Revised Understanding of Transferring a Black Oil Model to Compositional

(Re-revised March 2015)

STARS has a preference for polynomial approximations, e.g. the user is encouraged to define K-values by the coefficients K_{v1}, … K_{v5} as described in an earlier blog. This attempt was only partly successful, and I felt this could be improved. After some consideration I concluded that it would be easier to simply define the K-values by a table and forget everything about the polynomial coefficients.

The oil phase in the black oil model was defined as dead oil in the sense that pressure would remain above initial bubble point throughout. The constant R_s (gas resolution factor) was 130 Sm^3/Sm^3, with bubble point 200 bars, and Bo at bubble point was 1.4.

Still, when converting the black oil PVT to a compositional description I found it was a great advantage to first extend the black oil PVT to a complete live oil model with the dead oil part as a subdomain. So the first task is to make curves of R_s vs. bubble point vs. Bo.

Bo should obviously be unity at SC (1 bar, std. temperature), and pass through the required point Bo(200 bars) = 1.4. From experience the curve should be slightly convex, but the actual shape is probably not critical. So ended up with a curve as shown in Figure 1.

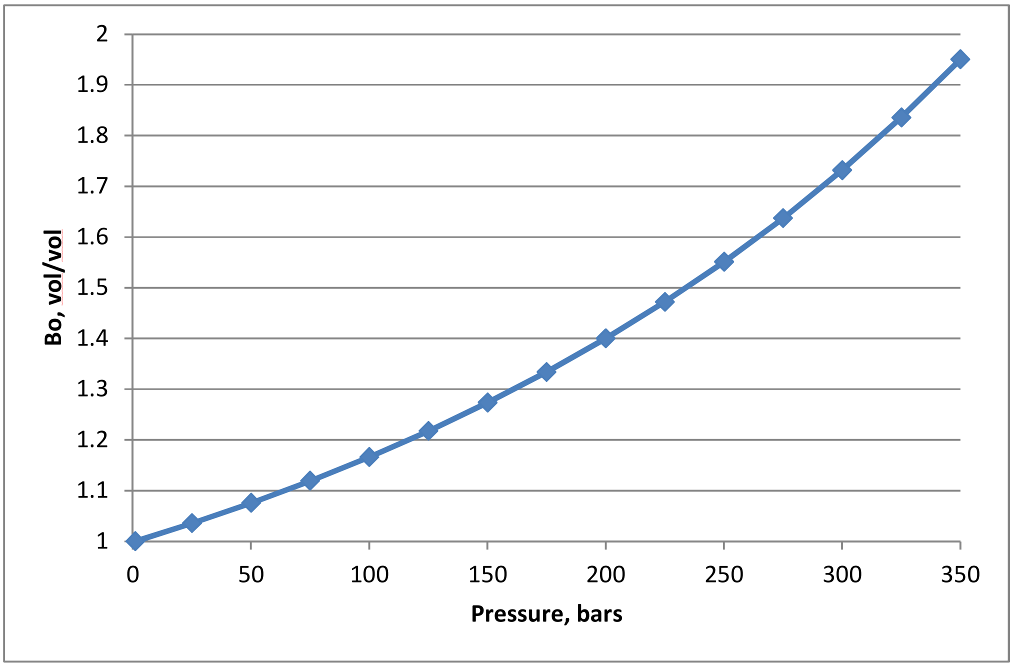

Figure 1. Live oil primary Bo vs. bubble point pressure

The secondary branches (Bo vs. pressure at dead oil conditions for a given bubble point) were almost constant, with only a small negative slope.

