Thermal Simulation And Interpretation

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1 - Introduction

The purpose of this document is to describe the latest thermal models available in Rubis and Emeraude, to present some comparisons / validations between those models, and to highlight possible issues with the quantitative interpretation of temperature profiles. The Emeraude model described herein is part of Emeraude v2.60. The Rubis thermal model will be released as a non-commercial option of Ecrin v4.20.

2 - Rubis thermal model

The Rubis thermal model development followed an initiative from Elf in 1994 [SPE 28588, Maubeuge et al.]. In collaboration with Total, the original ideas and equations were extended within the Rubis framework, to address transient multiphase flow in a coupled wellbore-reservoir system. With the Rubis thermal option, temperature can be output as a function of time at any depth in the wells, in the reservoir as temperature fields, or as logs at a user specified time interval, see below.
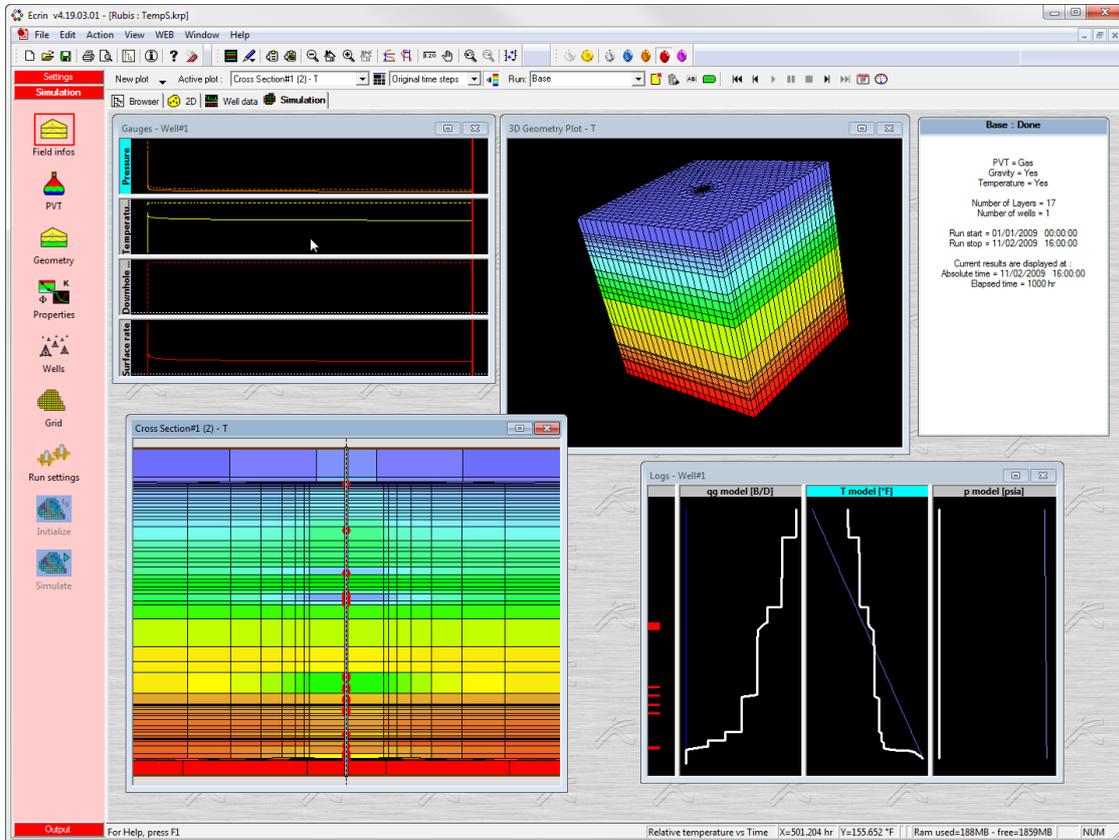
In single phase, the model uses the usual Black Oil PVT of Ecrin. In multi-phase a Peng Robinson EOS with Volume Translation is used for the hydrocarbon phases, while the water is treated as a single component.

