The University of Tulsa

Petroleum Engineering Department

OPTIMIZATION OF HORIZONTAL WELL COMPLETION

Joint Industry Project

Annual Advisory Board Meeting

January 29, 1999

OPTIMIZATION OF HORIZONTAL-WELL COMPLETION
Joint Industry Project (JIP)

January 29, 1999
Tulsa

AGENDA

8:30 AM	**BREAKFAST**
9:00 AM	**WELCOME** *Mohan Kelkar, The University of Tulsa*
9:10 AM	**INTRODUCTORY REMARKS** *Erdal Ozkan, Colorado School of Mines* *Cem Sarica, Pennsylvania State University*
9:30 AM	**PROGRESS REPORTS** "Investigation of Effects of Completions Geometry on Single-Phase Liquid Flow Behavior in Horizontal Wells" *Weipeng Jiang, The University of Tulsa*
10:15 AM	**COFFEE BREAK**
10:45 AM	**PROGRESS REPORTS** "Reservoir Performance Modeling and Comprehensive Model" *Yula Tang, The University of Tulsa*
11:45 PM	**LUNCH**
1:15 PM	**POSSIBLE FUTURE STUDIES** *Erdal Ozkan, Colorado School of Mines* *Cem Sarica, Pennsylvania State University*
2:15 PM	**BUSINESS REPORT** *Mohan Kelkar, The University of Tulsa*
2:30 PM	**COFFEE BREAK**
3:00 PM	**OPEN DISCUSSION**
3:30 PM	**FACILITY TOUR**
4:30 PM	**ADJOURN**

EXECUTIVE SUMMARY

The objectives of this JIP are to provide completion guidelines for horizontal wells and to develop software to be used in the design of optimum well completions. Completion optimization will provide members of the JIP with a low or no cost means of increasing the economic benefit expected from horizontal wells. Current members of the JIP are Amoco Production Company, Department of Energy (DOE), Mineral Management Services (MMS), Phillips Petroleum Company, and Unocal/Sprit 76. This JIP is a collaborative effort of reservoir and production disciplines of petroleum engineering spearheaded by co-principal investigators, Mohan Kelkar of the University of Tulsa, Erdal Ozkan of Colorado School of Mines and Cem Sarica of the Pennsylvania State University.

In a horizontal well, depending upon the completion method, fluid may enter the wellbore at various locations along the well length. The pressure distribution in a horizontal well can influence the well completion and well profile design, as well as having an impact on the production behavior of the well. Therefore, both the pressure-drop versus flow behavior along the well and the relationship between the pressure-drop along the well and the influx from the reservoir need to be understood.

The JIP has successfully completed the first year. During the last year, significant progress has been accomplished. Modifications to an existing TUFFP experimental facility have been completed. Ten new test sections have been designed and manufactured. The data acquisition and the analysis of the data for the two of the test sections have already been completed and the data acquisition for the third test section will soon start. The data analysis indicates that phasing of slots in slotted liners has significant effect on the wellbore flow and thus the friction factors. The influx/main flow rate ratio also appears to be significantly influenced by the phasing of the slots. The data acquisition analysis of the remaining test sections will be completed by May, 1999 and new friction factor correlations will be developed to predict the effects of opening density and phasing on wellbore hydraulics. The final evaluation of the experimental results will be available by August, 1999.

On the reservoir engineering studies part, we have gathered the relevant information available in the literature and become acquainted with the mathematical theory required to build the analytical reservoir model. As of this meeting, we have developed the two fundamental analytical reservoir models needed for this project: These models predict the pressure drop

because of flow toward perforated or slotted-liner completed horizontal wells. Presently, we are working on the development of asymptotic approximations and simplifications of the rigorous model. By April, 1999, we are expecting to complete the analytical modeling and continue with the development of the computational algorithms. At that time, an early form of the completion pseudoskin expression will be available. The last phase of our study will involve the coupling of the wellbore and reservoir flow models and developing the completion optimization software. We are expecting to finish this phase by September, 1999. The remaining time of the project will be devoted to the analysis of various completion scenarios and development of completion optimization guidelines.