The R_s vs. bubble point curve was constructed in the same fashion

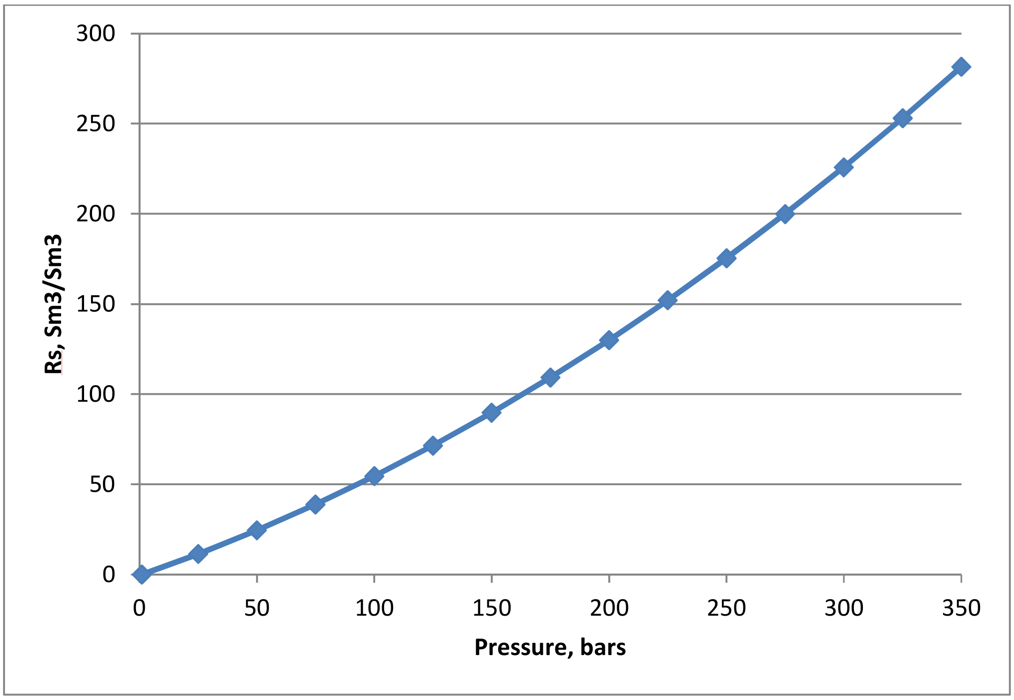

Figure 2. Rs vs. bubble point pressure

With these curves as basis could now construct the oil mole fractions x_3 according to the formula in the STARS manual:

$$x_3 = \frac{R_s(p_{bp})\rho_g^{ST} / M_g}{\rho_o^{ST} / M_o + R_s(p_{bp})\rho_g^{ST} / M_g}$$

In this formula the densities ρ_o and ρ_g, and the molecular weights M_o and M_g are relatively uncertain, which means they are parameters which can and will be adjusted later.

The densities in this formula are *component* densities, which differ somewhat from *phase* densities used in the standard black-oil thinking. This is discussed in the rel-perm interpolation blog entry, for now notice that “permitted” variation for component density and compressibility is much smaller than what we typically see for the phase variables.
The “black-oil densities” were:

$\rho_o = 850$ kg/m^3, $\rho_g = 0.8$ kg/m^3, while some “typical values” for molecular weights are;

$M_o = 0.04$, $M_g = 0.05$

The formula for *mole density* from the STARS manual:

$$\rho_o^c(p, p_{bp}) = \frac{\frac{\rho_o^{SC}}{M_o} + \frac{R_s(p_{BP})\rho_g^{SC}}{M_g}}{B_o(p_{BP})\{1 - C_o(p - p_{BP})\}}$$

where C_o is the oil component compressibility, typically around 10^{-6}, so can be neglected in this context.

Inserting our example value in the formula gives:

$$\rho_o^c(p, p_{bp}) = \frac{\frac{880}{0.04} + \frac{130 \cdot 0.66}{0.05}}{1.4\{1 - \quad \approx 0\}} = 16940$$

Multiplying this value with molecule weight converts it to component density. Using the average gas / oil molecule weight gives ρ_o^c = 762 kg/m^3, but as the molecule weight is somewhat uncertain, this is only an estimate, with values in the range 700 – 850 probably being acceptable. (Used 750 for the remainder).

The main message here is that the component density is smaller than the phase density, and from experience we have found that using a too large number for oil component density can lead to “strange” results as well as numerical problems.

