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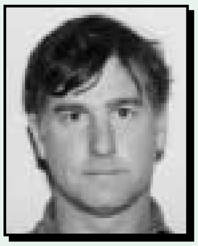
Streamline Technology: Reservoir History Matching and Forecasting = Its Success, Limitations, and Future



Richard Baker has worked on a number of reservoir characterization /reservoir simulation projects world wide in Russia, Indonesia, South America, Middle East and North America. He is currently president of Epic Consulting Services. He has taught courses in reservoir characterization and reservoir simulation both in Canada and internationally. He previously was a senior reservoir engineer at Shell and Husky Oil.

He has interests in reservoir management, naturally fractured reservoirs, reservoir characterization, horizontal wells, EOR and reservoir simulation. He has obtained a M.Sc. degree in Chemical Engineering from University of Calgary and B.Sc. in Mechanical Engineering from University of Alberta.

Although reservoir flow simulation is a mature technology, there is a general lack of understanding in the oil and gas industry as to when it should be applied, the limitations of it and how recent technical improvements have changed simulation. Streamline models have dramatically changed simulation work and made predictions better. Simple workflow and quality control issues are absolutely critical to insuring reasonable forecasts.

There are various technologies that will substantially improve simulation forecasts and reduce error bars. Some of these new technologies are:

1. Streamline based flow simulation
2. Assisted history matching (AHM) techniques
3. Four dimensional seismic (time lapse 3D seismic)
4. Parallel computing
5. Integrating flow simulation with geo-mechanical effects.

This article focuses primarily on the first two points.

Streamline Based Flow Simulation

Streamtube and streamline technology, to a large extent, have been driven by the realization that heterogeneity controls recovery factors for many fields. This realization caused the derivation of more complex geological models, but unfortunately also highlighted the gap between geological detail and simulation capability.

Streamtube technology was originally developed in the 1960s[1, 2]. Two dimensional streamtube models were initially available for homogeneous permeability regular flow patterns, such as a five-spot pattern. Streamtube models were later generated for irregular well positions and areally heterogeneous reservoirs. Old streamtube models only allowed constant well rates and positions (i.e., no infill wells, no rate changes or the shutin of wells were allowed). Gravity effects, and therefore the vertical sweep efficiency were not always accounted for. Thus, streamtube modelling often could not allow for infill drilling or shutin wells, and streamlines were fixed in space. As a result of these limitations such early applications were limited and basically evaluated only the areal sweep efficiency of a pattern.

To account for vertical sweep efficiency, Chevron[3] developed two-step hybrid streamtube models in which vertical cross sections were first simulated and then combined with areal streamtube models[4-6]. Thus, vertical sweep, then areal sweep, were evaluated. However, infill drilling and large changes in production/injection rates meant that streamtube geometry changed resulting in limitations with this technique. Streamline technology is now practical in many field cases because it includes:

- Gravity
- 3D effects
- Changing well conditions
- Multiphase flow.

Streamline technology includes gravity effects and allows well rate changes (starting/stopping of wells)[7-11]. This allows engineers to perform a one-step process that evaluates both vertical and areal sweep, and also accounts for well changes. There has been an explosion of studies that have highlighted the usefulness of streamlines[12-19]. In many field situations gravity and vertical heterogeneity are important parameters for waterflood recovery.

How Is Streamline Technology Different From Finite Difference Simulation?

In a conventional finite difference simulation, there is a pressure-solve segment and a transport-solve (saturation) segment. In finite difference we solve for pressure then calculate flow based on the pressure distribution (for IMPES solutions), but flow transport is from block to block, whereas, in a streamline/streamtube simulation model, fluids are transported along streamlines, as shown in Figure 1.

Because the transport problem is very non-linear the finite difference solution method can be very sensitive to grid block size and grid block orientation. As a result of non-linearity time-step control also strongly affects some finite difference simulations.

In a streamline simulation, the pressure equation is solved on an underlying grid as in the same method as a conventional simulation. Next, streamlines are computed orthogonal to pressure contours. Therefore, a "natural" transport network is constructed and fluid is transported along each streamline to track oil/water/gas movement within the reservoir. Streamlines therefore have an inherent advantage because the fluid is transported in the direction of the pressure gradient along the streamlines and not between grid blocks as shown in Figure 1. Because of this greater stability, larg-