This JIP will be completed at the end of 1999. Although significant progress will have been made, there will be many significant aspects of horizontal well completions yet to be investigated. Some of the examples are the pre-packed screens, damage caused by perforating horizontal wells, single phase flow of gases, multiphase flow of oil, gas, water, and sand through horizontal well completions, and completion optimization of slanted wells. We are well positioned and have the momentum to continue with further horizontal well completion studies even after the completion of this JIP. We are currently enthusiastically working on formulating the next project.

Optimization of Horizontal-Well Completion

Introductory Remarks

Erdal Ozkan, *Colorado School of Mines*
Cem Sarica, *The Pennsylvania State University*
Mohan Kelkar, *The University of Tulsa*

optimization of horizontal-well completion

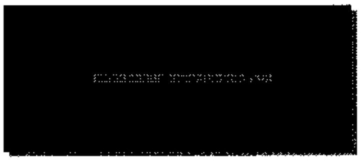
introduction

objectives of the JIP:

1. provide guidelines for optimization of horizontal well completions
2. develop user friendly completion optimization software
3. obtain expressions to incorporate completion effects into reservoir simulations

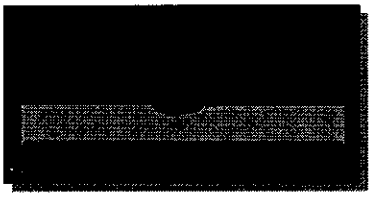
completion optimization

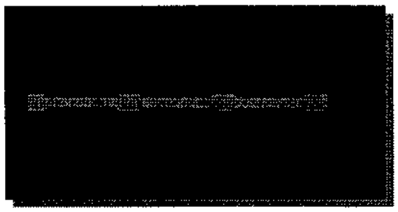
No Pressure Drop in Wellbore



Pressure Drop in Wellbore

Convergence of flow around perforations or slots



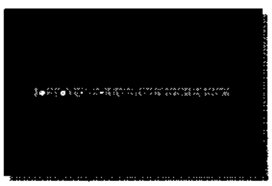


completion optimization

ACTUAL

improve reservoir performance

improve wellbore performance



IDEAL

optimization of horizontal-well completion

completion optimization

- **develop wellbore and reservoir models**
- **couple wellbore and reservoir**

wellbore model: mostly experimental

develop apparent friction factor correlations that take into account the shape, distribution, and inflow rate of openings on well surface

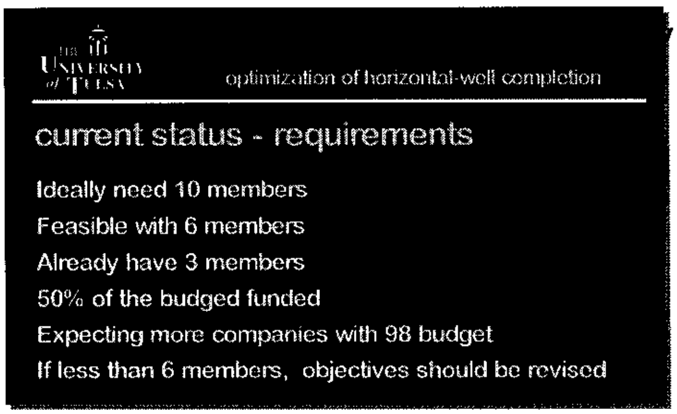
reservoir model: analytical

develop a model to account for convergence of flow towards wellbore openings

optimization of horizontal-well completion

introduction

The JIP started on Jan. 23, 1998



optimization of horizontal-well completion

introduction

Today, on Jan. 29, 1999

The members of the JIP are:

- Amoco Production Company
- Department of Energy
- Mineral Management Services
- Phillips Petroleum Company
- Unocal/Spirit 76

