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PRODUCTIVITY AND INJECTIVITY OF HORIZONTAL WELLS

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By
Khalid Aziz

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Work Performed Under Contract No. DE-FG22-93BC14862

Stanford University
Stanford, California

National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
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Productivity and Injectivity of Horizontal Wells

By
Khalid Aziz

March 2000

Work Performed Under Contract No DE-FG22-93BC14862

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Thomas B. Reid, Project Manager
National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by
Department of Petroleum Engineering
Stanford University
Stanford, CA 94305-2220

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1. Forward

This report provides a brief account of some of the projects completed over the past five years under DOE Grant No. DE-FG22-93BC14862 and the associated Industrial Affiliates Program. A complete listing of documents (papers, theses, reports and software) on projects completed is given at the end of this report.

The Stanford Project on the Productivity and Injectivity of Horizontal Wells commenced on March 10, 1993 to deal with research issues concerning performance predictions for horizontal wells. The US DOE provided the major funding. In conjunction with the DOE sponsored research, the project established an Industrial Affiliates Program of domestic and international petroleum organizations. The number of participating organizations doubled from 8 in 1993 to 15 members in 1998.

The project has focused on a full spectrum of research topics related to developing improved methods for predicting the performance of horizontal wells for a wide range of reservoir applications. The project has enjoyed a close relationship with the Reservoir Simulation (SUPRI-B) and Stanford Center for Reservoir Forecasting (SCRF) research groups at Stanford. The results of our research efforts have been reported in our twenty Quarterly and five Annual Reports to DOE and in several publications (see Appendix A for a complete list).

Software described in this section is available from the U.S. Department of Energy or from

Professor Khalid Aziz
Petroleum Engineering
Stanford University
Stanford, CA 94305
e-mail: aziz@stanford.edu

2. Abstract

One of the key issues addressed by our group was pressure drop in long horizontal wells and its influence on well performance. Very little information is available in the literature on flow in pipes with influx through pipe walls. Virtually all of this work has been in small diameter pipes and with single-phase flow. In order to address this problem new experimental data on flow in horizontal and near horizontal wells have been obtained. Experiments were conducted at an industrial facility on typical 6 1/8 ID, 100 feet long horizontal well model. Our new data along with available information in the literature have been used to develop new correlations and mechanistic models. Thus it is now possible to predict, within reasonable accuracy, the effect of influx through the well on pressure drop in the well.

New ways of coupling reservoirs with non-conventional wells have been developed. These techniques can be used both for analytical and numerical reservoir treatment. We have demonstrated the use of these new models for predicting well productivity index, well index for simulation, well to well interference and optimum well length. A preliminary version of a new numerical model (reservoir simulator) has also been developed. This simulator allows the use of flexible grids. With further developments, this approach will lead to much greater reliability of non-conventional well predictions than is possible with currently available commercial simulators.

Another key area addressed in this work is the problem of coning and cresting of water or gas towards a horizontal well that is intended for producing oil. Such problems require extremely fine grid, which leads to huge computer times for computations. Analytical models have been proposed for handling such problems. We have developed a new analytical model that is superior to all previous models, but we have shown that even this model is of very little value in actual field applications. A more practical approach is to develop correlation based on carefully conducted simulations. A very practical such correlation has been developed. We have also developed a procedure for obtaining the optimum grid for the simulation of cresting problems.

Reports in the literature, based on extensive surveys of operating horizontal wells, have shown that existing tools yield highly unreliable predictions. We have conducted a systematic study to answer the question:

Why is it so hard to predict the performance of horizontal wells? Our results have shown that one of the most important causes of poor predictions is the improper handling of geology near the well.

As shown in this report by the highlights of some of the work completed under this project, significant progress has been made towards improving tools for predicting performance of horizontal wells. We have also identified several important problems that remain.

3. Executive Summary

Major contributions in each of the areas addressed in our research are identified in this summary. The report does not discuss all of the projects completed under this contract. It only provides highlights of some of the projects.

Analytical Techniques: Developed analytical solutions for single-phase fluid flow into horizontal and multilateral wells for transient and pseudo-steady state conditions. Pressure drop in the well was included in the model. These models can be used for predicting well productivity index (PI) and the well index (WI), which is required in reservoir simulation.

A semi-analytical technique was developed for calculating the critical cresting rates for horizontal wells.

Simulation Techniques: Developed techniques for accurate modeling of multiphase flow into horizontal wells in geologically complex reservoirs. These include flexible and streamline grids. A new scale-up method based on the concept of dissipation energy and streamtubes was also developed. Based on extensive simulation runs, simple correlations were developed for quick estimation of breakthrough time, maximum oil rate, and post breakthrough behavior (WOR or GOR).

Wellbore Pressure Drop: Conducted more than 1000 large-scale two-phase wellbore flow experiments in a full size wellbore model at the Marathon Petroleum Technology Center. Pressure drop, liquid holdup, and flow pattern data in horizontal wells were obtained. A mechanistic flow model for well flow was developed.

Applications: Applied techniques developed on practical problems. Investigated innovative applications of horizontal wells for primary production, water injection, and EOR. A practical problem was considered to assess the sources of errors in predicting horizontal well performance. The crucial role of geological heterogeneity near the well was demonstrated.

Experimental Work: Conducted experiments to investigate the gravity drainage process during gas injection. Horizontal wells were simulated both for injection and production. Results were compared with simulations.

During the past five years, results of our research have been presented in various papers and reports. A complete list is included in Appendix A. Some of our research work has resulted in computer programs. These programs are included on the enclosed diskettes. They may be useful for other researchers working in this field and for companies interested in developing commercial software.

4. Introduction

Researchers at Stanford University have completed a five-year project on the productivity and injectivity of horizontal wells. The project was initiated as a result of industry surveys that clearly identified the inability of techniques available in the early 1990s to make accurate predictions of individual well performance. Our project was intended to identify the causes of poor predictions followed by the planning and development of new design and analysis techniques where appropriate. Our proposal to the Department of Energy included work in the following major areas:

1. Development of fast analytical techniques for calculating productivity/injectivity of non-conventional wells by appropriate coupling of reservoir with wells.
2. Development of special flexible gridding techniques for horizontal and multilateral wells (or wells of arbitrary orientation).
3. Analysis and modeling of coning and cresting problems in horizontal wells.

4. Investigation of the influence of near well heterogeneities on well performance and techniques for incorporating essential heterogeneities in predictive models.
5. Establishing the importance of pressure drop in horizontal wells in determining well productivity.
6. Development of models for predicting pressure drop in wells with influx through the wall.
7. Application of new models to field cases.
8. Investigation of new applications of horizontal wells for EOR projects.

It was recognized at the inception of this project that there were no suitable models available for single-phase and multiphase flow in perforated wells. Substantial experimental data were required to develop and test such models. To accomplish this goal a parallel project was established with industrial support. Experiments were planned and executed in Marathon's Petroleum Technology Center in Littleton, Colorado. While the Department of Energy did not support this work, it was closely integrated with DOE sponsored projects as discussed in this report.

The industrial consortium established by the project to fund portions of the work not supported by the Department of Energy also provided technical guidance throughout this project. An annual meeting of the consortium was held to review research conducted and to develop future plans.

At the last meeting of the industrial consortium held on October 2 and 3, 1998 several new projects were identified and we were encouraged to continue research in these important areas. Members of this consortium are listed in the next section.

Important new results were obtained in all of the areas mentioned above. Highlights of some of the results of our research are discussed in Section 5. Complete details of the project are contained in the reports and papers listed in Appendix A.

5. Highlights of Research Results

This report is not intended to give complete details of research conducted under this project. Only highlights of selected projects are given here. Full details are available in the reports and papers listed in Section 7.