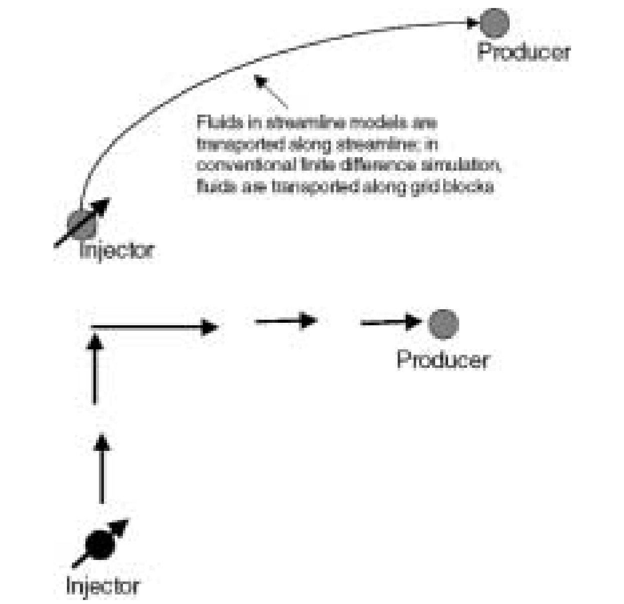


FIGURE 1: Difference between finite difference model vs. streamline model for transporting fluids [adapted from Grinestaff, SPE 54616(20).]

er time-steps with less sensitivity to grid block size and orientation can be used(10).

Displacement along any streamline follows a one-dimensional solution with no crossflow among the streamlines. Therefore, well response is simply the summation of a series of 1D flow simulations.

As suggested above, three-dimensional streamline models have some very significant applications/advantages over conventional simulations. The application/advantages are:

1. Speed
2. Easier visualization/conceptualization of injector-producer coupling of flow
3. Better drainage area identification
4. Easy calculation of production allocation factors for waterfloods or gas floods
5. Easy ranking of complex geological/geostatistical models
6. Easy incorporation of entire field models
7. Assisted history matching (more on this later)
8. Potentially, a more accurate solution.

Simply put, streamline simulation can be 100 times faster than conventional simulation. However, in practical field studies the overall computing time "speed up" factor is in the 10 – 15 fold range. For field studies, the total history match cycle time can be reduced by two to five times.

Whereas conventional simulation run times increases with grid block numbers in an exponential fashion, (n = 2 to 3), streamline simulation increases almost linearly with grid block numbers. Thus, streamline simulation allows much larger models(11).

A clear advantage of streamlines is that streamline technology allows easy visualization of both drainage area allocation factors and injector-producer relationships as shown in Figure 2. This visualization is extremely useful in optimizing waterfloods/gas floods because the benefits of injection can be easily quantified(18). Streamlines are projected from injectors to producers; thus, injection/production allocation factors are calculated by summing up the flow bundles and flow rates from a particular injector-producer well pair divided by the total well rate. Also, dense packing of streamlines represents those areas with high flow rates, whereas areas with low streamline density have low flow rates(19).

The visualization aspect of streamlines and allocation factor are very useful for seeing the effects of infill drilling on pattern flows and reservoir drift. Note, the pattern flow shown by green highlights. Figures 2 and 3 illustrate how dramatically the streamline patterns shift with an inclusion of an injector (note the green highlights shown in a map view of a portion of a waterflood).

Streamlines can be used to identify injector-producer pairs and associated regions that should be changed to improve the history

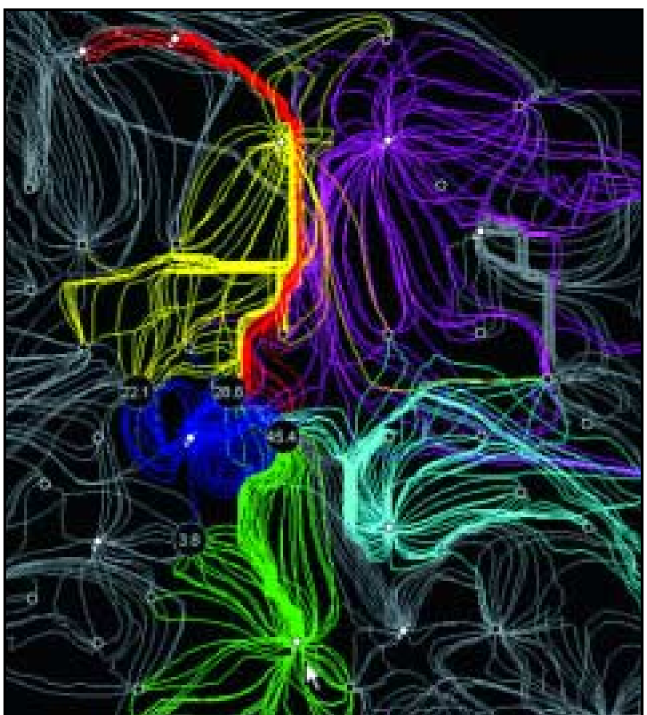


FIGURE 2: Example of typical reservoir flows. (Streamline Time = 01/01/1991.)