The formulation of the thermal problem is a coupled system made of a mass balance equation, and an energy balance equation in terms of enthalpy, h. In the reservoir, those equations can be expressed in the general form below (written for single phase but easily extended to multi-phase by a sum over the phases):

$$\frac{\partial}{\partial t}(\phi\rho) + \nabla.(\rho\mathbf{V}) = 0$$

$$\phi\rho\frac{\partial h}{\partial t} + (1-\phi)\rho_r\frac{\partial h_r}{\partial t} + \rho\mathbf{v}\nabla h - \frac{\partial P}{\partial t} = \rho\mathbf{g}\mathbf{v} + \nabla(\lambda^*\nabla T)$$

λ^* is the average thermal conductivity of the rock + fluid medium. λ^* is obtained with the mixing model below, assuming constant fluid λ_f and rock λ_r thermal conductivities.

$$\lambda^* = \lambda_f^{\Phi} \cdot \lambda_r^{1-\Phi}$$

In the wellbore the mass and energy balances take into account the exchanges within the wellbore, and between the wellbore and the formation. After cutting the wellbore into segments in front of the reservoir cells, the mass balance can be derived by equating the mass variation in a segment with the sum of the mass inflow/outflow (subscript 'b' below = wellbore; subscript 'r' = reservoir):

$$V \cdot \frac{d\rho}{dt} = \sum_b q_b + \sum_r q_r$$

Similarly, the energy conservation expresses the variation of energy $\partial E/\partial t$ as the sum of the exchanges with the segments above and below, and the exchanges with the reservoir:

$$\frac{\partial E}{\partial t} = \sum_b (h + e_c + e_p) \cdot q_b + \sum_r (h + e_p).q_r + D \cdot \Delta T$$

The terms e_c and e_p represent the kinetic and potential energies. The last term is the thermal exchange due to conduction with the reservoir. The conductance 'D' is an overall transfer coefficient accounting for the thermal properties of all the completion elements between the wellbore and the formation.

$\partial E/\partial t$ - the transient expansion term - is considered in front of the reservoir in single phase but not above. In multi-phase it is omitted everywhere in the wellbore. Note also that while the wellbore energy equation considers convection in the wellbore (1st term) and conduction with the formation (3rd term), longitudinal conduction is neglected in a wellbore segment.

Finally, it should be noted that the pressure drop within the wellbore is based on classical correlations accounting for slippage, frictions, etc. as defined in the wellbore model.

In single phase, the enthalpy h is calculated from its derivatives below, in a double integration on T and P from an arbitrary reference (T_0, P_0):

$$\frac{\partial h}{\partial P} = \frac{1 + \frac{1}{\rho} \cdot \frac{\partial \rho}{\partial T}}{\rho} \quad \text{and} \quad \frac{\partial h}{\partial T} = c_p \quad \text{where } c_p \text{ is the specific heat capacity}$$

In multiphase the single component enthalpies are calculated from similar principles. The phase enthalpies are then calculated from the molar composition of the phases.

3 - Emeraude 'Energy' model

This is a direct simplification of the Rubis model geared towards PL and thus steady state conditions. This model assumes that there is no vertical conduction within the reservoir.

