frac{c_{2,j}}{\rho_{s,j}^o} \right) (1 - \beta_{ij}) \quad (5)$$

$$c_{3,mix} = \left( \sum_{i=1}^{nc} \frac{w_i}{c_{3,i}} \right)^{-1} \quad (6)$$

where  $nc$  is the number of components in the mixture,  $w_i$  is the mass fraction of the component “ $i$ ” in the mixture, and  $\beta_{ij}$  is a binary interaction parameter with default value of zero. The binary interaction parameter can be used to tune the model when experimental viscosity data for the mixture are available. The following correlation was found to provide satisfactory results for diluted bitumen:

$$\text{for } \Delta SG_{norm} \leq 0.355: \quad \beta_{sol-oil} = 0 \quad (7a)$$

$$\text{for } \Delta SG_{norm} \geq 0.355: \quad \beta_{sol-oil} = 0.055 - 0.155 \Delta SG_{norm} \quad (7b)$$

where

$$\Delta SG_{norm} = 2 \frac{|SG_2 - SG_1|}{SG_2 + SG_1} \quad (8)$$

where  $SG$  is specific gravity. Note, the  $SG$  of bitumen is near unity while the effective  $SG$  of liquid solvents can be as low as 0.4; for example, for dissolved propane.

### Modified Walther Correlation

The original Walther (1931) correlation relates the kinematic viscosity of a liquid to temperature. Mehrotra and Svrcek (1989) modified the correlation to relate the dynamic viscosity of heavy oil to temperature. Yarranton et al. (2012) modified the correlation to account for both pressure and temperature as follows:

$$\mu = \mu^o (1 + \alpha (1 - 0.0033T) \Delta P) \quad (9)$$

$$\log(\log(\mu^{\circ} + 1)) = A - B \log(T) \quad (10)$$

where  $\mu_i^{\circ}$  refers to the viscosity of a component (mPa.s) or a fluid mixture at a atmospheric pressure,  $T$  is the temperature in K, and  $\Delta P$  is the deviation from atmospheric pressure in kPa.  $A$ ,  $B$ , and  $\alpha$  are fluid specific constants that were correlated to molecular weight for crude oil pseudo-components.

The correlation treats a mixture as a single-fluid and the parameters for the mixture are calculated as follows:

$$A_{\text{mix}} = \sum_i^n \sum_j^n w_i w_j \frac{A_i + A_j}{2} (1 - \beta_{ij}) \quad (11)$$

$$B_{\text{mix}} = \sum_i^n \sum_j^n w_i w_j \frac{A_i + A_j}{2} (1 + \beta_{ij}) \quad (12)$$

$$\ln\{\ln(\alpha_{\text{mix}} + 1)\} = \sum_i^n w_i \ln\{\ln(\alpha_i + 1)\} \quad (13)$$

Note that no interaction parameters were required for components with molecular weights above 44 g/mol (propane). The molecular weight of heavy oils and bitumens is in the order of 500 g/mol.

## Examples

The different approaches were tested on a dataset including the viscosity and density of mixtures of bitumen and ethane, propane, butane, pentane, heptane, and carbon dioxide as well as dead and live oil viscosities of a range of conventional crude oils. Some examples are provided below.

Figure 1 shows how the EF model fits viscosity data for a bitumen over a range of temperature and pressures. Figure 2(a) shows the EF model predictions for mixtures of propane diluted bitumen. Similar results were obtained for other n-alkanes as well as CO<sub>2</sub> over a broad range of conditions (temperatures from 20 to 180°C, pressures up to 10 MPa, and solvent contents up to the onset of asphaltene precipitation). In general, the model predicted the viscosities of mixtures with average absolute relative deviations (AARD) less than 20%. Note that the viscosity predictions are sensitive to the accuracy of the input densities.

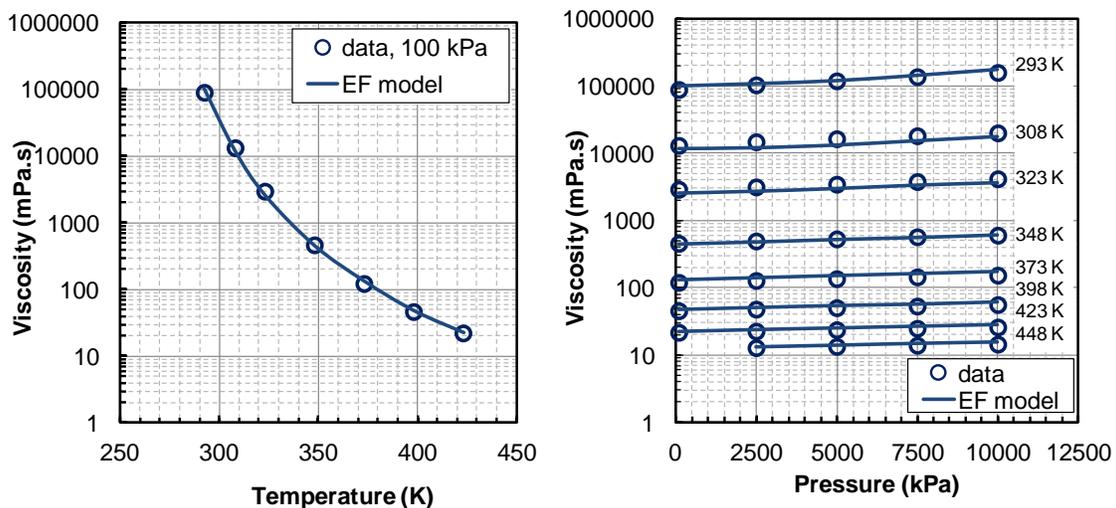


Figure 1: EF model fitted to viscosity of dead bitumen versus temperature (left) and pressure (right).