5.1. Coning and Cresting

One of the problems that a production engineer must face is the prediction of water and gas breakthrough times and post-breakthrough behavior (WOR, GOR). While reservoir simulators can be used to make such predictions (Figure 1). Computational and data requirements often make this approach impractical for some situations⁵².

Figure 1 - Simulation of a horizontal well showing the effect of wellbore pressure drop on gas movement towards the heel. The reservoir contains a gas cap and figure shows gas saturation contours.

One of the earliest studies we conducted was on developing analytical solutions of the problem of water and gas cresting into a horizontal well. As a part of this study existing solutions were also evaluated. Calculations performed by Arbabi and Fayers¹ for a 500 meter long horizontal well showed that critical rate calculated by different methods ranged from 18 m³/day to 442 m³/day. They also showed that numerical simulation of the same problem gave a critical rate of about 19 m³/day. They developed a new method that provided results close to those from the simulator. Our analysis also showed that all analytical solutions require boundary conditions that are unreasonable for most practical situations, and that critical rates are far too low for the economic development of most oil reservoirs.

Because the post-breakthrough behavior cannot be predicted by analytical methods, the second phase of this work involved the development of a dimensionless correlation. Souza² conducted this work as a part of his Ph.D. research and the results are also reported in Reference 3. The "data" for the correlation were developed through simulations over a full range of parameters of practical interest. Optimum gridding

strategies were also developed. The resulting correlations are fast and easy to use. They provide quick estimates before expensive simulations are conducted. The figure below shows some results from our correlation – which takes only a few seconds – and reservoir simulation which takes several minutes.

Figure 2 - Comparison between simulation and correlation for a 2-phase cresting problem. ²

5.2. Multiphase Flow in Pipes and Perforated Wells

Figure 1 shows results of a real offshore field where pressure drop in the well has a substantial influence on well performance. Results shown are obtained with a commercial simulator with pressure drop in the well included in the calculations. In this case the drawdown is much higher at the heel than at the toe. This figure clearly demonstrates the need for including wellbore pressure drop in the analysis of horizontal wells in high permeability reservoirs.

5.2.1. Experiments

Over 1000 experiments were conducted in a 6.18 inch ID pipe with various combinations of inflow along the test section. Measurements of pressure drop holdup and flow pattern were made for single and multiphase flow, with and without liners, with and without wall influx, different types and density of perforations, and for horizontal and inclined pipes. A small portion of the test section is shown in Figure 3. These experiments form the basis of correlations and models discussed in the next section. Details are reported in Reference 4.

Figure 3 - Experimental Setup at Marathon Technology Center. ⁴

The figure below shows typical results of experiments and their comparison with some of the standard methods of predicting pressure drop.

Figure 4 - Stanford experiments and their comparison with Stanford methods for calculating pressure drop in pipes. ⁵

5.2.2. Correlations

In the first phase of our work in this area we developed procedures for modifying friction factor when fluid influx or efflux takes place through the pipe wall. In addition a special acceleration term has to be included in the pressure drop correlation. These correlations are discussed in Reference 46 and have been used in our work on reservoir/well coupling reported later in this report.

5.2.3. Mechanistic Models

The figure below compares some of our experiments with a new mechanistic model developed in our work. This figure confirms that even complex mechanistic models have difficulty predicting the behavior of horizontal wells⁵. While most of the predictions are within 20% of experiments, this model is superior to other mechanistic models. There is however considerable room for improvements.

Figure 5 - Comparison of experiments with the Stanford mechanistic model.⁵

5.2.4. Simple Homogeneous Models

Because mechanistic models are difficult to use we decided to also develop a simple homogeneous model. The results of this model are shown in Figure 6. The advantage of this model is that it is not based on flow pattern predictions. This eliminates of the main difficulties with mechanistic models, where criteria for transitions between flow patterns is a major issue. With additional work, we are optimistic that such simple models can be developed for use in most horizontal well applications. It is interesting to observe that in this case the simpler homogeneous model performs better than the more complex mechanistic model.

Figure 6 - Comparison of the new homogeneous model with experiments.⁵

As shown in figure above, the simple homogeneous model does an excellent job and should be adequate for most practical applications. It should be pointed out that our homogeneous model accounts for slip between phases and therefore is different from homogeneous models used in many commercial simulators.

5.3. Reservoir Wellbore Coupling

While simulation using multiphase, multidimensional numerical models is the standard way to predict the performance of horizontal wells, analytical models that provide the exact solution for homogeneous reservoirs are still needed. These solutions can be used to

1. test numerical simulators,
2. do fast calculations of productivity index, and
3. obtain correct well index for input to simulators.

We have developed and tested models for horizontal wells that account for pressure drop in the well (finite conductivity well)^{39, 45, 48} and can be used for transient, steady state and pseudo state conditions. Additional work has allowed us to extend the model to wells of arbitrary configuration as shown in figure below⁵⁷. This new model can handle an arbitrary number of wells in a brick-shaped domain. A typical well configuration is shown in the figure below.

Figure 7 - A scheme for handling wells of arbitrary configuration.⁵

One interesting application of this model is the evaluation of different options for multilateral wells. For example the figure shown below has several wells with the same total length for the completed section.

Figure 8 - Options considered in Figure 9. ⁶

In the figure below we have plotted the productivity index improvement compared to a vertical well in the same reservoir at a specific production rate. Similar results can be obtained at other flow rates to see the effect of pressure drop on the performance of various options.

Figure 9 - Productivity of multilaterals (see Figure 8) compared to that of a fully penetrating vertical well in the same reservoir. ⁶

This model can also be used to clearly show how the PI of a horizontal well changes with flow rate. If friction in the well is ignored (as is the case at low rates) PI is independent of flow rate. But, as shown in figure below, at high flow rates PI drops due to friction in the well.

Figure 10 - Effect of wellbore friction on well productivity. ⁶

5.4. Simulation

5.4.1. Well Index

The models discussed in the previous section can be used to calculate the correct well index for any kind of well. The figure below shows results for several different grids used to model a horizontal well. Notice that a non-uniform fine grid gives the worst results in this case. While these results can be corrected by the use of an appropriate well index, better results are obtained with uniform fine grid⁷.

Figure 11 - Effect of gridding on oil rate from a horizontal well producing at constant pressure. ⁷

5.4.2. Gridding

One of the major contributions of our research has been the development of a flexible grid simulator called FLEX^{8,9,10}. This simulator can use full tensor permeabilities and many types of flexible grids. An example of the type of grid that can be used in this simulator is shown in figures below.

Figure 12 - Grid used in FLEX to honor well and geological features.⁸

Flexible grids are essential for accurately modeling non-conventional wells in geologically complex reservoir. The grid must follow the well and major geological features. This is a complex problem, particularly for three-dimensional simulations with full tensor permeabilities. Work completed so far has focused on investigating the advantages and disadvantages of various gridding approaches. Further work is needed to make the use of flexible grid feasible for practical applications. Some of the primary issues to be resolved are: efficient solution of linear and nonlinear equations resulting from the approximation of flow equations over flexible grids, generation of optimal grids in two and three dimensions, flux calculations across gridblock boundaries when the permeability tensor is full, and accounting for pressure drop in the well.

5.5. Uncertainty in Making Predictions

We have done detailed investigations on the causes of uncertainty in making well performance predictions³⁸. The figure shown below is an example of 20 predictions made for the same well using geological descriptions that honor the same data.

Figure 13 - Twenty predictions with the same geological data.¹¹

Some of the other factors investigated in this study are the effects of results on

- level of upscaling,
- method of upscaling,
- pressure drop in the well,
- gridblock size, and
- well index.

We have shown that geological heterogeneities, particularly near the well have a crucial effect on results. Unfortunately, it is not easy to model fine scale heterogeneities in routine simulation studies. Either a very fine grid must be used or an appropriate upscaling technique must be developed. Use of fine grid leads to extremely small time steps and convergence problems. Use of standard upscaling methods leads to the loss of information about important geological features. Additional work is required in both of these areas. We have found that simulation results obtained without close attention to these two factors can be very far from reality.