FIGURE 3: Example of typical reservoir flows. (Streamlines Times = 12/31/1999.)

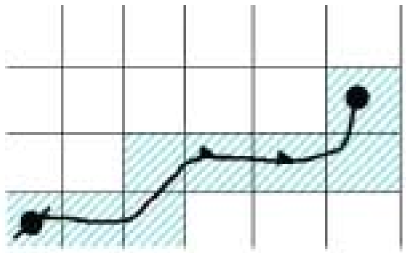


FIGURE 4: Identification of history match regions.

match[20, 21] as shown in Figure 4. This is very useful in the history matching process, where one of the key aspects is determining what parameters and where those changes should be made (i.e., in what regions). Streamline technology clearly identifies those regions.

The greater speed of streamline simulation allows the user to include more grid blocks (i.e., providing greater spatial resolution), therefore requiring less upscaling, in a model with a more realistic permeability distribution, and which better captures the outer boundary conditions (offset wells; pressures, aquifers etc). In other words, a larger (or field size) simulation with more heterogeneity can now be accounted for and can dramatically improve the history match forecast accuracy.

Computer limitations resulted in gridding restrictions for early finite difference models. They tended to be small in areal extent and therefore only small portions of a field were modelled. Examinations of streamline patterns for most waterfloods such as that depicted by Figure 2 shows why pattern element simulation models fail. Geological heterogeneity (heterogeneous permeability distributions) or even different well deliverability very often means the element of symmetry method of simulating waterfloods or gas floods is not a representative model (note that drainage patterns are highly non-symmetrical and very unique). In almost all of the field cases we have studied, we have dealt with drainage patterns that are non-symmetrical and allocation factors that are not well approximated by geometric allocation factors. The non-symmetrical drainage pattern is a very strong function of both permeability/geological distribution and differential withdrawal (voidage) rates between wells. Any attempt to model such a flood with an element-of-symmetry approach and geometric allocation factors, in my opinion, would tend to yield incorrect and probably optimistic answers. Because of reservoir voidage considerations, it is important to include outer boundary wells in simulation studies. The computational speed of streamlines allows us to use large field models and therefore to include more realistic boundary conditions.

Streamline models are well suited for modelling viscous dominated reservoir problems that are characterized by an approximate voidage balance:

> *"Reservoir problems that fit within the assumptions of streamtube derivation, even those involving hundreds of wells, can often be successfully modelled for a modest expenditure of computer and personal resources.[3]"*

Paradoxically, it is these same convective situations with high heterogeneity and/or mobility ratios that finite difference simulations have difficulty. Therefore, streamline and finite difference simulations complement each other.

Streamline models are not a panacea and do have limitations. In cases where compressible drive energy (solution gas drive or gas cap drive systems) contributes to the majority of reservoir energy, finite difference methods are superior. Some waterfloods do not have good voidage balance (voidage replacement ratio < 0.9) and this can result in a poor application for streamline technology. For capillary crossflow dominated waterflood reservoirs, conventional

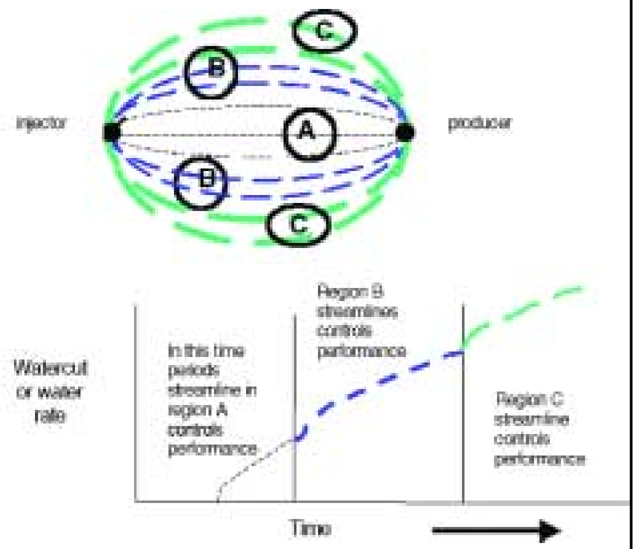


FIGURE 5: Relationship between (watercut or water rate) vs. time and spatial position of streamlines (map view).

finite difference simulation models still have significant advantages. A rule of thumb for use of streamline simulation is a VRR > 0.9 or a water drive index > 0.9. These rules mean that the majority of reservoir energy comes from a waterflood or water drive, and not from expansion or solution gas drives.

In gravity-dominated situations simulation speed-ups are not as pronounced but there is still a substantial savings in total cycle time due to other benefits (particularly when implementing changes with the visualization tools alluded to earlier).