Under steady state conditions, it suffices to consider 2 points in the reservoir, the outer one representing the undisturbed conditions at some distance R_e, T_{geo} and P_e, and the sandface conditions, T_{sf} and P_{sf}. The energy and mass balance equations take the general form introduced earlier.
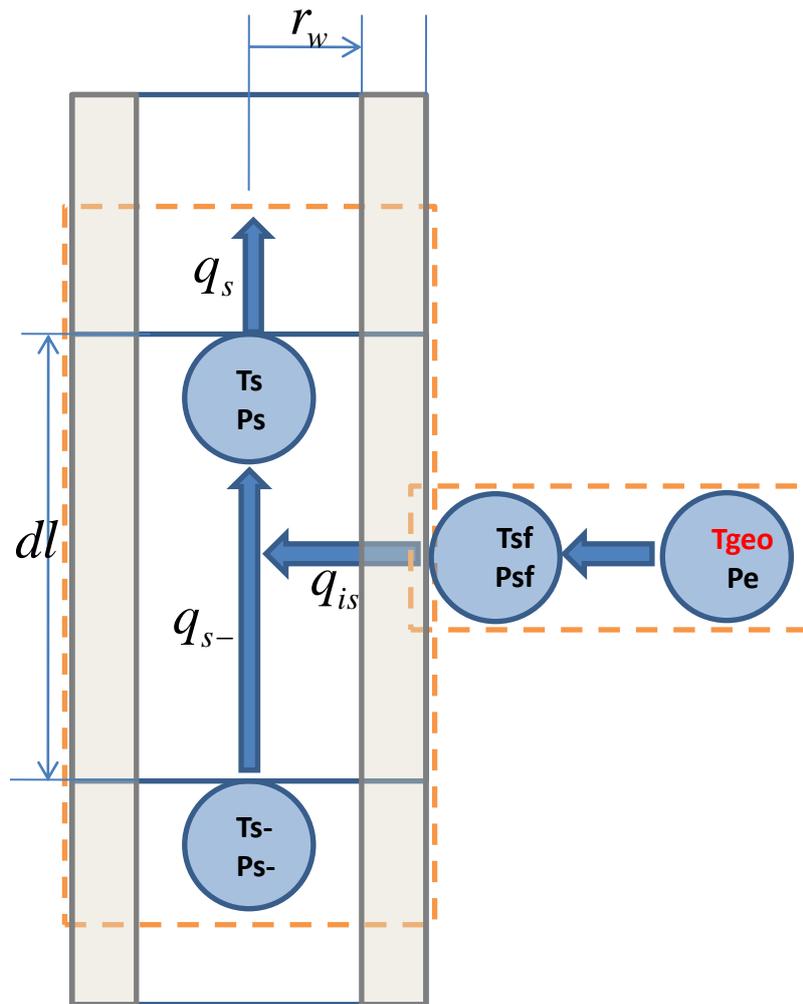
The energy balance is written below in discretized form on a well segment with the notations of the Figure ($E1$ =wellbore, $E2$ =reservoir). Note that we refer to mass rate by q and to volumetric rates by Q.

$$E1 = Q_{s-} \cdot \rho_{s-} \left(h_{s-} + \frac{1}{2A^2} \cdot \frac{q_{s-}^2}{\rho_{s-}^2} - g \cdot dl \right) - q_s \cdot \left(h_s + \frac{1}{2A^2} \cdot \frac{q_s^2}{\rho_s^2} \right) + q_{is} \cdot \left(h_{sf} + \frac{1}{2A_{sf}^2} \cdot \frac{q_{is}^2}{\rho_{sf}^2} - g \cdot \frac{dl}{2} \right) + D_{wb} \cdot \left(T_{sf} - \tilde{T}_s \right) = 0$$

$$E2 = q_{is} \cdot \left(h_{sf} + \frac{1}{2A_{sf}^2} \cdot \frac{q_{is}^2}{\rho_{sf}^2} - h_{res} \right) + D_{wb} \cdot \left(T_{sf} - \tilde{T}_s \right) + D_{res} \cdot \left(T_{sf} - T_{geo} \right) = 0$$

The terms with a tilde are for average segment pressure and temperature. In these equations the enthalpies (h), densities (ρ) and flow rates (q, Q) are those of the fluid mixture. An important difference with Rubis is that Emeraude uses a Black-Oil PVT and the enthalpy is expressed from this model. First, the phase enthalpy is obtained using the integration on T and P as described before, from the coefficient of thermal expansion of the fluid, and the specific heat capacity. Mixture properties are defined as a mass weighted average of the phase properties.