6. Description of Software

Not all of the programs written during this research project are suitable for distribution. Programs suitable for use by practicing petroleum engineers are contained in a self extracting file called SSDO898.exe. Once executed, this file will expand to provide several directories and a file called DOE.html. This file can be viewed by any browser. It provides complete documentation for all of the programs with appropriate links to each module. A brief summary of the programs provided is given below:

1. **Mechanistic Model for Multiphase Pipe Flow**
This program is based on extensive research utilizing experimental data and mechanistic modeling for liquid/gas flow in pipes. It can be used to predict pressure drop in pipes where the flow has stabilized.
2. **Productivity of Horizontal Wells**
This program provides an analytical solution for a well in a brick-shaped three-dimensional homogeneous (anisotropic) reservoir. The well can be at any location and the well axis must be parallel to one of the boundaries. The well may be produced at constant rate or constant pressure. The program can be used to obtain the PI or WI of the well. The pressure drop in the well is ignored in this program.
3. **Optimum Horizontal Well Length Calculation**
This program accounts for the wellbore pressure drop and includes a simple economic model. It can predict the optimum well length under steady state conditions.
4. **Wellbore/Reservoir Coupling**
This is a general program for solving coupled reservoir/wellbore problems. The analytical solution for the reservoir is the same as in 2 above, but the wellbore pressure drop is included. The well is divided into segments and superposition is used to account for the influence of each segment on the solution. This is a very general model.
5. **Well Pressure Profile Calculation**
This program allows the well to be of arbitrary profile in a three-dimension reservoir. Other restrictions are the same as in 2 above.
6. **Correlation for Cresting Behavior in Horizontal Wells**
This program can calculate breakthrough times and post breakthrough behavior for horizontal wells. The correlation is based on extensive runs with a commercial reservoir simulator.
7. **Analytical Solution for Critical Cresting Rate in Horizontal Wells**
This program can calculate critical rates for horizontal well by seven different methods, including a new method developed at Stanford University.

7. Recommendations for Future Work

While considerable progress has been made over the past five years, many important problems need further investigation:

- **Simulation While Drilling (SWD).** Our industrial members have identified real time data integration and predictions while the well is being drilled as an important problem.
- **Upscaling in Well Region.** We have shown that the performance of horizontal wells is strongly affected by near well heterogeneities. Modeling of these heterogeneities requires unreasonably fine grids. New upscaling techniques are required for the near well region.
- **Analysis of Field Data.** Testing of new simulation techniques on carefully collected field examples is required.
- **Application of Multilateral and Horizontal Wells.** There are many situations where currently vertical wells are used but where non-conventional wells may prove beneficial. These possibilities should be explored.
- **Multiphase Flow in Wells.** Additional experiments are needed to obtain sufficient data for the development of models to predict pressure drop in wells with influx.

8. Members of Industrial Consortium

The following companies have supported this project through their membership in SUPRI-HW Industrial Consortium:

1. Agip S.p.A., Milan, Italy; 1993-1997
2. Amoco Production Co., Houston, Texas; 1994-1998
3. ARTEP (Association de Recherche sur les Techniques d'Exploitation du Pétrole, a consortium of Institut Français du Pétrole, Elf Aquitaine, and TOTAL), France; 1993-1998
4. BP Exploration Inc., Houston, Texas; 1993-1996
5. Chevron Petroleum Technology Co., La Habra, California; 1993-1998
6. Intevep, S.A., Caracas, Venezuela; 1994-1998
7. Gas Research Institute, Chicago, IL; 1993
8. Marathon Oil Co., Littleton, Colorado; 1993-1998
9. Maxus Energy, a subsidiary of YPF, Dallas, Texas; 1996-1998
10. Mobil Exploration & Producing Technology Center, Dallas, Texas; 1996-1998
11. Norsk Hydro, A.S., Oslo, Norway; 1993-1998
12. Petrobras America, Inc., Houston, Texas and Rio de Janeiro, Brazil; 1993-1998
13. Phillips Petroleum Co., Bartlesville, Oklahoma; 1996-1998
14. Shell E&P Technology Co., Houston, TX; 1998
15. Smedvig Technologies, A.S., Forus, Norway; 1998
16. Texaco EPTD, Houston, Texas; 1993-1998
17. Union Pacific Resources Co., Fort Worth, Texas; 1994-1998
18. Mineral Management Services, U.S. Dept of Interior, Camarillo, California; 1995-1998

9. Nomenclature

$q(i_w)$	flow rate of well i
$M(i_w, j, k)$	segment of k of later j of well i_w
$\Delta p(i_w, j, l: k)$	pressure drop between segments i and l of lateral j of well i_w
ΔL	segment length
ϕ	flow potential

10. References

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10. Verma, S. and K. Aziz. "FLEX: An Object-Oriented Reservoir Simulator," SPE 36007, Proceedings, SPE Petroleum Computer Conference, Dallas, Texas, June 2-5, 1996.
11. Aziz, K., S. Arbabi and C. Deutsch. "Why Is It So Difficult to Predict the Performance of Non-Conventional Wells?," SPE 37048 and CIM 96-13, Proceedings, SPE/CIM Second International Conference on Horizontal Well Technology, Calgary, Canada, November 18-20, 1996. Revised September 1997. To be published in the J. Canadian Petroleum Technology.

11. Acknowledgements

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APPENDIX A

Technical Reports Other Publications Resulting from this Project

Technical Reports Other Publications Resulting from this Project

Reports submitted to DOE (in chronological order)

	Year Distributed	Author, Title, Grant period
1.	1993	Fayers, F.J., Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, March 10 - June 30, 1993.
2.	1993	Fayers, F.J., Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, July 1 - September 30, 1993.
3.	1994	1994 Fayers, F.J., Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, October 1 - December 31, 1993.
4.	1994	1994 Fayers, F.J., Aziz, K. and Hewett, T. Productivity and Injectivity of Horizontal Wells, January 1 - March 31, 1994.
5.	1994	1994 Fayers, F.J., Aziz, K., Hewett, T. and Arbabi, S. <u>Productivity and Injectivity of Horizontal Wells, Annual Report for the Period March 10, 1993 to March 9, 1994, Contract No. DE-FG22-93BC14862.</u> U.S. Department of Energy, Bartlesville Project Office
6.	1994	1994 Fayers, F.J., Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, April 1 - June 30, 1994.
7.	1994	1994 Fayers, F.J., Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, July 1 - September 30, 1994.
8.	1995	1995 Fayers, F.J., Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, October 1 - December 31, 1994.
9.	1995	Fayers, F.J., Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, January 1 - March 31, 1995.
10.	1995	Fayers, F.J. <u>Productivity and Injectivity of Horizontal Wells, Annual Report for the Period March 10, 1994 to March 9, 1995, Contract No. DE-FG22-93BC14862.</u> U.S. Department of Energy, Bartlesville Project Office
11.	1995	Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, April 1 - June 30, 1995.
12.	1995	Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, July 1 - September 30, 1995.
13.	1996	Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, October 1 - December 31, 1995.
14.	1996	Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, January 1 - March 31, 1996.
15.	1996	Aziz, K. and Hewett, T. <u>Productivity and Injectivity of Horizontal Wells, Annual Report for the Period March 10, 1995 to March 9, 1996, Contract No. DE-FG22-93BC14862.</u> U.S. Department of Energy, Bartlesville Project Office
16.	1996	Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, April 1 - June 30, 1996.
17.	1996	Aziz, K., Hewett, T.A. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, July 1 - September 30, 1996.