The JIP is successfully proceeding toward its original objectives set in the kick-off meeting of Jan 23, 1998

optimization of horizontal-well completion

introduction

The JIP started at the University of Tulsa in Jan. 98

In Aug. 98, transformed into a collaborative effort of

- The University of Tulsa
- Colorado School of Mines
- The Pennsylvania State University

optimization of horizontal-well completion

introduction

The Project team:

- Mohan Kelkar
- Erdal Ozkan
- Cem Sarica
- Yula Tang
- Weipeng Jiang
- Virginia Bentley

optimization of horizontal-well completion

current status

The JIP has successfully completed the first year

Significant progress has been accomplished in

Experimental study of wellbore flow

J. Weipeng & C. Sarica

Analytical study to model reservoir flow

Y. Tang & E. Ozkan

optimization of horizontal-well completion

summary - *flow in the wellbore*

- **Modifications to an existing TUFFP experimental facility have been completed**
- **Ten new test sections have been designed and manufactured**
- **Data acquisition and the analysis of the data for two test sections have been completed**
- **Data acquisition study for the third test section is soon to start**

optimization of horizontal-well completion

summary - *flow in the wellbore*

Results indicate that

- **Phasing of slots has significant effect on wellbore flow and friction factors**
- **Influx/main flow rate ratio is affected by the phasing of the slots**

optimization of horizontal-well completion

summary - *flow in the wellbore*

Timetable

- **Data acquisitions and analyses of the remaining test sections** ***May 1999***
- **Development of the new friction factor correlations** ***April 1999***
- **Final evaluation of the experimental results** ***August 1999***

optimization of horizontal-well completion

summary - *flow in the reservoir*

- **Gathered relevant information in the literature**
- **Developed the mathematical background**
- **Derived the analytical solutions for perforated and slotted liner completed horizontal wells**

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summary - *flow in the reservoir*

Analytical solutions

- **General transient pressure solutions to predict pressure drop**
- **Long-time asymptotic approximations and simplifications are being derived**
- **Alternate computational forms are being considered**

optimization of horizontal-well completion

summary - *flow in the reservoir*

Timetable

- **Completion of modeling and computational algorithm** — ***April 1999***
- **Development of the early form of completion pseudoskin** — ***April 1999***
- **Coupling of wellbore and reservoir models** — ***September 1999***
- **Development of the completion optimization software** — ***September 1999***
- **Evaluation of completion scenarios and development of guidelines** — ***September 1999***

final remarks

- **This JIP will be completed at the end of 1999 with significant results**
- **There will be many significant aspects of horizontal well completion yet to be investigated**

  Examples :
  - *pre-packed screens*
  - *perforation damage*
  - *single-phase gas flow*
  - *multi-phase flow*
  - *inclined wells*
- **Time to plan ahead!**

An Investigation of the Effects of Completions Geometry on Single-Phase Liquid Flow Behaviors in Horizontal Wells

Weipeng Jiang

Projected Completion Dates

Data Acquisition Program	Completed
Experimental Instrument Calibration	Completed
Test Section Design	Completed
Data Acquisition	May, 1999
Data Analysis and Modeling	May, 1999
Final Report	August,1999

Objective

The overall objective of the Joint Industry Project is to develop guidelines as to the optimization of well performance by controlling the fluid influx along the well length. The JIP goals include modeling of flow around perforations and slots on the surface of horizontal well and developing correlations to integrate the effects of fluid ingress through small openings on the surface of the well into the standard horizontal pipe flow equations.

The objective of this project is to experimentally investigate the flow behavior in perforated horizontal wells with multiple perforations and horizontal wells completed with slotted liners. An experimental work is being conducted to investigate the effects of the different completion geometries, densities and phasings upon the flow behavior in the horizontal well. Based on the experimental study, a wellbore flow model will be developed which may be used in any completion scenarios.