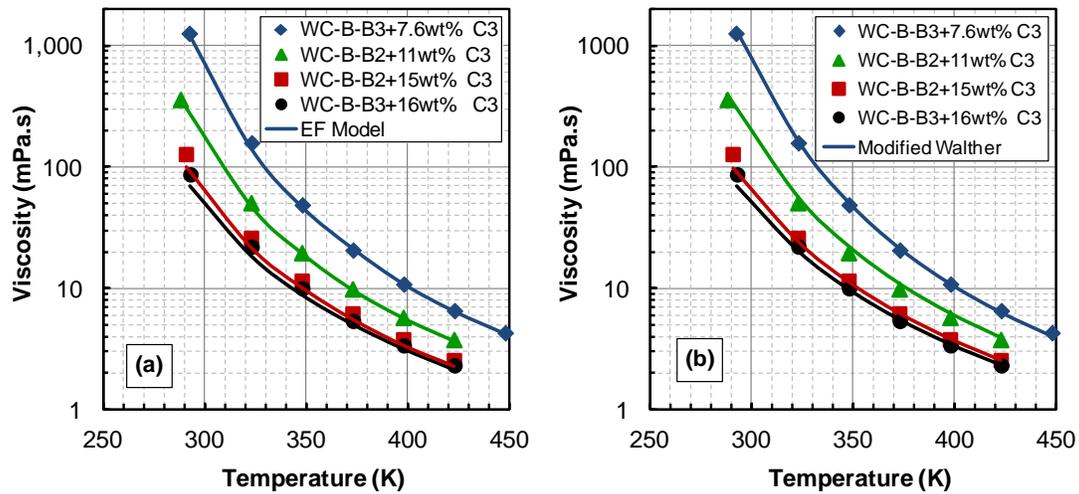


Figure 2: Comparison of predicted and measured viscosity of propane diluted bitumen at 10 MPa: a) EF model, the binary interaction parameter was calculated from Eq. 7; b) Modified Walther correlation.

Figure 3 shows the Modified Walther correlation fitted to viscosity data for a condensate, a heavy oil, and some bitumens. Figure 2(b) shows viscosity of propane diluted bitumen predicted with the correlation. The results with the Modified Walther correlation are comparable to those with the EF model. In general, the Modified Walther predicted the viscosity of the same set of mixtures with average absolute relative deviations (AARD) less than 30%. The Modified Walther correlation does not require a density input but is only valid for liquids.

Both the EF model and the Modified Walther correlation were adapted to work with the pseudo-component characterizations of crude oils used in equation of state models (Motahhari et al., 2013, Yarranton et al., 2012). The oil characterizations were based on extrapolations of C30+ gas chromatographic assays. The viscosities of a wide range of crude oils (including bitumen) were predicted within a factor of 3 (Modified Walther) and 5 (EF) with no tuning. Single parameter tuning to a dead oil viscosity data point allowed the viscosity data over a broad range of temperatures and pressures to be fitted to within 30% (Modified Walther) and 20% (EF).

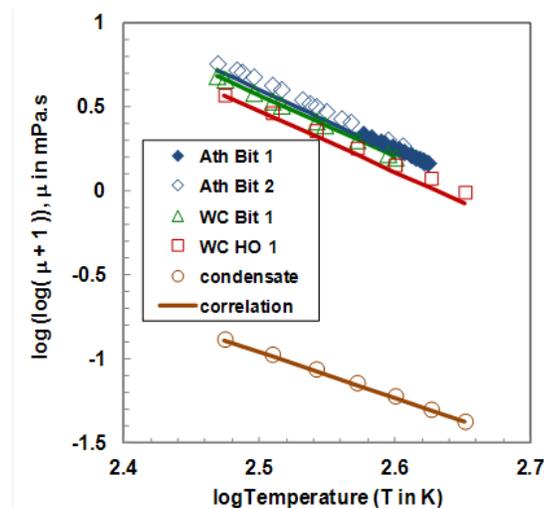


Figure 3: Modified Walther correlation fitted to viscosities of a condensate, a heavy oil, and three bitumen samples.

## Conclusions

The Expanded Fluid model fits pure component viscosity data and predicts mixture viscosities to within 30% over a wide range of conditions. The EF model is well suited for simulation applications where it is required to calculate viscosities for gases, liquids, and fluids. However, an accurate density input is required for good results. The Modified Walther correlation does not require a density input, provides similar results, but is only applicable to liquids. Both correlations were adapted to determine crude oil viscosity based on C30+ GC assays. The correlations provided order-of-magnitude viscosity estimates with no tuning and could fit viscosity data to within 30% after tuning to a single dead oil data point.

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