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Production Optimization Through Coupled Facility/Reservoir Simulation

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Abstract

Proper field management for optimal performance of hydrocarbon reservoirs must capture the interdependence of the subsurface reservoir behavior and surface facility constraints. In this work we describe how full coupling improved development of a Saudi field by reducing water production by 30% while maintaining the target plateau for the required period of time.

This was achieved by an iterative procedure that was able to devise an optimal producing strategy. The strategy involved time-dependent well production/injection rate allocations in response to field behavior. The strategy devised take into account production network constraints, network bottlenecks/under-utilization, and reservoir engineering complexities in producing three different reservoirs that make up the field.

This work was realized by linking Saudi Aramco's in-house developed simulator (POWERS) with a commercially available surface network simulator (PE-GAP). The paper will highlight some of the major challenges in creating the link from engineering as well as from software/hardware perspectives.

Due to this successful endeavor, the workflow will be applied to more fields. Furthermore connection to SCADA system for real-time monitoring is under developed.

Introduction

Motivation

Field A, a giant Saudi oil field, consists of eight oil bearing reservoirs, of which the three largest were selected for initial development. The development team assigned to Field A was tasked with developing the field to maintain a 30+ years plateau period while maintaining the blended crude quality within a very narrow range. Additionally, maintain potential drilling and water production was to be kept at a minimum.

The three developed reservoirs have distinctly different crude grades, H_2S concentrations, and reservoir properties. The two lighter crudes were to be produced into a common manifold system, while the heavier, lower pressure reservoir would produce into a separate system. Two gas oil separation plants (GOSPs) are utilized to produce the blended crude streams and separate out water and gas from the crude.

The development team needed a means of accounting for the interaction between wells producing into a common manifold system while being able to optimize production rates to maintain the aggressive plateau target. Additionally, because of the varying reservoir properties the development team felt the only true representation of the reservoir performance would come from the detailed numerical reservoir simulation model. Finally, H_2S concentrations also needed to be kept below a certain threshold value due to facilities constrains. It therefore became necessary to have a seamless connection between the reservoir simulation models, the well models, and the models for the surface gathering system.

Literature survey

One needs to model interdependence of reservoir and surface facilities accurately for reliable prediction of production from a reservoir. Pressures at wells are boundary conditions for the reservoir and on the other hand flows in the surface network depend on reservoir pressure and productivity in the reservoir near the well. Therefore, flow rate and pressure drop in the system should be consistent for any accurate solution. It is difficult to maintain such consistency when reservoir and facility simulations are made independently. Because of this reason, reservoirs have been coupled with surface facilities in many studies[1-6.]

In a study done over thirty years ago, Dempsey, *et. al*[1]. used an iterative scheme to couple solutions in the piping network and the reservoir. They solved a tightly coupled system where iterations were done over all solution processes within every time step during the simulation. The sub-global iteration determined a balance between rates and pressures within the piping network, and the reservoir simulation segment solved the pressure flow problem within the reservoir. Flow rates obtained from sub-global iterations were applied as boundary conditions in the solution of the reservoir flow problem. Trick[2] coupled a commercial reservoir simulator tightly with a commercial network simulator at the Newton iteration level. He used popular parallelization tool Parallel Virtual Machine (PVM) interface for data exchanges between two simulators. Tight coupling was also used by Breaux *et. al.*[3] in their study. Recently Al-Shaalan *et. al.*[4] coupled Saudi Aramco's in house reservoir simulator POWERS(TM) with a surface facility simulator PIPESOFT(TM). They implemented a tight coupling at the Newton iteration level. As the coupled simulation proceeds, the surface simulator PIPESOFT receives continuous data for reservoir pressure, productivity index, water cut and gas oil ratio from POWERS. As a result, the facility simulator is able to predict well flow rates accurately.