Experimental Program

Test Facility: An existing small scale Tulsa University Fluid Flow Projects (TUFFP) test facility (Fig.1) is used to acquire data for different horizontal well completion geometries. The test facility is composed of three parts: a flow loop, test sections (Fig. 2) and an instrumentation console. The flow loop consists of the liquid handling system (water tank, and screw and centrifugal pumps) and metering and flow control sections (turbine meters, temperature transducers, a pressure transducer and control valves). The test section consists of a perforated or slotted test pipe, 50 layers of cloth to ensure uniform influx from the openings, a 6-in. diameter casing housing and instruments to measure the pressures and differential pressures. Water is used as the testing fluid.

Tests: Ten new test sections were designed in order to investigate the effects of slot/perforation density and phasing. Each test section is made up of a 10-ft long, 1 in. diameter horizontal pipe with a 4-ft long test section. Experiments are being conducted under steady state flow conditions with

Reynolds number ranging between 5,000 and 60,000.

The following parameters are considered:

- Perforation density and phasing.
- Slot density and distribution.

Table 1 and Table 2 list the different combination of the above parameters for perforated pipes and slotted liners, respectively. In total, 17 different combinations will be available for the analysis of the effects of the completion geometry on the horizontal well behavior. 7 of the 17 combinations, which are denoted by "X" in Table 1 and Table 2, have already been investigated by Yuan (1997). Remaining 10 combinations, which are denoted by "•" in tables, are currently being investigated.

Progress

Since the last progress report, three new test sections have been constructed. A total number of 186 tests have been conducted using the two of the test sections. Processing of the first test section data is complete and a preliminary analysis is given in this report. The processing of the second test section data is currently underway and the results will be presented at the Advisory Board meeting. Remaining test sections are currently being manufactured. The data acquisition is expected to be completed by the end of May 1999.

Following is a preliminary analysis of the data acquired from the first test section (18 slots with a phasing of 90^0). Figure 3 presents all of the data plotted as f_T vs N_{Re}. As it is seen from the figure, when the influx/main flow ratio increases the friction factor also increases. The relationship between the friction factor and the Reynolds number may have different characteristics than those of regular horizontal pipes, nevertheless, in both cases the friction factors exhibit similar behavior at high Reynolds numbers.

In Fig. 4, Fig. 5 and Fig. 6, the f vs. N_{Re} curves are plotted for the influx/main flow ratios of 1/50, 1/100 and 1/200. The most notable observation after comparing these three plots is the significant effect of the phasing on the flow behavior. In general, the friction factor decreases as the phasing changes from 360° to 90° for constant influx/main flow ratios and slot densities at a given Reynolds number. Figures 4-6 also reveals that as the phasing is changed from 360° to 90° the decrease in the friction factor does not exhibit the same behavior for all influx/main flow ratios. For the influx/main flow rate ratio of 1/50, f_T vs N_{Re} curves of 360°, 180°, and 90° phasing cases are separated from each other with almost equal distances. The behavior is quite different when the influx/main flow ratio is either 1/100 or 1/200. In both cases, the friction factor changes from 180^0 phasing to 90° phasing are significant compared to the changes from 360° to 180°.

Future Tasks:

Our future tasks include the following:

- Construction, data acquisition and data analysis of the remaining test sections.
- Modeling and final report.

References:

Yuan, H: "Investigation of Single Phase Liquid Flow Behavior in Horizontal Wells," Ph.D. Dissertation, The University of Tulsa, 1997.

Table 1: Test section matrix for perforated pipes (perforation diameter: 1/8 inches).