Using these values, and the $R_s(p)$-curve above in the formula gave an x_3 relationship as shown in Figure 3:

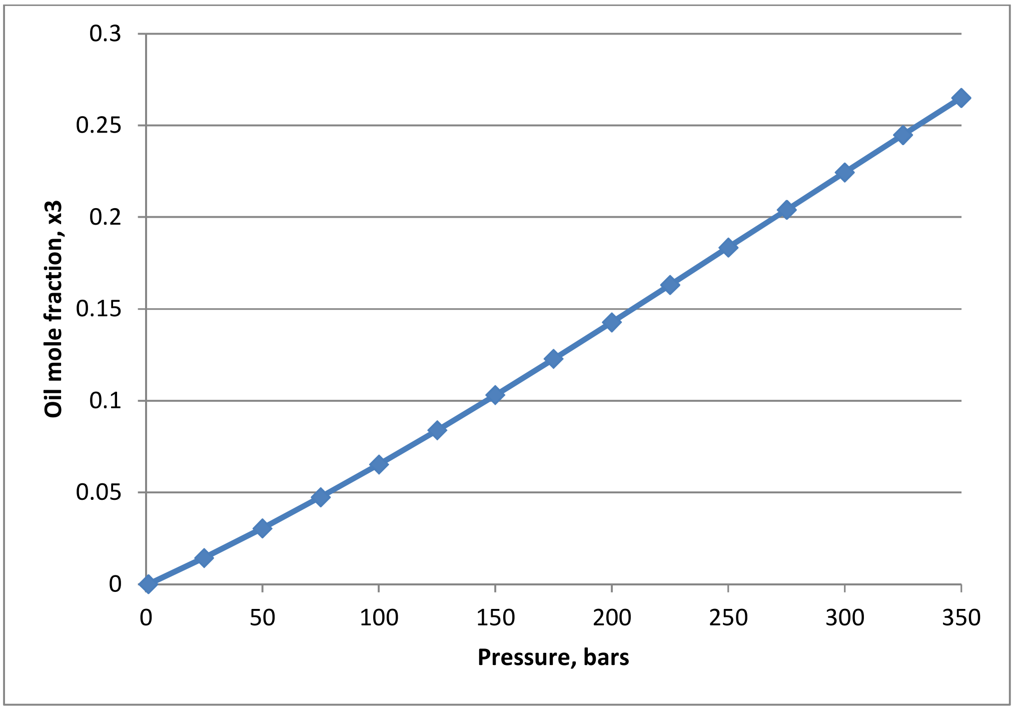

Figure 3. Oil mole fraction (x3) vs. pressure

The phase equilibrium data is now easily constructed, as the water and dead oil components don’t vaporize, so $y_1 = y_2 = 0$. Then, as $y_1 + y_2 + y_3 = 1$, $y_3 = K_3x_3 = 1$, so that $K_3(p_{bp}) = 1/x_3$.