18. 1997 Ouyang, L.-B., Arbabi, S. and Aziz, K. General Single Phase Wellbore Flow Model, Technical Report.
19. 1997 Souza, A., Arbabi, S. and Aziz, K. Productivity and Injectivity of Horizontal Wells, October 1 - December 31, 1996.
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21. 1997 Aziz, K., Hewett, T. and Arbabi, S. Productivity and Injectivity of Horizontal Wells, Annual Report for the Period March 10, 1996 to March 9, 1997, Contract No. DE-FG22-93BC14862. U.S. Department of Energy, Bartlesville Project Office
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| 28. | 1994 | Arbabi, S. and F.J. Fayers. "Coning and Cresting Behavior in Vertical and Horizontal Wells—Critical Rates and Breakthrough Times," Stanford University, Petroleum Engineering Department, SUPRI-HW Report, April, 1994. |
| 29. | 1994 | Aziz, K., F.J. Fayers, S. Arbabi and N. Petalas. "Opportunities for Improvements in Oil and Gas Production with Horizontal Wells," Keynote Address, Proceedings, Second JNOC-TRC International Symposium, Chiba, Japan, November 1-6, 1993. Published <i>Special Publication of the Technology Research Center, JNOC</i> , Vol 4, (1994). |
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| 31. | 1996 | Petalas, N. and K. Aziz. "Development and Testing of Mechanistic Models for Multiphase Flow in Pipes: Phase I—A Preliminary Approach for Stabilized Flow at All Inclinations," Stanford University, Petroleum Engineering Department, SUPRI-B and SUPRI-HW Report, April, 1996. |
| 32. | 1996 | Ouyang, L.-B. and K. Aziz. "Development of New Wall Friction Factor and Interfacial Friction Factor Correlations for Gas-Liquid Stratified Flow in Wells and Pipelines," SPE 35679, Proceedings, SPE Western Regional Meeting, Anchorage, Alaska, May 22-24, 1996. |

33. 1996 Verma, S. "Flexible Grids for Reservoir Simulation," Ph.D. dissertation, Stanford University, Petroleum Engineering Department, June, 1996.
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39. 1997 Penmatcha, V.R., S. Arbabi and K. Aziz. "Effects of Pressure Drop in Horizontal Wells and Optimum Well Length," SPE 37494, Proceedings, SPE Production Operations Symposium, Oklahoma City, Oklahoma, March 9-11, 1997.
40. 1997 Ouyang, L.-B., L.K. Thomas, C.E. Evans and K. Aziz. "Simple but Accurate Equations for Wellbore Pressure Drawdown Calculation," SPE 38314, Proceedings, SPE Western Regional Meeting, Long Beach, California, June 25-27, 1997.
41. 1997 Souza, A. "Correlations for Cresting Behavior in Horizontal Wells," Ph.D. dissertation, Stanford University, Petroleum Engineering Department, March, 1997.
42. 1997 Verma, S. and K. Aziz. "A Control Volume Scheme for Flexible Grids in Reservoir Simulation," SPE 37999, Proceedings, SPE Reservoir Simulation Symposium, Dallas, Texas, June 8-11, 1997.
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47. 1998 Petalas, N. and K. Aziz. "A Mechanistic Model for Multiphase Flow in Pipes," CIM 98-39, Proceedings, 49th Annual Technical Meeting of the Petroleum Society of the CIM, Calgary, Alberta, Canada, June 8-10, 1998.

48. 1998 Penmatcha, V.R. and K. Aziz. "A Comprehensive Reservoir/Wellbore Model for Horizontal Wells," SPE 39521, Proceedings, SPE India Oil and Gas Conference and Exhibition, New Delhi, India, April 7-9, 1998.
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50. 1998 Aziz, K. and L.-B. Ouyang. "Productivity of Horizontal and Multilateral Wells," Proceedings, 10th International Conference on Horizontal Well Technology and Applications, Houston, TX, August 24-26, 1998.

Other papers, theses and reports prepared in connection with the Horizontal Well project

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Distributed | Author, Title, Publication information |
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| 51. | 1994 | Al-Harthi, O. "End Effects on Productivity Index of Horizontal Wells," Master's thesis, Stanford University, Petroleum Engineering Department, 1994. |
| 52. | 1994 | Berge, L. "Sensitivity Studies of Wellbore Friction for a Horizontal Well," Stanford University, Petroleum Engineering Department, SUPRI-HW Report, November, 1994. |
| 53. | 1995 | Penmatcha, V.R. "Skin Factor Calculations for Vertical, Deviated, and Horizontal Wells," Stanford University, Petroleum Engineering Department, SUPRI-HW Report, March, 1995. |
| 54. | 1995 | Ouyang, L.-B. "Stratified Flow Model and Interfacial Friction Factor Correlations," Master's thesis, Stanford University, Petroleum Engineering Department, June, 1995. |
| 55. | 1997 | Souza, A.L.S., S. Arbabi and K. Aziz. "Practical Procedure to Predict Cresting Behavior in Horizontal Wells," SPE 39063, SPE Journal, December 1998, pages 382-392. |
| 56. | 1998 | Wan, J., V.R. Penmatcha, S. Arbabi and K. Aziz. "Effects of Grid Systems on Predicting Horizontal Well Productivity," SPE 46228, Proceedings, SPE Western Regional Meeting, Bakersfield, CA, May 10-13, 1998. |
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APPENDIX B

Description of Software

Energy Science and Technology Software Center

Abstract Submittal

1 Identification:

a. Software Acronym:

HWELL

b. Short Title

Productivity of Horizontal Wells

2 Authors:

Several students, research staff and faculty have contributed to the software. Authors of each module are identified in the documentation and in the software. The work was performed under the direction of Professor Khalid Aziz (Stanford University, Stanford, California)

3 Software Completion Date:

8/31/98

4 Brief Description:

HWELL is a collection of programs contained in a self-extracting file SSD0898.exe. This collection consists of seven individual modules and a documentation module. Each module contains source code, IBM PC (DOS) executable file and sample data. These modules can be used for calculating productivity of horizontal and deviated wells, pressure drop in the well, breakthrough times for gas or water and post breakthrough behavior. A brief description of program modules is given below:

Mechanistic Model for Multiphase Pipe Flow

This program is based on extensive research utilizing experimental data and mechanistic modeling for liquid/gas flow in pipes. It can be used to predict pressure drop in pipes where the flow has stabilized.

Productivity of Horizontal Wells

This program provides an analytical solution for a well in a brick-shaped three-dimensional homogeneous (anisotropic) reservoir. The well can be at any location and the well axis must be parallel to one of the boundaries. The well may be produced at constant rate or constant pressure. The program can be used to obtain the PI or WI of the well. The pressure drop in the well is ignored in this program.

Optimum Horizontal Well Length Calculation

This program accounts for the wellbore pressure drop and includes a simple

economic model. It can predict the optimum well length under steady state conditions.

Wellbore/Reservoir Coupling

This is a general program for solving coupled reservoir/wellbore problems. The analytical solution for the reservoir is the same as in 2 above, but the wellbore pressure drop is included. The well is divided into segments and superposition is used to account for the influence of each segment on the solution. This is a very general model.

Well Pressure Profile Calculation

This program allows the well to be of arbitrary profile in a three-dimension reservoir. Other restrictions are the same as in 2 above.

Correlation for Cresting Behavior in Horizontal Wells

This program can calculate breakthrough times and post breakthrough behavior for horizontal wells. The correlation is based on extensive runs with a commercial reservoir simulator.

Analytical Solution for Critical Cresting Rate in Horizontal Wells

This program can calculate critical rates for horizontal well by seven different methods, including a new method developed at Stanford University.

5 Method of Solution:

Analytical solutions of three-dimensional flow equations and correlation of data using regression techniques.

6 Computers for which software is written:

Programs are all written for IBM compatible Personal Computers.