Perforation Density	Phasing		
	360	180	90
5 shots/ft	X	•	•
10 shots/ft	•	X	•
20 shots/ft	•	•	X

Table 2: Test section matrix for slotted liners (slots 2 in. long and 1/16 in. wide)

Slot Liners Density	Slot liners Phasing		
	360	180	90
18 slots/4 feet	X	X	•
12 slots/4 feet		•	•
36 slots/4 feet		•	X

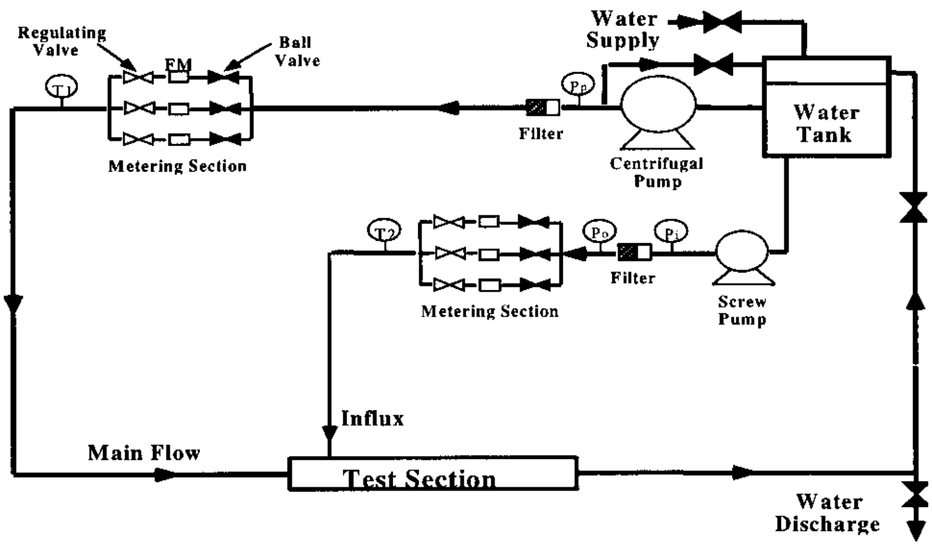

Fig.1: Schematic Description of the Test Facility