Tight coupling ensures consistencies between reservoir and surface network solutions at every time step. Such coupling is expensive to implement and may be unnecessary in many cases. Hooi, *et. al.*[5] used a loose coupling in which the reservoir and the surface system did not use the same time steps. They had a driver program which was responsible for determining when the conditions in the surface system would be computed and for coordinating the time step. As expected, loose couplings are faster and are generally sufficient if interface conditions between the reservoir and the surface system do not change significantly between synchronization intervals. This is a reasonable assumption for our current model. Therefore, we implemented a loose coupling between our reservoir and facility simulators. We chose Saudi Aramco's in-house simulator POWERS which is used routinely to simulate giant reservoirs in Saudi Arabia and commercial surface network simulator **General Allocation Package** (GAP™), which is capable of providing optimized flow rates within user specified constraints. Our study is different from the earlier study by Al-Shaalan *et. al*.[4] in coupling algorithm and in the role of the surface facility simulator. They used the surface facility simulator to compute flows in the network based on reservoir conditions. All well managements were done by the reservoir simulator. We on the other hand utilize optimization capability of the facility simulator and allow it to manage wells which are coupled. Wells which were not coupled were controlled by the reservoir simulator.

Reservoir Simulator

In this paper, we give a brief description of the mathematical formulation of POWERS[7]. Details of its formulation are given in Ref. 7-11. POWERS uses a finite volume formulation to compute flows inside a reservoir by solving mass conservation equations for multi-component multiphase fluid flows in porous media. Governing equations are derived from mass conservation equations coupled with phase equilibrium relations and constraints to require sum of phase saturations to be unity and also sum of mole fractions to be unity. If fluid properties can be expressed as a function of pressure and bubble-point pressure, a simplified approach known as black oil formulation can be used. In such models, there may be up to three fluid components — water, oil and gas. Some reservoir may be modeled to contain only two components, namely water and oil, or water and gas. It is important to consider more detailed fluid compositions to determine properties in volatile oil reservoirs and also where enriched gas is injected for enhanced recovery. These reservoirs are modeled using compositional formulation where thermodynamic equilibrium calculations are performed using an equation of state. Reservoir fluid in these models is composed of water and a few hydrocarbon components. Flow velocities in governing equations are calculated using Darcy’s formulation. In black oil simulations, solutions are obtained in terms of pressure and saturations by either Implicit Pressure Explicit Saturation (IMPES) or a fully implicit method. Heterogeneous nature of rocks in a fractured reservoir may be modeled using Dual Porosity and Dual Permeability (DPDP) formulation. In DPDP formulation, reservoir rock is represented by a collection of highly permeable fractures and low permeable matrices (or homogeneous solid rocks). Flows in fractures and matrices are coupled. Because of their very small sizes, typical fractures can not be resolved on a computational grid. Therefore, each grid block is modeled to contain a lumped fracture and a matrix region.

Rock descriptions in a simulation model are derived from an underlying geological model of the reservoir. Typically many grid blocks of a geological model are consolidated into a single simulation grid block. This process is known as up scaling. Proprietary software packages are used to upscale geological model data into simulation input data for POWERS. In-house software packages are used to generate well production, injection and completion histories directly from Saudi Aramco's corporate data base. These data are used for history matching simulation. In a prediction study, computations are guided by production strategies given in simulator input data. Such computations take into account of various parameters such as the production target specified by the user, limitations of surface facilities, well rate/pressure restrictions, etc. Governing equations describing flows are discretized to get a set of equations for primary variables. These equations are linearized and solved using Newton-Raphson technique. Linearized system of equations is solved within each Newton step using a parallel linear solver known as the reduced system solver. Solution technique used in POWERS is based on generalized conjugate residual (GCR) method and orthomin with truncated Neumann series preconditioner. The restart version of GCR is used.

POWERS uses three dimensional Cartesian grid blocks to discretize the reservoir. In general, flows inside a reservoir can be reasonably represented on a non uniform Cartesian grid. For accurate simulation, one may need additional resolution near a well, while such resolution may not be necessary away from a well. In those cases, computational grid near a well can be refined to generate a composite grid consisting of a base grid and locally refined grid (LGR) patches. Current version of POWERS supports two level grid systems — the base grid and one level fine grid patches. An iterative multi grid scheme is used to solve governing equations. At each step of iteration the coarse grid solutions are obtained and they are used to update residuals on the fine grid. Fine grid equations are then solved and solutions are used to update residuals on the base grid. This iterative process is repeated until a converged solution is obtained.