To close the system we need to know the sandface and the reservoir pressures P_{sf} and P_e These are either input by the user or computed based on well and reservoir information. The computation uses the steady-state pressure drop equation; it involves the reservoir properties, the mechanical Skin (S) the geometrical Skin (S_G):

$$\Delta P_{se} = P_e - P_s = \frac{(Q \cdot \mu)}{2\pi \cdot k_H \cdot h_T} \cdot [\frac{h_T}{Lw} \cdot S + \ln(\frac{re}{rw}) + S_G]$$
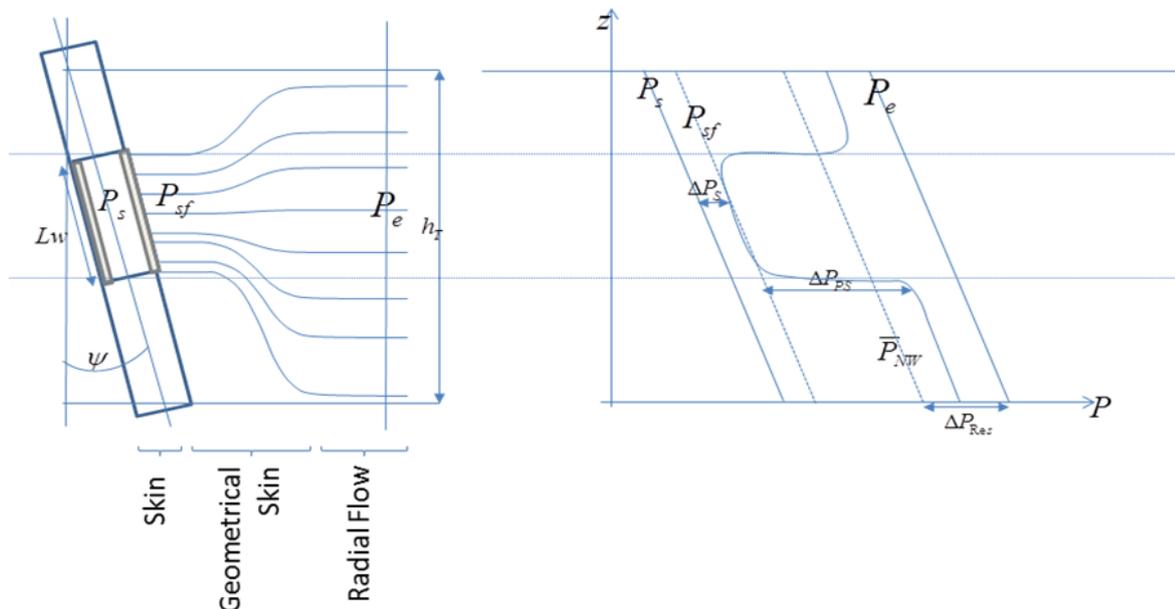
The pressure drops are computed iteratively at the average wellbore segment pressure point and flowing wellbore temperature. The geometrical Skin depends on the slant, the anisotropy, the geometry of the perforations relative to the formation. It is evaluated from Chen et al. (1995) with anisotropic correction from Pucknell & Clifford (1991).

The thermal conductance terms are defined as:

$$D_{res} = \lambda^*_{res} \cdot 2\pi \cdot dL / \ln(r_e / r_w)$$

$$D_{wb} = U \cdot 2\pi \cdot dL \cdot r_w$$

U is the overall heat transfer coefficient between the wellbore and the formation.

Note: Despite the introduction describing this model as a steady-state simplification of the Rubis model two transient corrections are considered. One affects the conduction term from the wellbore to the reservoir; the other one introduces a correction in the reservoir convection term which is equivalent to a transient Joule-Thomson effect. The latter is applicable only for liquids, and it affects the solution only with very low rates and high porosity.