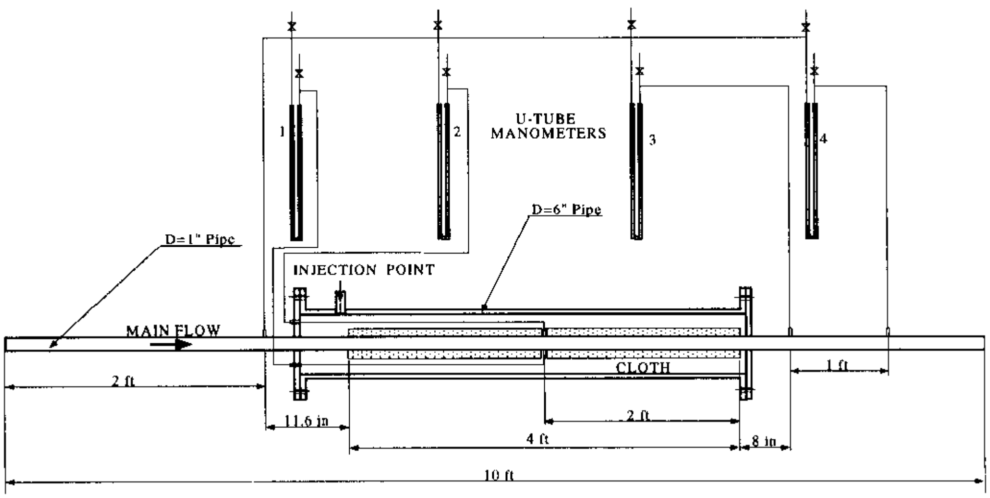

Fig.2: Schematic Description of the Test Section

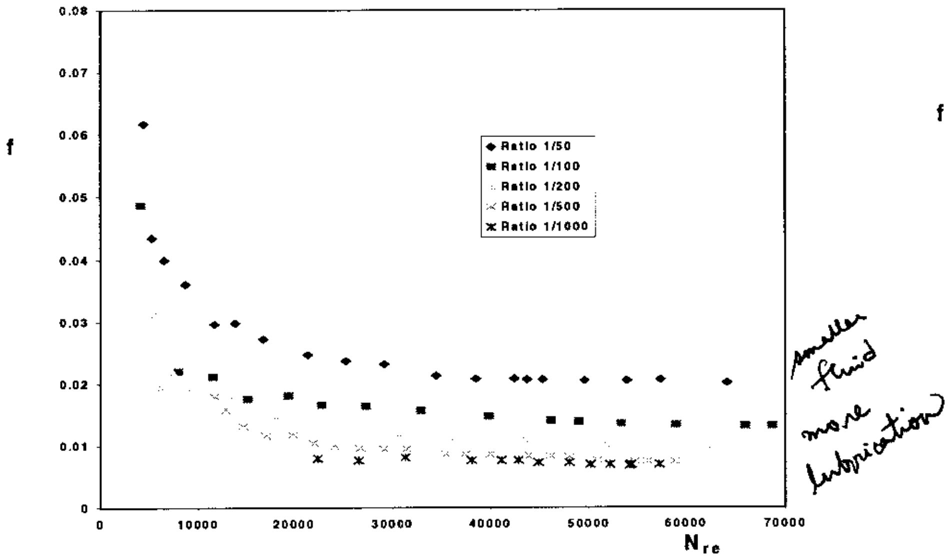

Fig.3: Data of Test Section No. 1

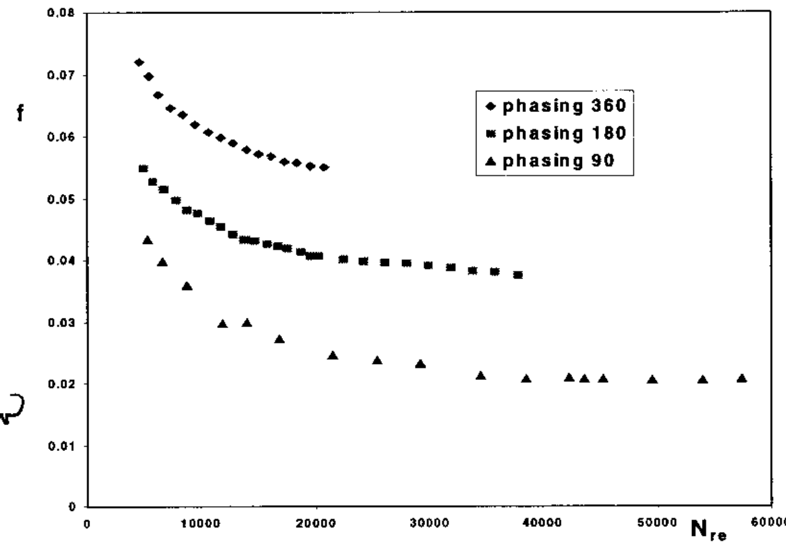

Fig.4: f vs. Nre (ratio=1/50, density=18 slots/4 ft)

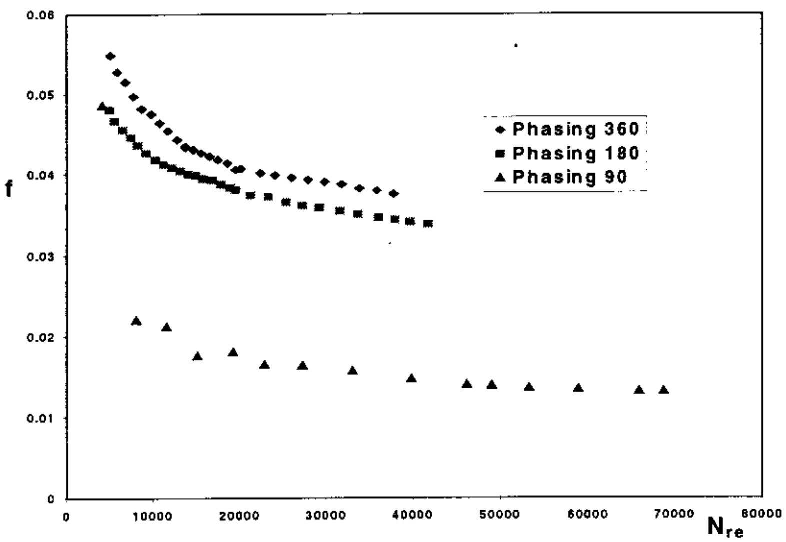

Fig.5: f vs. Nre (ratio=1/100, density=18 slots/4 ft)