POWERS uses MPI and OpenMP parallelization to run on Linux Clusters. Implementation details of POWERS on the Linux cluster have been described in Ref. 9-11.

Surface Network simulator

We use commercial software package GAP[12] for surface facility simulations developed by Petroleum Experts Ltd. This software can provide optimized solution for surface facility for given reservoir condition. Reservoir pressure can be given from decline curves, material balance model or full reservoir simulation models. GAP can model both production and injection systems containing oil, gas, condensate and/or water wells. Optimizer in GAP can control production rates using wellhead chokes, ESP operating frequencies or allocating lift gas to maximize production while honoring constraints at the gathering system, wells and reservoir levels. GAP can be linked to reservoir simulator using a software connector RESOLVE(TM), developed also by Petroleum Experts. Details of functionalities available in GAP can be found Ref 12. We chose to use GAP as our facility simulator for it ability to optimize productions.

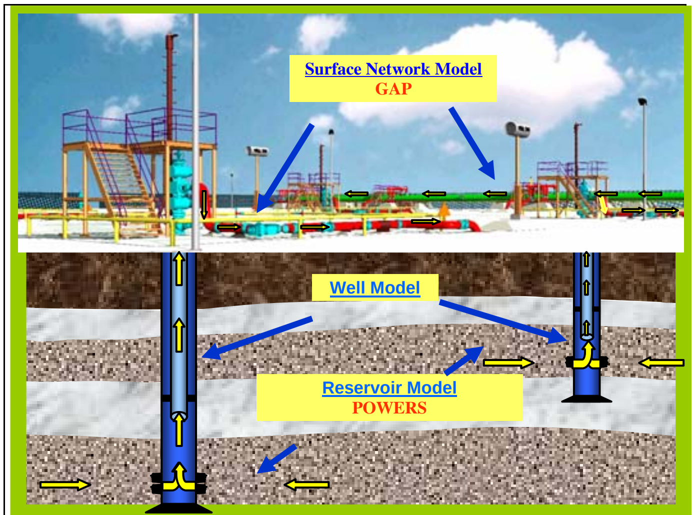

Figure 1: Coupled reservoir model and surface network system

Coupling POWERS to GAP

POWERS and GAP have been loosely coupled at the sand face in the reservoir. Figure 1 shows the coupled system, where POWERS computes subsurface flows inside the reservoir and GAP computes optimized flows in the surface network. POWERS is a parallel reservoir simulator and runs on a Linux cluster while GAP runs on a Windows PC in the serial mode. Computations in POWERS and GAP are interdependent and they proceed in a sequential mode, i.e., POWERS waits while GAP is computing and vice versa. Program control as well as simulation data are exchanged between POWERS and GAP using shared files. NFS Maestro(TM) is used to map file systems on the Linux system to Windows PC. Volume of data exchanged during coupled simulation is small and the time spent for such exchanges is insignificant for our cases. We found NFS Maestro to be very reliable for our simulations. To improve flexibility of our simulation, we also experimented with socket communications.

GAP is a vendor product and is able to communicate with a reservoir simulator only through a software communicator know as RESOLVE, developed by the same vendor. We developed a driver for RESOLVE to couple GAP with POWERS. This driver enables RESOLVE to read POWERS output and communicate them to GAP. Outputs from GAP are written by RESOLVE in a file which is then read by POWERS as its input data for reservoir simulations. Appropriate mapping routines have been implemented inside the RESOLVE driver and POWERS to facilitate data exchanges. POWERS and RESOLVE reads and writes instructions from each other in a shared file to synchronize computations as simulation proceeds.

POWERS provides transient reservoir conditions at all well locations to GAP in terms of inflow performance relationship (IPR), i.e., well flow rates as a function of flowing bottom hole pressures. IPR data varies as reservoir pressure and saturations changes near a well. These changes are very gradual under normal operating conditions. GAP computes optimized flow rates based on IPR data it receives from POWERS via RESOLVE within constraints set by the simulation engineer.