4 - Rubis vs. Emeraude model comparison

A number of single phase comparisons have been made between the two models. Below is an illustration with Emeraude Guided Session B10. The temperature match view in track#1 shows the Emeraude flowing temperature (green) overlaying the Rubis profile (red) for the same rates.
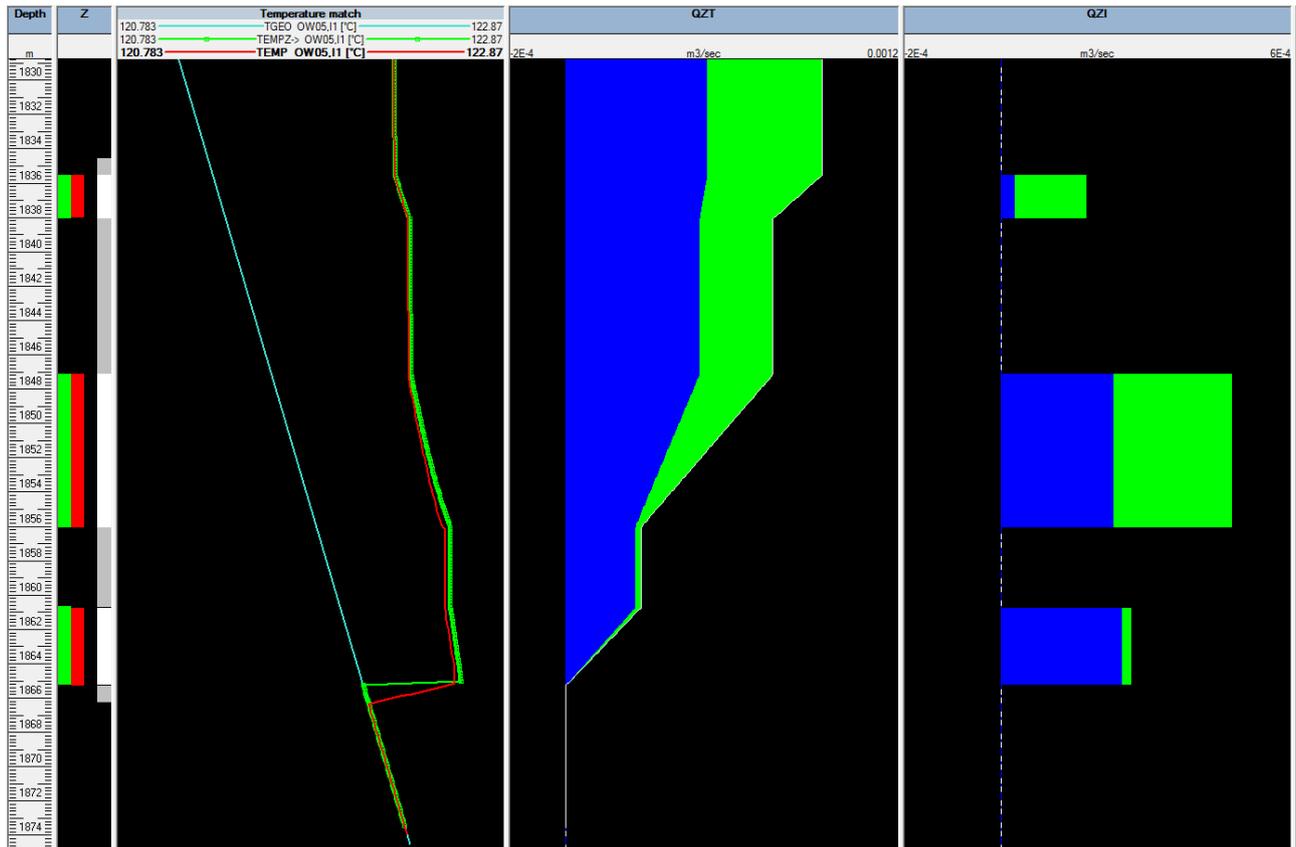

Surface: Qg=1MMscfD - Temp: Rubis, Emeraude

In multi-phase the comparison can only hold if the PVTs are identical. However, since Rubis uses a compositional PVT while Emeraude uses Black-Oil correlations, it is difficult to have exactly the same input.

The only alternative is to load fine sample sets of tables so that the enthalpy calculation are consistent. Recall that enthalpy which is obtained by integrating over T and P is heavily dependent on the density.

A number of water-oil scenarios were run where Bo tables at several temperatures were output from Rubis and used as input to Emeraude. The figure next shows such an example with the Emeraude temperature profile (green) overlaying the Rubis input (red) for the same rates. Even though the match is not perfect - probably because of the remaining interpolation errors in the Table - the two models are very close.