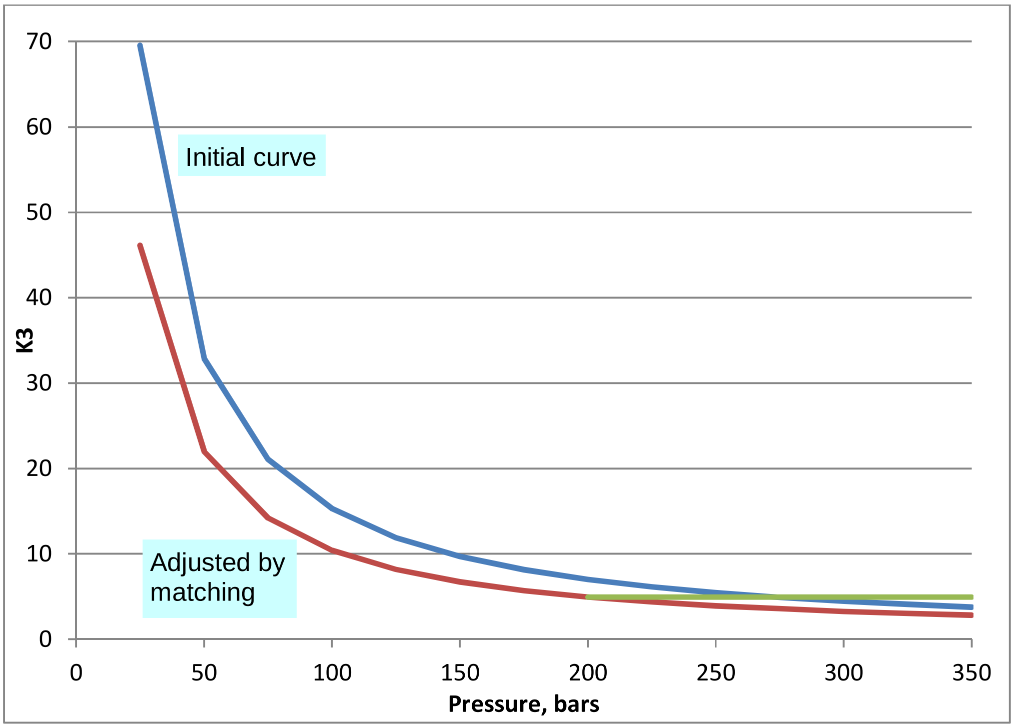

Figure 4. Solution gas K-value (K3) vs. bubble point pressure

Figure 4 shows the K_3-curve obtained from Figure 3 in blue.

This curve was now defined to STARS by the KVTABLE keyword, which has a syntax tuned for equidistant tables. The input K_3-values were as defined in the table:

P_{bp} (bars)	K_3
1	∞
25	69.53
50	32.85
75	21.07
100	15.30
125	11.91
150	9.70
175	8.15
200	7.00
225	6.13
250	5.45
275	4.90
300	4.46
325	4.08
350	3.77

STARS requires you define a table max and min (p_lo, p_hi), and then uses the number of values found to determine sub-interval lengths. The same goes for temperature variation, but as this model is isothermal, we just define two identical lines. So the STARS table is input as:

```
GASLIQKV
** Table limits, p_lo p_hi T_lo T_hi
KVTABLIM 2500 35000 90 91
KVTABLE 'SolGas'
69.53 32.85 21.07 15.3 11.91 9.7 8.14 7.0 6.13 5.45 4.9 4.46 4.41 3.77
69.53 32.85 21.07 15.3 11.91 9.7 8.14 7.0 6.13 5.45 4.9 4.46 4.41 3.77
```

Running this model gave a GOR (surface gas-oil-ratio) of 60, which is about half of the required 130.

In the formula for x_3 the densities are the component densities. Typical oil component density is something like 10^{-6} kg/m^3, and although some variation is permitted, the value used should probably not differ more than about half an order of magnitude from this. The main degrees of freedom are thereby the gas component density and the molecular weights. Both "oil" and "gas" are probably a mixture of pure components, which means that actual molecular weights are pretty arbitrary, or stated differently, candidates for matching. As the K_3-curves are based on a formula, it's easier and more logical to change the formula coefficients than tweaking the curve directly.

After some trial and failure, found that molecular weights $M_o = 0.04$ and $M_g = 0.01935$, resulting in the red curve in Figure 4, gave perfect match to GOR, 130 Sm^3/Sm^3.

> **Observation**: Whatever I later did to other parameters didn't change this GOR-value, which means that *the K-values determine the surface GOR uniquely in a dead-oil setting*.
> (The GOR(K) relation is dependent on oil component density though.)

Also did a *sensitivity test*: As the dead oil GOR is unchanged for all pressures above initial bubble point, tried to define K3 = constant above bubble point (green extension to red curve in Figure 4). This didn't have any effect.