7 Operating System:

IBM DOS

8 Programming languages Used:

Fortran (70%) and C++ (30%)

9 Software Limitations:

Several assumptions were made. Analytical solutions are for homogeneous anisotropic reservoirs. Coning and cresting correlations are for two-phase flow. Other limitations are clearly indicated in the documentation.

10 Unique Features of the Software:

The analytical solutions allow the user to account for pressure drop in the well to calculate well productivity and optimum well length. Coning and cresting

software provides a fast way to make initial estimates of breakthrough time and post breakthrough behavior.

11 Related and Auxiliary Software:

Software modules are ready to use. No other software is needed.

12 Other Programming or Operating Information of Restrictions:

All of the modules are based on academic research. They are not tested for field applications and are not intended for use by inexperienced engineers. It is essential that the user consult the references associated with the module of interest to fully understand software limitations.

13 Hardware Requirements:

Any IBM compatible PC is suitable for running software modules.

14 Time Required:

Time required depends on the specific module and the size of the problem. It varies from a few seconds to a few minutes.

15 References:

All of the programs use research that is reported in the technical literature. Each module contains references appropriate for that module. Key references are:

Arbabi, S. and F.J. Fayers. "Comparative Aspects of Coning Behavior in Horizontal and Vertical Wells," Proceedings, 8th European Improved Oil Recovery Symposium, Vienna, Austria, May, 1995.

Souza, A. "Correlations for Cresting Behavior in Horizontal Wells," Ph.D. dissertation, Stanford University, Petroleum Engineering Department, March, 1997.

Souza, A.L.S., S. Arbabi and K. Aziz. "Practical Procedure to Predict Cresting Behavior in Horizontal Wells," SPE 39063, SPE Journal, December 1998, pages 382-392.

Ouyang, L.-B., N. Petalas, S. Arbabi, D.E. Schroeder and K. Aziz. "Experimental Study of Single Phase and Two-Phase Fluid Flow in Horizontal Wells," SPE 46221, Proceedings, SPE Western Regional Meeting, Bakersfield, CA, May 10-13, 1998. Revised March 9, 1998.

Ouyang, L.-B. "Single Phase and Multiphase Fluid Flow in Horizontal Wells," Ph.D. Thesis, Stanford University, Petroleum Engineering Department, August 1998.

Aziz, K. and L.-B. Ouyang. "Productivity of Horizontal and Multilateral Wells," Proceedings, 10th International Conference on Horizontal Well Technology and Applications, Houston, TX, August 24-26, 1998.

Wan, J., V.R. Penmatcha, S. Arbabi and K. Aziz. "Effects of Grid Systems on Predicting Horizontal Well Productivity," SPE 46228, Proceedings, SPE Western Regional Meeting, Bakersfield, CA, May 10-13, 1998.

Verma, S. "Flexible Grids for Reservoir Simulation," Ph.D. dissertation, Stanford University, Petroleum Engineering Department, June, 1996.

Verma, S. and K. Aziz. "A Control Volume Scheme for Flexible Grids in Reservoir Simulation," SPE 37999, Proceedings, SPE Reservoir Simulation Symposium, Dallas, Texas, June 8-11, 1997.

Verma, S. and K. Aziz. "FLEX: An Object-Oriented Reservoir Simulator," SPE 36007, Proceedings, SPE Petroleum Computer Conference, Dallas, Texas, June 2-5, 1996.

Aziz, K., S. Arbabi and C. Deutsch. "Why Is It So Difficult to Predict the Performance of Non-Conventional Wells?" SPE 37048 and CIM 96-13, Proceedings, SPE/CIM Second International Conference on Horizontal Well Technology, Calgary, Canada, November 18-20, 1996. Revised September 1997. To be published in the J. Canadian Petroleum Technology.

16 Subject Classification Code and Keywords

a. Subject Classification Code:

Not available.

b. Keywords:

Horizontal well; pressure drop in well; optimum well length; cresting; coning; breakthrough time; non-conventional wells; mechanistic model; reservoir well coupling.

Stanford University Petroleum Engineering Department Software Distribution

August 1998 Edition

This Software Distribution contains the source and executable code from research carried out under DOE Contract DE-FG22-93BC14862, the Stanford Project on Productivity and Injectivity of Horizontal Wells (SUPRI-HW), and the Stanford Reservoir Simulation Industrial Affiliates (SUPRI-B).

Contents:

Introduction

The code for each research project is stored in separate directories as detailed below. Each of these directories also contains a keyword abstract document and a text file describing the software. The code included in this software distribution is as follows:

Mechanistic Model for Multiphase Pipe Flow

- Mechanistic Model for Multiphase Pipe Flow
- Productivity of Horizontal Wells
- Optimum Horizontal Well Length Calculation
- Wellbore/Reservoir Coupling
- Well Pressure Profile Calculation
- Correlations for Cresting Behaviour in Horizontal Wells
- Analytical Solutions for Critical Cresting Rate in Horizontal Wells

Productivity of Horizontal Wells

Optimum Horizontal Well Length Calculation

The applications included in this distribution are intended for 32-bit Microsoft Windows™ environments and can be run from a console, or DOS window. To use any of these applications, simply copy the files from the desired directory to a directory on your system and execute the application from a MS-DOS Command Prompt.

Wellbore/Reservoir Coupling

Well Pressure Profile Calculation

Correlations for Cresting Behaviour in Horizontal Wells

Analytical Solutions for Critical Cresting Rate in Horizontal Wells

License Information

► Mechanistic Model for Multiphase Pipe Flow

This program calculates pressure drop and volume fraction liquid using the mechanistic model of Petalas and Aziz as described in:
Petalas, N., and Aziz, K., "A Mechanistic Model for Stabilized Multiphase Flow in Pipes" a report for the members of the Stanford Reservoir Simulation Industrial Affiliates and the Stanford Project on the Productivity and Injectivity of Horizontal Wells, Petroleum Engineering Dept., Stanford University August, 1997

It consists of the following files. files:

- PETAZ.FOR - The program source code. This is written in Fortran 77.
- MFLOW.CMN - A Fortran "include" file containing the common block definitions used within the program. Required for compilation.
- PARAMS.FOR - A Fortran "include" file containing the various parameter definitions used within the program. Required for compilation.
- PETAZ.EXE - The compiled executable. A PC with a numeric processor (or a 486DX or Pentium class) is required in order to run it.

The input variables required by the PETAZ.EXE application are:

Variable	Description
DENSL	Liquid density, (lb/ft ³)
DENSG	Gas density, (lb/ft ³)
AMUL	Liquid viscosity, (centipoise)
AMUG	Gas viscosity, (centipoise)
SIGMA	Gas-liquid surface tension, (dyne/cm)
DIA	Pipe inside diameter, (inch)
ROUGH	Pipe absolute roughness, (ft)
ALPH1	Pipe angle of inclination, (degrees)
VSL	Superficial liquid velocity, (ft/sec)
VSG	Superficial gas velocity, (ft/sec)

These can be input into the program directly or specified from a previously generated data file. The program will display the predicted flow pattern as well as the calculated pressure drop (per unit length) and volume fraction liquid. The input parameters are automatically saved to a text file which can later be edited and used for subsequent analyses. The file name that is used to save the input data is PETAZ.INP, although it can be changed by the user.

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► Productivity of Horizontal Wells

This code is an implementation of the original model of Babu and Odeh (1989) to calculate the productivity of a horizontal well in a box-shaped drainage volume with uniform influx along the well. The program was written by Raju Penmatcha as part of his Ph.D. research work "Modeling of Horizontal Wells with Pressure Drop in the Well" Stanford University, CA, December 1997. The following [files](#) are included:

- BABU.CXX - The program source code written in C++. Required for compilation.
- BABU.EXE - The compiled executable. This has been compiled using Microsoft Visual C++ (Version 5.0).
- BABU.H - A "header" file required for compilation.
- BABU.IN - Commented Input file for example problem.
- EXAMPLE - Output file for example problem generated by redirecting the program output: `babu.exe >example`.
- MAIN.CXX - Additional source code (C++). Required for compilation.
- README - Informational text file on program usage and description.