Surface: Qw=220 STB, Qo=180 STB, Qg=115MscfD - Temp: Rubis, Emeraude

5 - Influence of PVT

As seen previously the enthalpy calculation is heavily influenced by the PVT properties. The Figure below shows in track#1 the same case simulated with either a Standing or a Vasquez & Beggs correlation. The impact is very large.

Effect of Bo: Standing and Vasquez & Beggs

But PVT is obviously not the only parameter with a strong influence on the solution. *A sensitivity study is provided with the Emeraude installation that describes the effect of such parameters as the fluid heat capacity, formation conductivity, etc. You can check this document for more information.*

6 - Thermal interpretation

The general question can be formulated as follows: 'from an input temperature profile, is it possible to back-calculate the rates of the various inflow zones?'

We know that the temperature profile is an integral response influenced by the quantity and the nature of the fluid produced. Many parameters come into play and have a strong coupling, starting with the PVT description of the fluids. Our capacity to solve the inverse problem starts with the ability to treat the direct problem properly. This can only be achieved (with a proper model) if we have all the required parameters: thermal properties of the formation, completion, reservoir properties and pressure, etc. Good PVT does also imply pressure measurements so we need at least some pressure inside the wellbore and an estimate of the layer (static) pressure.

Even in single phase non-uniqueness can arise. In section 3, we saw how the temperature change inside the formation can be calculated based on the overall layer pressure drop (*Pe-P*). If this value can be easily assessed for the bottom zone, it is not the case above and wrong estimates will lead to wrong rates. The Figure below shows a gas case with 2 distinct splits (QZT on track#1, QZI on track#2) corresponding to distinct assumptions of pressure drops, that lead to almost identical thermal profiles (and total rates).


Single phase gas: two distinct assumptions of layer pressure drops
produce the same thermal response with different rate splits
dP, psia= [500-600,500-500,500-600,500-400,500-500]

In earlier versions of Emeraude (before v2.60) an original thermal model was introduced combining a simple enthalpy balance in front of the inflow zones, and a Ramey equation outside. This model is now referred to as 'Segmented model'. The Segmented model also differed in the way the reservoir was handled by considering that any thermal exchanges in the formation were Joule-Thomson effects, linked to 'some' user input pressure drops.

Tests run between the Energy and the Segmented models have shown that there is no physical explanation for this pressure drop: it is not the layer overall pressure drop, nor the Skin pressure drop, and knowing this value upfront seems very difficult. Yet, uncertainty on the reservoir cooling/heating gives an equivalent uncertainty on the determination of the layer inflows.