As mentioned earlier, coupling between POWERS and GAP is loose. Data exchanges between GAP and POWERS happens at some prescribed intervals set by the simulation engineer in RESOLVE. GAP and POWERS also exchange data if there is any change in the schedule of a well (i.e., open/ shut-in, etc. prescribed by the user). During the coupled simulation, POWERS simulates until the target date given by RESOLVE honoring well flow rates computed by GAP. POWERS stops running either when it gets a termination signal from RESOLVE or it reaches the end of simulation time given by the user. We designed our algorithm such that if POWERS is unable to honor well flow rates (within specified tolerance) supplied by RESOLVE, it writes IPR at that time and sends an appropriate signal to RESOLVE with the current date. RESOLVE then could continue the simulation by sending a new synchronization date with new flow rates to POWERS. We avoided such scenarios in our simulations by choosing synchronization time interval sufficiently small such that changes in reservoir conditions during that interval small.

Results and discussion

The A field, where the coupling was first implemented, is an important field and was handled thoroughly by experienced reservoir engineers. A satisfactory detailed future production strategy was devised based on the uncoupled simulation study. After implementing the coupling with the surface network, the new optimized production strategy results from the coupled model shows significant reduction in water production while maintaining the desired plateau. Comparisons of coupled versus uncoupled simulation results are shown in figures 2 and 3 in arbitrary units for the next 20 years. In figure 2, we compare predicted oil production rate where production target is set at 1.6 units. As shown in figure 3, water production rate in the coupled simulation is much less than that in the uncoupled simulation while oil production rates in two simulations are almost identical. This reduction in water cut is very favorable because it insured less field wide pressure drop as production continues.

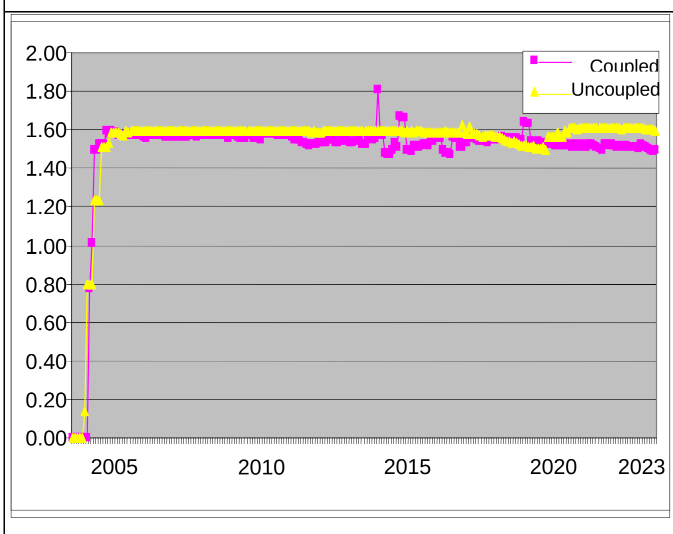

Figure 2: Comparison of oil production rates between coupled and uncoupled simulations