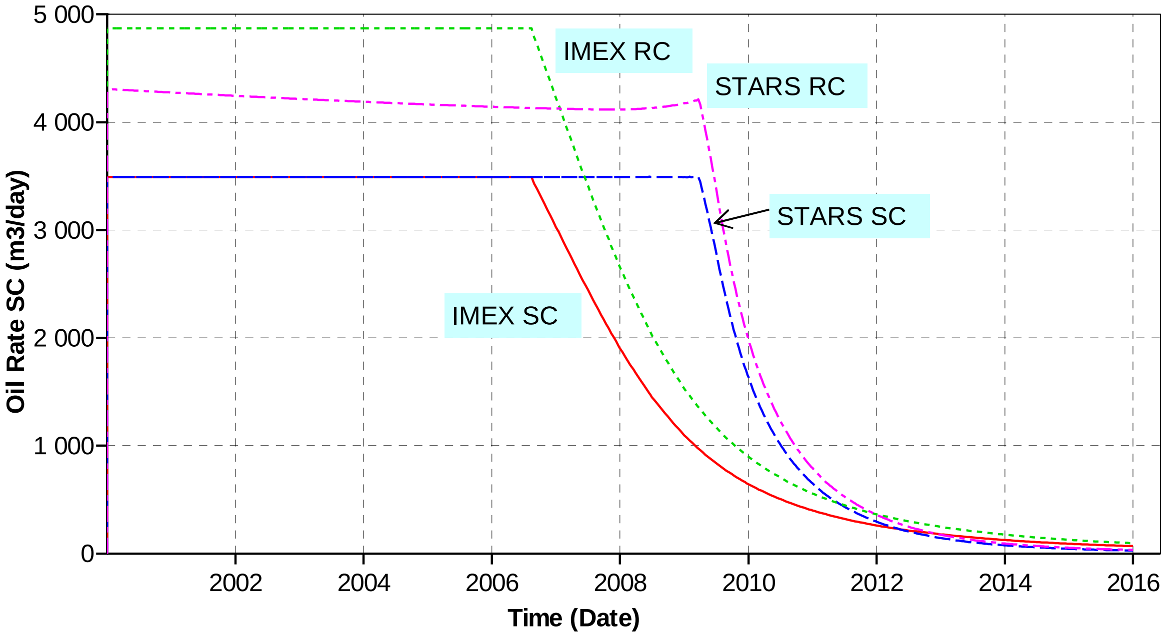

Figure 5. Oil rates (SC and RC) for IMEX and STARS simulations after GOR has been matched by adjusting K-values. (GOR = 130 for both IMEX and STARS)

Having got the GOR correct and established the one-to-one correspondence between GOR and K-values, the next task is to match RC production and the production *shape*.
Candidates for matching:

- Oil and gas component compressibility (keyword CP). As noted we have only limited freedom for varying these:
    - Oil component compressibility should not differ too much from the "typical" value 10^{-6}.
    - Gas component compressibility must be in the range $0 - 10^{-4}$ (STARS requirement), but experience with varying this parameter restricted this range even further; using values outside the range 0.5E-4 – 3E-4 most often produced unphysical or unacceptable results.
    - During matching the oil compressibility was kept (almost) constant, while gas compressibility was varied within the permitted range.
- Oil and gas viscosity. As noticed in another blog entry, component viscosity is quite different from phase viscosity, and relatively uncertain, hence can be used as a matching parameter.

Simulation experiments results:

- *Reducing CP* (oil or gas) results in *earlier WBT* and *increases RC rate.*
- *Increasing* oil component *viscosity* results in *slower oil rate descent* and somewhat *earlier WBT.*

As these two parameter effects are not isolated, but affect results in partly the same manner, it proved difficult to find a combination that resulted in both correct WBT and level of RC rate. First varied gas compressibility to get a reasonably good match on STARS and IMEX RC rates (Fig. 6).