Assisted History Matching

Production data is the most common data type and thus allows us to better characterize the reservoir if it can be de-convolved into its components and parameters. History matching is a critical step in integration because it allows the static geological model to be rationalized with production data. History matching has a critical role in monitoring displacement processes, constructing good reservoir models and predicting future performance. I believe that assisted history matching (AHM) will become a standard tool in the next five years and with this better and more accurate models will be developed.

Automatic history matching in which an algorithm basically controls the history match process has not had widespread practical use to date. Assisted history matching (AHM), on the other hand, shows some promise to be a practical tool for conditioning permeability fields[20, 21]. Manual engineering input is always required in AHM field studies because it is not always clear at the start of a history match which parameters are important and how to adjust those parameters. Therefore, assisted history matching still requires the manual input in it.

AHM will allow engineers to better quantify the quality of the history match and develop a higher confidence level in parameter estimation and forecasts. The key reason for AHM is that numerous geological realizations can be easily screened and history matched to see if the geological realization fits. The problem with the conventional manual history match approach is that it is often extremely difficult to determine if further model improvement is achievable/necessary or if alternate models can explain the response.

Unfortunately, fine-tuning history matching is very tedious when carried out by conventional means because of the difficulty of estimating which grid blocks. This is especially true for large grid block models with large reservoir volumes. In other words, in any history match problem, we must identify the key parameters that affect the history match as well as the location of those parameters. Determining the location where to adjust those parameters is a key stumbling block particularly for inexperienced engineers. AHM with streamline technology may allow better convergence for fine tuning models, because it allows a methodology for identifying problem regions based on the streamline and their associated producer/injector pairs. Examining streamline patterns with time of flight and allocation factors can highlight which regions affect the history match as shown in Figure 4.

According to Nolen[23] one of the principle obstacles to widespread use of automatic history matching was the non-uniqueness of history matching. In other words:

> *The production history of an oil reservoir does not contain enough information to allow determination of the permeability and porosity of every cell, let alone relative permeability. To define a tractable minimization problem, it is necessary to apply permeability and porosity modifications to groups of grid cells[22].*"

For the sake of discussion, as shown in Figure 5, if we imagine that each streamline in this waterflood simulation has perfect piston-like displacement, we can see that the streamlines marked "A" which have shorter time of flight periods. These will strongly control early water breakthrough whereas streamlines marked "B" and "C" control later stage watercut. Thus, streamline technology helps in grouping cells that need to be modified.

Besides the identification of history match regions where changes need to be made, there is a second advantage when working with streamlines. We can easily see how the travel time along a single streamline can be increased or decreased by changing permeability. Darcy's Law defines flow along a single streamline path connecting injector to producer; (see page 4).

$$v = \frac{k}{\mu}\frac{\Delta P}{\Delta S}$$

where:

k = permeability
μ = viscosity
ΔP = pressure difference
ΔS = distance travelled along the streamline
v = velocity

By multiplying permeability up in all the grid blocks along the streamline, the velocity of fluid will increase and travel time will decrease proportionally and in a quasi-linear fashion[24, 25]. Therefore, by adjusting permeability fields in specific regions (e.g., see Regions A, B, and C, in Figure 5) we can history match watercut in a waterflood or GOR in a gas flood. To increase the velocity of water and achieve an early water breakthrough profile we can adjust permeability, porosity or movable oil saturation in region A.

The research[20 – 28] in this area, in the last few years, has made large strides in making assisted history matching into a more useful field tool.

History matching can be thought of as composed of two parts. The first part, or outer loop, generally considers the overall architecture of the reservoir. In other words, are layers connected to each other or do faults/shale layers compartmentalize the field? The second part or inner loop is concerned with the permeability and porosity distribution within a layer or region. The majority of time is spent in a conventional manual history match simulation study on the inner loop, because it is not always clear on how good the history match can be. Sometimes engineers spend so much time on the inner loop that they may overlook changing something critical in the outer loop such as a major geological feature. In other words, when a model is calibrated by a manual approach, numerous runs are spent changing parameter values with relatively few runs adjusting the conceptual model (outer loops). AHM allows engineers to solve the inner loop problems more efficiently. Solving inner loop problems more efficiently would then allow a more thorough/comprehensive investigation of reservoir models.

Summary

1. Streamline technology is a very useful and practical technology for waterflood optimization; in eight field cases I have seen some significant advantages of the technology.
2. Streamline and conventional finite difference simulation can complement each other.
3. Streamline technology and know-how is still developing.
4. Assisted history matching (AHM) technique for conditioning permeability distributions is an area of active research, large potential, and will likely soon develop into practical technology.

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