The input variables required by the BABU.EXE application are:

Variable	Description
A	reservoir length (ft), x-direction
B	reservoir width (ft), y-direction (well is always parallel to this direction)
H	reservoir height (ft), z-direction
CT	system total compressibility (1/psi)
BO	formation volume factor of oil (RB/STB)
PHI	porosity at initial pressure
VISO	oil viscosity (cp)
KX	permeability in x-direction (mD)
KY	permeability in y-direction (mD)
KZ	permeability in z-direction (mD)
Q0	Constant production rate from the well (STB/day)
X0	well location in x-direction, ft
Y1	location of well heel in y-direction, ft
Y2	location of well toe in y-direction, ft
Z0	well location in z-direction, ft
X	location in x-direction to evaluate the well pressure (ft)
Y	location in y-direction to evaluate the well pressure (ft)
Z	location in z-direction to evaluate the well pressure (ft)
RW	well radius (ft)

These must be specified in the file BABU.IN, which can be modified with any text editor (See example). The program's output will be displayed on the screen, unless it is redirected when the application is started.

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▶ Optimum Horizontal Well Length Calculation

This program calculates the optimum well length for a single horizontal well based on steady state conditions and a very simple economic model. The methodology used is based on the research presented at the Fourth Review Meeting of the Stanford Horizontal Well Project. Appropriate comments are included in the source files. The program was written by Raju Penmatcha as part of his Ph.D. research work "Modeling of Horizontal Wells with Pressure Drop in the Well" Stanford University, CA, December 1997. The following [files](#) are included:

- FRICFAC_CORR.H - "Header" file containing function declarations for friction factor correlations. Written in C++. Required for compilation.
- HWELL.CPP - C++ Source code file containing the Class Method Definitions for the Hwell class. This class calculates PI and Q based on the Economides (1990) model. Assumptions are Single Phase Oil Flow, mixed steady state in the horizontal plane and pseudo steady state in the vertical plane.
- HWELL.H - A "header" file required for compilation. This file is required by the HWELL.CPP code.
- MPMODEL.CPP - C++ Source code file containing the Class Method Definitions for the Multi-Purpose model with finite well length and any type of flow, i.e. no-friction, laminar or turbulent flow. It is a derived class from the base class Hwell.
- MPMODEL.H - A "header" file required for compilation. This file is required by the MPMODEL.CPP code.
- OPTIMUM.EXE - The compiled executable. This has been compiled using Microsoft Visual C++ (Version 5.0).
- OPTIMUM.IN - Commented Input file for example problem.
- OPTIMUM.OUT - Automatically created output file.
- OPTMP.CXX - Main source code (C++) file. Required for compilation.
- README - Informational text file on program usage and description.

The input variables required by the OPTIMUM.EXE application are:

Variable	Description
K	permeability in md
BO	formation volume factor of oil (RB/STB)
VISO	oil viscosity (cp)
RE	drainage radius of the cylindrical area in ft
RW	well radius (ft)
DELP	drawdown in psi at heel of horizontal well
TIME	steady state production time in days
PO	Oil price in \$/STB
CH	cost for drilling one ft of horizontal well in \$
CV	cost to drill vertical in \$
CM	Maintenance cost per day of production in \$
ALPHA	well relative roughness
DEN	oil density at reservoir conditions in lbm/ft ³
PE	reservoir boundary pressure in psi
SKIN	well skin

These must be specified in the file OPTIMUM.IN, which can be modified with any text editor (See example). The program's output will be stored in the file OPTIMUM.OUT. The results will include Revenue in dollars vs. Well length in ft. Based on these, the optimum length of the horizontal well can be determined.

Wellbore/Reservoir Coupling

Two programs are included in this section:

- CLASFRIC - Couples flow between the reservoir and the wellbore. It can be run under constant flow rate or constant BHP constraints. It can also be run under constant flow rate followed by a constant BHP constraint.
- CONDELP - Same as CLASFRIC, except that this program runs under constant drawdown at the heel of the well. For example, if a 10 psi constant drawdown is specified in the input file, the program ensures that $P_{avg} - P_{wf}(\text{heel}) = 10$ psi at all times. It runs under this constraint until the pressure at the heel of the well reaches the minimum BHP. When minimum BHP is reached, it shifts to the minimum BHP constraint where it no longer maintains a constant drawdown at the heel.

The maximum number of time steps allowed in both programs is 200. The maximum number of well segments allowed is 80. If numbers more than these are required, then changes should be made to the MAXNTIMES and MAXTOTWELLS variables in the file "fmat.h", and the programs recompiled. These programs were written by Raju Penmatcha as part of his Ph.D. research work "Modeling of Horizontal Wells with Pressure Drop in the Well" Stanford University, CA, December 1997.

The following [files](#) are included for the CLASFRIC program:

- BABU.CXX - Program source code written in C++ to calculate the productivity of a horizontal well based on the work of Babu & Odeh in SPE 18334 (1988).
- BABU.H - A "header" file required for compilation of CBABU.CXX.
- CLASFRIC.EXE - The compiled executable. This has been compiled using Microsoft Visual C++ (Version 5.0).
- FMAT.CXX - Program source code written in C++ required for compilation.
- FMAT.H - A "header" file required for compilation of FMAT.CXX.
- FRICFAC_CORR.CXX - Program source code written in C++ containing function declarations for friction factor correlations. Written in C++. Required for compilation.
- FRICFAC_CORR.H - "Header" file containing function declarations for friction factor correlations. Written in C++. Required for compilation.
- INFILE.CXX - Program source code written in C++ to process input data.
- INFILE.H - A "header" file required for compilation of INFILE.CXX.
- MAIN.CXX - Program source code written in C++ defining program entry point.
- PIPEFLOW.CXX - Program source code written in C++ containing the Class definition for the Multi-Purpose model with finite length well and any type of flow (no-friction, laminar or turbulent). This is a modified form of the MPmodel code used in [OPTIMUM.EXE](#).
- PIPEFLOW.H - A "header" file required for compilation of PIPEFLOW.CXX.
- README - Informational text file on program usage and description.
- SOLVER.CPP - Program source code written in C++ required for compilation.
- SOLVER.H - A "header" file required for compilation. This file is required by the SOLVER.CPP code.
- [EXAMPLE1](#) - A directory containing sample a input file (BBWELL.IN) as well at the resulting output file (BBWELL.OUT).
- [EXAMPLE2](#) - A directory containing sample a input file (BBWELL.IN) as well at the resulting output file (BBWELL.OUT).
- [EXAMPLE3](#) - A directory containing sample a input file (BBWELL.IN) as well at the resulting output file (BBWELL.OUT).

The following [files](#) are included for the CONDELP program:

- BABU.CXX - Program source code written in C++ to calculate the productivity of a horizontal well based on the work of Babu & Odeh in SPE 18334 (1988).
- BABU.H - A C-language "header" file required for compilation of CBABU.CXX.
- CONDELP.EXE - The compiled executable. This has been compiled using Microsoft Visual C++ (Version 5.0).
- FMAT.CXX - Program source code written in C++ required for compilation.
- FMAT.H - A C-language "header" file required for compilation of FMAT.CXX.
- FRICFAC_CORR.CXX - Program source code written in C++ containing function declarations for friction factor correlations. Written in C++. Required for compilation.
- FRICFAC_CORR.H - C-language "header" file containing function declarations for friction factor correlations. Written in C++. Required for compilation.
- INFILE.CXX - Program source code written in C++ to process input data.
- INFILE.H - A C-language "header" file required for compilation of INFILE.CXX.
- MAIN.CXX - Program source code written in C++ defining program entry point.
- PIPEFLOW.CXX - Program source code written in C++ containing the Class definition for the Multi-Purpose model with finite length well and any type of flow (no-friction, laminar or turbulent). This is a modified form of the MPmodel code used in OPTIMUM.EXE.
- PIPEFLOW.H - A C-language "header" file required for compilation of PIPEFLOW.CXX.
- README - Informational text file on program usage and description.
- SOLVER.CPP - Program source code written in C++ required for compilation.
- SOLVER.H - A C-language "header" file required for compilation. This file is required by the SOLVER.CPP code.
- EXAMPLE - A directory containing sample a input file (BBWELL.IN) as well at the resulting output file (BBWELL.OUT).