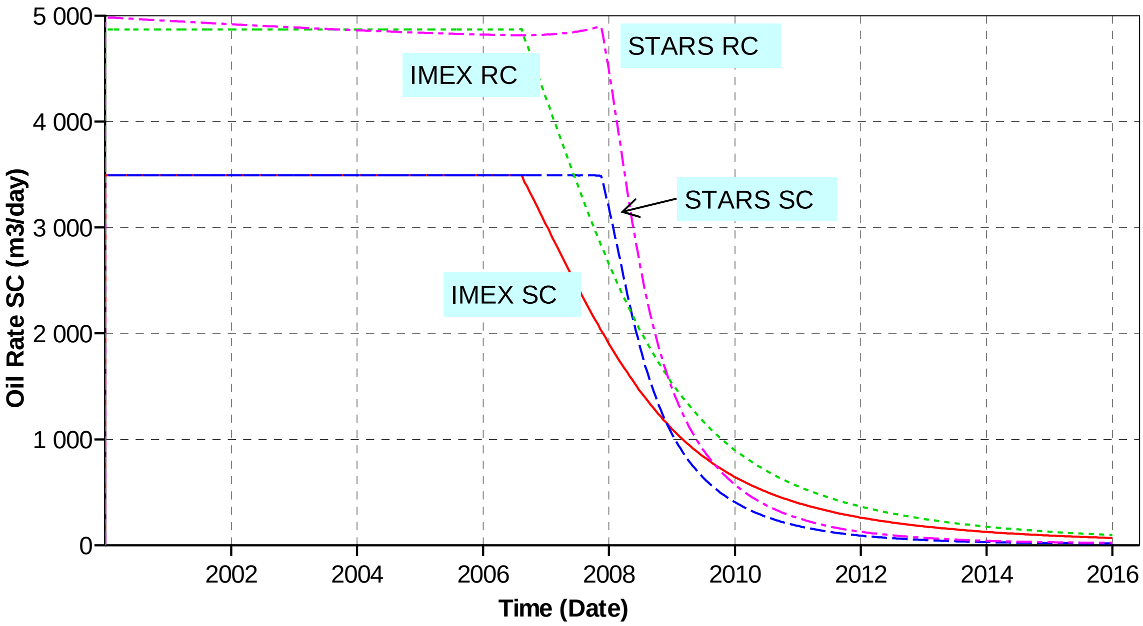

Figure 6. Oil rates (SC and RC) for IMEX and STARS simulations after RC oil rate has been matched by adjusting oil and gas component compressibility.

Then tuned the oil viscosity table (rescaled the original table by a constant factor), and ended up with an almost perfect match IMEX to STARS.