In multi-phase, interpretation can only get worse….There is a general agreement that the inverse problem is undefined in multiphase if the only available measurement is temperature. The Figure below provides an illustration where 2 distinct contribution splits (track#2 and #3; bottom zone), cause perfectly matching temperature profiles – all other parameters being equal. With only the temperature it is clear that it is impossible to choose one solution over another…
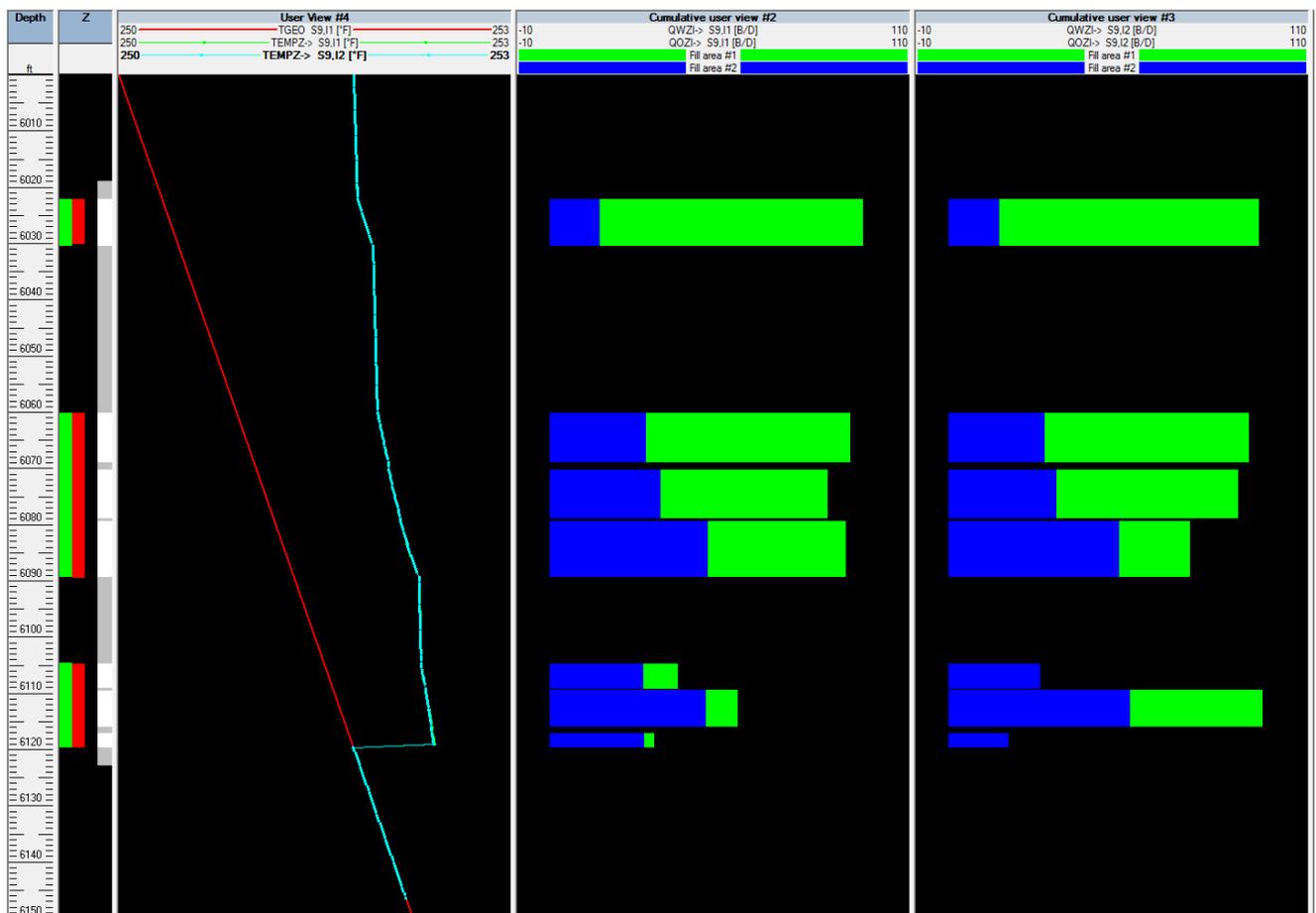
2 distinct O-W splits produce the same Temp profile

7 - Conclusions

Several thermal models have been developed as part of KAPPA software to date. The most comprehensive model – included in Rubis - addresses transient multi-phase flow, and solves implicitly the wellbore-reservoir problem. To the best of our knowledge, this is the most sophisticated solution available on the market today to simulate wellbore/reservoir temperatures.

Emeraude includes a steady state simplification with a 1-D reservoir model (with some transient corrections), which already goes beyond what most PL or DTS software use. The Emeraude and Rubis models have been compared on a number of cases and provide consistent responses, when the hypotheses are the same.

Sensitivity studies show the importance of the input parameters, such as the layer pressure drops (or petrophysical properties used to calculate it), the thermal parameters of the various elements, and the definition of the PVT, which has a dramatic impact on Joule-Thomson through the density derivatives.

Inverse problem solving, i.e. computing inflow rates from a temperature profile, can only be achieved with a reliable characterization of *all* the parameters involved, the uncertainty on input parameters translating automatically into an uncertainty on the answer. Because of the number of parameters however, even a single phase interpretation can turn out to be completely undefined and lead to random results. Clearly, hoping to solve in multiphase if only the temperature is supplied is totally unrealistic.