For each program, the input parameters are specified in the file BBWELL.IN, which can be modified with any text editor (See examples). The program's output will be to the screen, although it can be redirected.

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Well Pressure Profile Calculation

This program calculates the well pressure for a well of a general profile in a box-shaped reservoir with no flow boundaries. The method used is described in SPE paper 27980 by Economides et al. It was written by Pierre Maizeret as part of his M.S. Project.

The following files are included:

- CLSRC.F - Source code written in Fortran. Returns the dimensionless pressure P_d at the position $M_d(X_d, Y_d, Z_d)$ due to a well with a unit dimensionless flow rate modeled by a segment from $M_0(XD_0, YD_0, ZD_0)$ to $M_1(XD_1, YD_1, ZD_1)$ in a reservoir of dimensions (XDe, YDe, ZDe) . The dimensionless pressure is a result of the continuous point source solution CPSRC.F integrated along the path of the well using a Romberg integration procedure. Required for compilation.
- CPSRC.F - Source code written in Fortran. Returns the dimensionless pressure P_d at a point $M_d(X_d, Y_d, Z_d)$ due to a point source with a unit dimensionless flow rate located at $M_w(XD_w, YD_w, ZD_w)$ in a reservoir of dimensions (XDe, YDe, ZDe) . The dimensionless pressure is the result of the instantaneous point source (see IPSRC.F) solution integrated over time using an iterative Runge-Kutta integration method. The integration procedure calls the routines DERIVS.F, RKQS.F, RKCK.F, and ODEINT.F. Required for compilation.
- DERIVS.F - Source code written in Fortran. Required for compilation.
- DERSRC.F - Source code written in Fortran. Required for compilation.
- GBAND.F - Source code written in Fortran. Required for compilation.
- HORWELL.DAT - Commented Input file for example problem.

- **HORWELL.EXE** - The compiled executable. This has been compiled using Digital Visual Fortran Pro (Version 5.0).
- **IPSRC.F** - Source code written in Fortran. Evaluates the dimensionless pressure due to an instantaneous point source. Required for compilation.
- **MAIN.F** - Source code written in Fortran. This is the main program. It calls **READDATA.F** based on which a decision is made to either use the constant pressure algorithm, or the one corresponding to constant flux along the well. Required for compilation.
- **ODEINT.F** - Source code written in Fortran. Required for compilation.
- **PSOL.F** - Source code written in Fortran. Solves the "constant flux along the well" problem, where the pressure varies with position. The program evaluates the pressure at the middle of the well, at a distance R_w from the well in the y-direction. The output is given in two files: **HORWELL.P** (containing time and pressure in different wells), and **HORWELL.PD** (containing dimensionless time, dimensionless pressure, and dimensionless pressure derivative for each well). The pressure is calculated in subroutine **CLSRC.F**. Required for compilation.
- **QSOL.F** - Source code written in Fortran. Solves the "constant pressure along the well" problem, where the flow rate varies with position. The program first splits all the wells into NS segments and then solves the linear system (see **GBAND.F**), from which are obtained the flowrates for each segment and the overall pressures for each well. The output is given in three files: **HORWELL.P** (containing time and pressure in different wells), **HORWELL.PD** (containing dimensionless time, dimensionless pressure, and dimensionless pressure derivative for each well), and **HORWELL.FLOW** (time and flow rates for each well). Required for compilation.
- **READDATA.F** - Source code written in Fortran. Reads the input data file **HORWELL.DAT**. Required for compilation.
- **README.TXT** - Informational text file on program usage and description.
- **RKCK.F** - Source code written in Fortran. Required for compilation.
- **RKQS.F** - Source code written in Fortran. Required for compilation.

The input data are specified in the file **HORWELL.DAT** (see example) as follows:

Variable	Description
Xe	Dimension in the X-direction (ft)
Ye	Dimension in the Y-direction (ft)
Ze	Dimension in the Z-direction (ft)
Kx	Permeability in the X-direction (mD)
Ky	Permeability in the Y-direction (mD)
Kz	Permeability in the Z-direction (mD)
Ct	Total compressibility (/psi)
BO	Formation volume factor of oil (RB/STB)
PHI	Porosity
MU	Viscosity (cp)
Pi	initial pressure (psi)
NW	Number of wells
The following group of four entries are repeated once for each well	
M0(i) X,Y,Z	Coordinates of well origins(ft)
M1(i) X,Y,Z	Coordinates of well extremities(ft)
Q(i)	Well flow rate (bbl/d): +ve for producer, -ve for injector
Rw(i)	Well radius (ft)
T1	Start time
T2	End time
NT	Number of time steps
TSC	time step control (1 = uniform, 2 = logarithmic)
EPSP	Convergence tolerance value used in in cpsrc.f
EPSL	Convergence tolerance value used in in clsrc.f
CL	Limiting condition specifier(1 = constant flux, 2 = constant pressure)
NS	Number of segments in which to divide wells (must be an odd number)

The program produces the following output files:

File Name	Description
HORWELL.P	Contains time and pressure (psi) for each well and well segment. Wells are divided into 10 segments, but this number can be changed by modifying NWSEG in the routine PSOL.F. Larger values slow down the computations and usually are not necessary.
HORWELL.PD	Containing dimensionless time, pressure, and pressure derivatives for each well and well segment.
HORWELL.PLOT	Containing dimensionless time, pressure, pressure derivative, and pressure derivative*time. This is calculated for the 0.7 location along the well. This file could be used to plot the results.
HORWELL.FLOW	Containing time and flow rates (STB/day) for each well and well segment. This file is generated for the case of constant pressure. The total flow rate should be specified.

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Correlations for Cresting Behaviour in Horizontal Wells

This program calculates the breakthrough time and post-breakthrough cresting behavior for horizontal wells. The code was written by Antonio Luiz Serra De Souza as part of his Ph.D. research work. Further details are available from his Ph.D. Dissertation, "Correlations for Cresting Behavior in Horizontal Wells, Stanford University, March 1997.

The following files are included:

- COR.EXE - The compiled executable. This has been compiled using Digital Visual Fortran Pro (Version 5.0).
- COR.F - Source code written in Fortran.
- COR.IN - Input file for example problem.

- INCOR.F - Additional source code file written in Fortran.
- README - Informational text file.