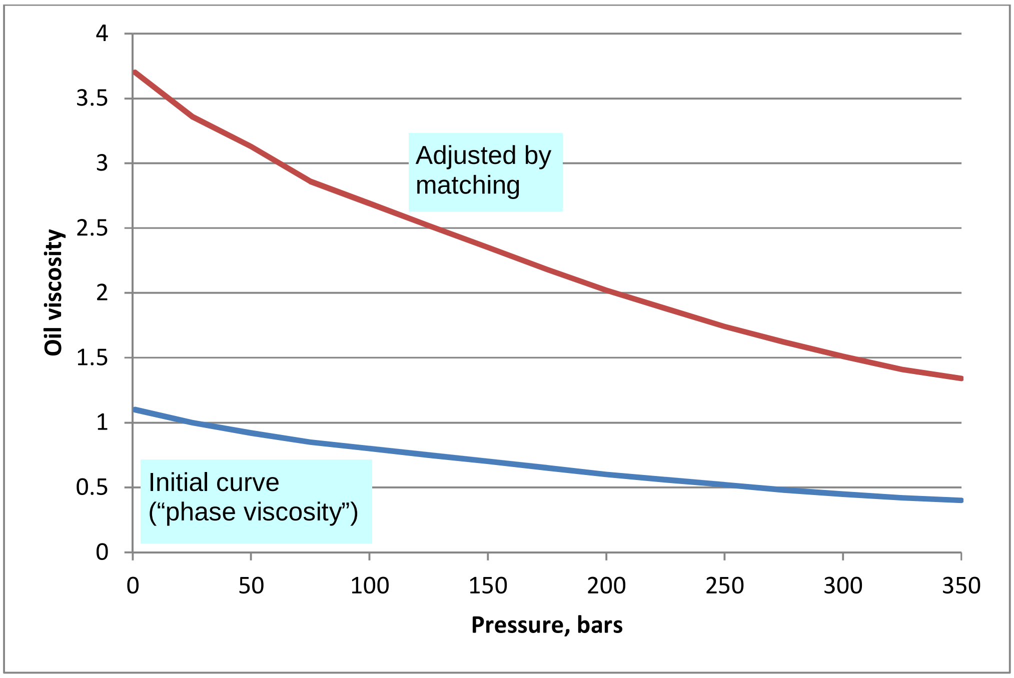

Figure 7. Oil component viscosity (cP); initial curve, and after matching

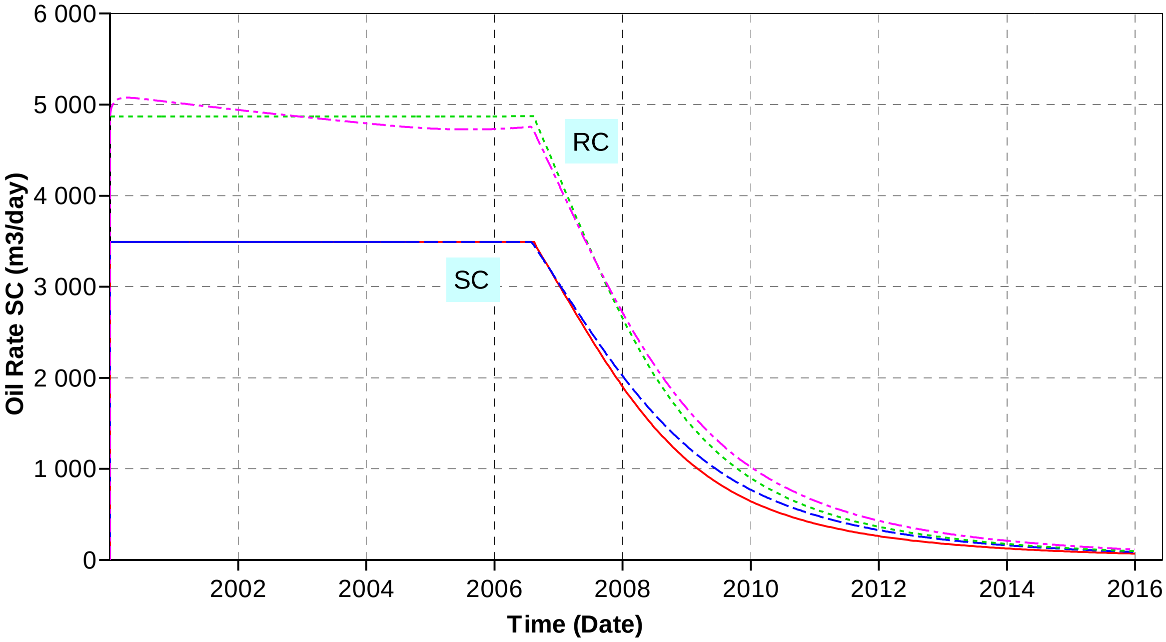

Figure 8. . Oil rates (SC and RC) for IMEX and STARS simulations after WBT and oil rate decline part has been matched by adjusting oil and gas component viscosity.