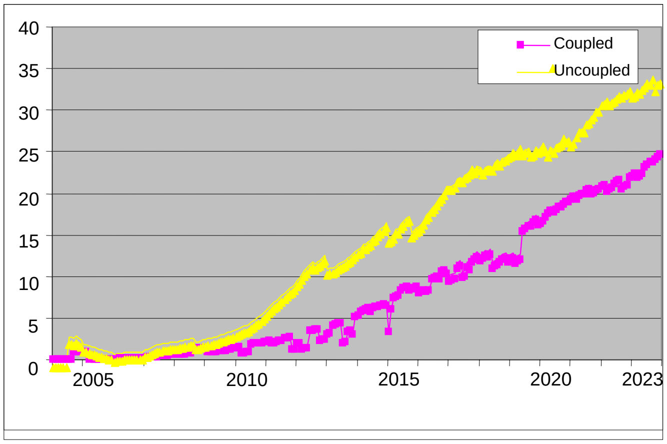

Figure 3: Comparison of water cuts between coupled and uncoupled simulations

The aggressively optimum plan carried along with its favorable features the problem of oscillation. Production profile for wells were continuously going up and down requiring impractical monthly maintenance of well targets. This is mainly contributed by the production rate being in the order of half the potential of the field which gave the surface simulation optimizer a lot of degrees of non-deterministic freedom of where to get the optimum production from. This problem was contained by properly prioritizing the wells as a function of their productivity. Other unsuccessful attempts to manage that problem included cascading constraints from field level to GOSPs to wells, and also changing some flow correlations and their constants.

Conclusions

The coupling of reservoir and surface network not only improved the production strategy of the A field, but also improved the "whole-field" modeling. This was achieved by providing reliable forecast, increasing the confidence of the strategy, and providing easier well planning and management tools.

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References

1. Dempsey, J. R., Patterson, J. K., Coats, K. H., and Brill, J. P.: "An Efficient Model for Evaluating Gas Field Gathering System Design," JPT, September 1971, pp. 1067-1073

2. Trick, M. D., "A different Approach to Coupling a Reservoir Simulator with a Surface Facility Model," SPE 40001, Presented at the 1998 SPE Gas technology Symposium, Calgary, March 1998.

3. Breaux, E. J., Monroe, S. A., Blank, L. S., Yarberry, D. W., Al-Umran, S. A.: "Application of a Reservoir Simulator Interfaced with a Surface Facility Network: A Case History," SPE 11479, SPE Journal, pp. 397-406, June 1985.

4. Al-Shaalan, T. M., Dogru, A. H. and Fung, L. S.: "Coupling Reservoir Simulator POWERS with Surface Facilities Network Simulator PIPESOFT," SPE SA 17, Presented at the 2001 SPE Technical Symposium of Saudi Arabia, Dhahran, June 2003.

5. Hooi, H. R., Goobie, L., and Choi, J.: "The Integrated Team Approach to the Optimization of a Mature Gas Field," SPE 26144, Presented at the SPE GAS Technology Symposium, Calgary, Canada, June 1993.

6. Coats, B. K., Fleming, G. C., Watts, J. W. and Rame, M.: "A Generalized Wellbore and Surface Facility Model, Fully Coupled to a Reservoir Simulator," SPE 79704, Presented at the SPE Reservoir Simulation Symposium, Houston, TX, February 2003.

7. Dogru, A. H., Li, K. G., Sunaidi, H. A., Habiballah, W. A., Fung, L., Al-Zamil, N., and Shin, D.; "A Massively Parallel Reservoir Simulator for Large Scale Reservoir Simulation," SPE paper 51886 presented at the 1999 SPE Reservoir Simulation Symposium, Houston, TX, February 1999.

8. Fung, L. S. and Dogru, A. H.: "Efficient Multilevel Method for Local Grid Refinement for Massively Parallel Reservoir Simulation," Paper M-28 presented at the ECMOR VII – European Conference on the Mathematics of Oil

Recovery, Lago Maggiore, Italy, September 2000.

9. Habiballah, W., Hayder, M., Uwaiyedh, A., Khan, M., Issa, K., Zahrani, S., Tyraskis, T., Shaikh, R., and Baddourah, M.: “Parallel Reservoir Simulation Utilizing PC-Clusters in Massive Reservoirs Simulation Models,” SPE 84065, Presented at the SPE Annual Technical Conference and Exhibition, Denver, CO, October 2003.

10. Habiballah, W. A. and Hayder, M. E.: “Large Scale Parallel Reservoir Simulations on a Linux PC Cluster,” Presented at the ClusterWorld Conference and Expo: The HPC Revolution, San Jose, CA, June 2003.

11. Habiballah, W. A. and Hayder, M. E.: “Parallel Reservoir Simulation Utilizing PC-Clusters,” Saudi Aramco Journal of Technology, pp. 18-30, Spring 2004.

12. GAP User Guide, Version 5.0, Petroleum Experts Ltd, Edinburgh, Scotland.