The input data for the program as specified in the file COR.IN, are arranged in 15 free-formatted lines as described below:

Variable	Description
Line 1: IUNIT ICASE IKR IQ IV IDEB	
IUNIT	System of units: 1 = Metric (Modified SI) Units, 2 = Field Units
ICASE	Type of flow: 1 = Water-Oil flow, 2 = Gas-Oil flow
IKR	Input format of Kr curves: 1 = Exponents and end-points are given in lines 10-12, 2 = A Table of Sw vs. K _{rw} vs. K _{ro} is given in lines 13-15 (as many as necessary)
IQ	Option indicating whether flow rate, or breakthrough time is specified: 1 = The total flow rate for the field is given as the value of QT (Line 9). The program will calculate the breakthrough time, given the final time, TIME (Line 9). 2 = The total flow rate for the field is given as the value of QT (Line 9). The program will calculate the breakthrough time, assuming the final time to be the breakthrough time multiplied by AFIM. 3 = The breakthrough time is specified as TIME (Line 9). The program will calculate the total maximum flow rate QT, assuming the final time to be the breakthrough time multiplied by AFIM.
IV	Vertical equilibrium option: 0 = The vertical equilibrium option is not used. m is calculated from the derived correlations. 1 = The vertical equilibrium option will be used. The value of m for post-breathrough behavior will be taken as 0.5.
IDEB	Debug option: 0 = Debugging off, the normal output is generated. 1 = The generated output will include the values of the factors of all the correlations. 2 = The generated output will include the values of the parameters for the numerical solutions for each iteration performed.
Line 2: HO HW W X NWEL	
HO	Total oil zone thickness, m (ft)

HW	Well location, m (ft)
W	Width of the reservoir (assumed equal to the well length), m (ft)
W	Total lateral length of the reservoir, m (ft)
NWEL	Number of Wells (integer value)
Line 3: PHI KX KZ	
PHI	Porosity
KX	Horizontal permeability, mD (mD)
KZ	Vertical permeability, mD (mD)
Line 4: BO BW BG RS	
BO	Oil formation volume factor, initial reservoir conditions at fluid contact, rm^3/stm^3 (rb/stb)
BW	Water formation volume factor, initial reservoir conditions at water-oil contact, rm^3/stm^3 (rb/stb)
BG	Gas formation volume factor, initial reservoir conditions at gas-oil contact, rm^3/stm^3 (rb/stb)
RS	Gas solubility ratio, sm^3/stm^3 (stb/stb)
Line 5: ROSTD RWSTD RGSTD	
ROSTD	Standard oil density, kg/m^3 (lb/ft ³)
RWSTD	Standard water density, kg/m^3 (lb/ft ³)
RGSTD	Standard gas density, kg/m^3 (lb/ft ³)
Line 6: VISCO VISCW VISCW	
VISCO	Oil viscosity, cp (cp)
VISCW	Water viscosity, cp (cp)
VISCW	Gas viscosity, cp (cp)
Line 7: DZ DZP	
DZP	The value of ΔZ to be used.
DZP	The value of ΔZ to be used when calculating the values of n_{op} , n_{wp} , and M_p for the pseudo functions.
Line 8: INO IN IM	
INO	Option to activate the calculation of the pseudofunction based on the oil-relative permeability exponent, n_o . 0 = n_o pseudofunction is not calculated. 1 = n_o pseudofunction will be calculated.
IN	Option to activate the calculation of the pseudofunction based on the water-relative permeability exponent, $n_w(n_g)$. 0 = $n_w(n_g)$ pseudofunction is not calculated. 1 = $n_w(n_g)$ pseudofunction will be calculated.

IM	Option to activate the calculation of the pseudofunction based on the mobility ratio, M , which changes the water/gas relative permeability end-point, $k_{rwo}(k_{rgro})$. 0 = M pseudofunction is not calculated. 1 = M pseudofunction will be calculated.
Line 9: QT TIME AFIM	
QT	The total flow rate for the field at standard conditions, stm^3/day (stb/day).
TIME	Breakthrough time or final time as determined by IQ value (line 1), days (days).
AFIM	Final time in number of breakthrough times. Refer to IQ description (line 1)
Line 10: SWC KROCW Required if IKR (Line 1) is equal to 1	
SWC	Connate water saturation.
KROCW	k_{ro} at S_{wc} .
Line 11: SOR KRWRO Required if IKR (Line 1) is equal to 1	
SOR	Residual Oil saturation.
KRWRO	k_{rw} or k_{rg} at S_{or} .
Line 12: NO NW Required if IKR (Line 1) is equal to 1	
NO	k_{ro} exponent.
NW	k_{rw} or k_{rg} exponent.
Line 13: SWC 0.0 KROCW Required if IKR (Line 1) is equal to 2	
SWC	Connate water saturation.
0.0	A zero must be entered.
KROCW	k_{ro} at S_{wc} .
Line 14: SW KRW KRO Required if IKR (Line 1) is equal to 2 Repeat this line as many times as necessary.	
SW	Value of water saturation.
KRW	Value of k_{rw} or k_{rg} for each S_w or S_g .
KRO	Value of k_{ro} for each S_w or S_g .
Line 15: 1 - SOR KRWRO 0.0 Required if IKR (Line 1) is equal to 2	
1 - SOR	1.0 minus the residual oil saturation must be entered here.
KRWRO	k_{rw} or k_{rg} at S_{or} .

The program produces the following output files:

File Name	Description
COR.OUT	Contains a copy of the input data, dimensionless variables, factors used to calculate the breakthrough time and post-breakthrough behavior, and pseudofunctions. The results for breakthrough time and post-breakthrough behavior are given in both, dimensionless and dimensional form.
CORW.DAT	Contains the dimensional results for the water-oil case as a function of time (days). There are six columns in this file: t, Q ₀ , f _w , WOR, NP and RF
CORDW.DAT	Contains the dimensionless results for the water-oil case as a function of dimensionless time (tD). There are six columns in this file: tD, Q _{0D} , f _w , WOR, NPD and RF
PERMW.DAT	Contains the water-oil relative permeabilities (when they are input as tables) as well as the values obtained by regression when calculating the exponents No and Nw. There are 5 columns in this file: Sw, Krw, Krwrg, Kro, Krorg. The subscript 'rg' refers to the values obtained by regression.
CORG.DAT	Contains the dimensional results for the gas-oil case as a function of time (days). There are six columns in this file: t, Q ₀ , f _g , GOR, NP and RF
CORDG.DAT	Contains the dimensionless results for the gas-oil case as a function of dimensionless time (tD). There are six columns in this file: tD, Q _{0D} , f _g , GOR, NPD and RF
PERMG.DAT	Contains the gas-oil relative permeabilities (when they are input as tables) as well as the values obtained by regression when calculating the exponents No and Ng. There are 5 columns in this file: Sg, Krg, Krgrg, Kro, Krorg. The subscript 'rg' refers to the values obtained by regression.
ACXTD.DAT	Contains the results for NpD as a function of tD for different wells
RFXTD.DAT	Contains the results for RF as a function of tD for different wells

► Analytical Solutions for Critical Cresting Rate in Horizontal Wells

This program calculates critical cresting rates for horizontal wells based on the seven methods listed below. It features a simple menu driven interface. The code was written by Sepehr Arbabi. Details are contained in Arbabi, S., and Fayers, F.J., "Comparative Aspects of Coning Behavior in Horizontal and Vertical Wells," Proceedings of 8th European Symposium on Improved Oil Recovery, Vienna, Austria, May 15-17, 1995.

The available correlations are:

- Efros (1963)
- Giger (1983)
- Giger (1989) and Karcher et al. (1986)
- Joshi (1988)
- Chaperon (1986)
- Guo and Lee (1992)
- Arbabi and Fayers (1995)

The following files are included:

- HWCRT.EXE - The compiled executable. This has been compiled using Digital Visual Fortran Pro (Version 5.0).
- HWCRT.F - Source code written in Fortran.

The following input data are required:

Variable	Description
H	Height of reservoir (ft)
Xe	Transverse well spacing (ft)
XKh	Horizontal permeability (mD)
XKv	Vertical permeability (mD)
XMU	Oil Viscosity (cp)
BO	Formation volume factor of oil (RB/STB)
dRHO	Density difference (gm/cc)
XL	Horizontal well length (ft)
RW	Wellbore radius (ft)
XLh	Distance between well and fluid-fluid contact (ft)

The program will prompt the user for the required input data and display its output directly to the screen. The output can be redirected.

► License Information

◆ Introduction

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