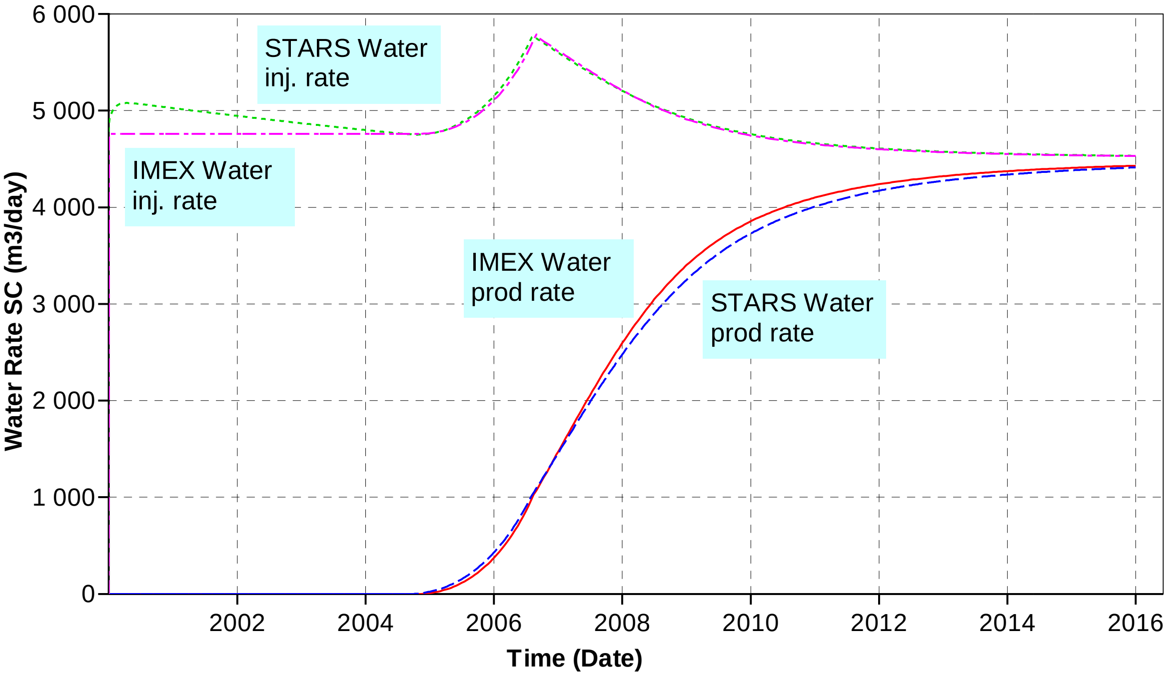

Figure 9. Water production and injection rates (SC) for IMEX and STARS simulations after final matching.

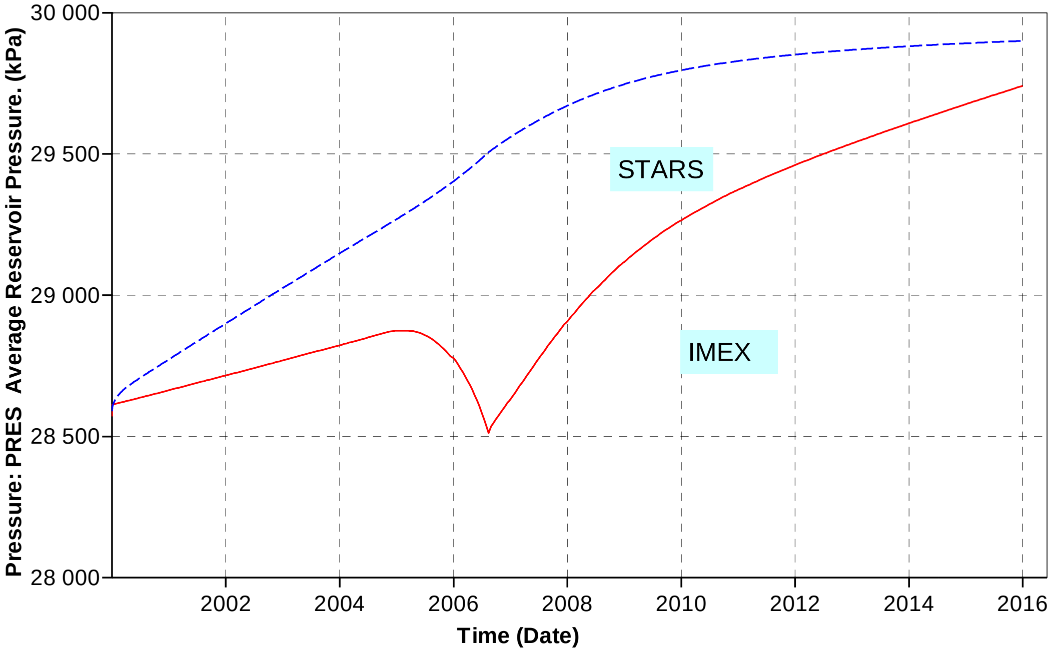

Figure 10. Average reservoir pressure for IMEX and STARS simulations after final matching.

Summary

- Match *surface GOR* by adjusting molecular weights, implying updating of K-values
- Match *RC rates* by adjusting oil and gas component compressibility
- Match *shape* of oil production during decline by scaling oil viscosity table.