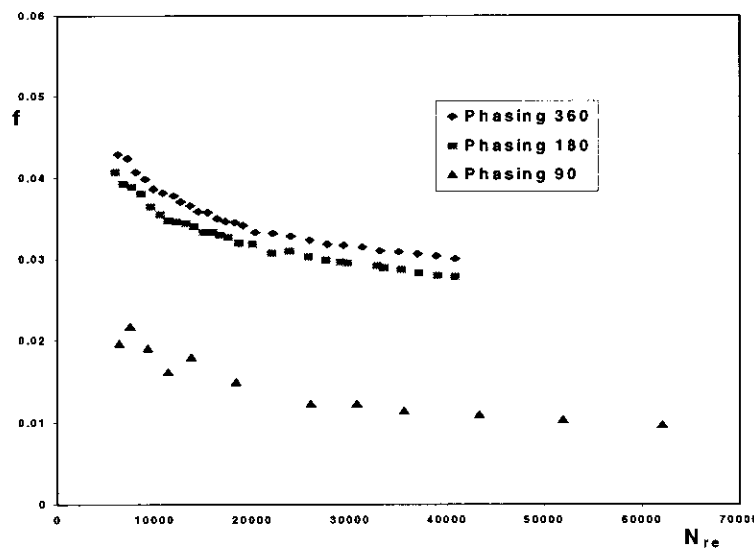

Fig.6: f vs. Nre (ratio=1/200, density=18 slots/4 ft)

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Optimization of Horizontal Well Completion

Investigation of the Effects of Completion Geometry on Single Phase Liquid Flow Behaviors in Horizontal Wells

Weipeng Jiang
The University of Tulsa

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Topics

- Objectives
- Significance of the Project
- Background
- Model Development
- Experimental Program
- Test Matrices
- Preliminary Results and Discussions
- Some Conclusions
- Future Tasks and Completion Dates

Objectives

- Experimentally investigate the completion geometry effects upon the single phase liquid flow behaviors in horizontal wells with perforations and horizontal wells completed with slot liners (10 test sections will be investigated).
- Develop a general friction factor expression.

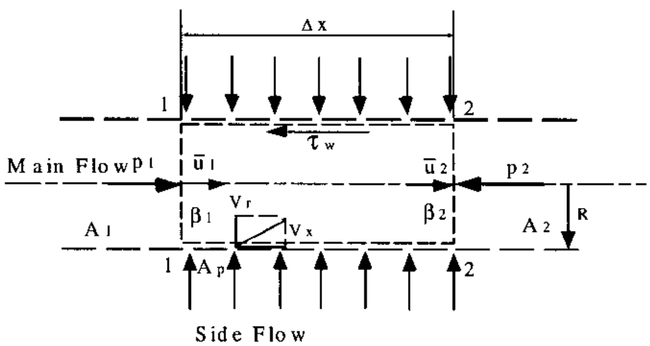
Significance

- Effects of pressure drop along horizontal wells
  - Production behavior
  - Wellbore design and completion
- Difference between a regular pipe and horizontal wellbore
  - Roughness
  - Interaction between influxes and main flow

Background

- Regular pipe friction factors
  - Dikken (1989)
  - Novy (1992)
- Fluid injection studies
  - Kloster (1990)
  - Asheim et al. (1992)
  - Su & Gudmundsson (1993,1994)
  - Yuan (1994)
  - Ouyang et al. (1996)
  - Yuan et al. (1996,1997)

Model Development



The control volume

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Model Development

- Momentum equation in axial direction

$$p_1 A - p_2 A - \tau_w \cdot \pi d \cdot \Delta x = \beta_2 \rho \overline{u_2}^2 - \beta_1 \rho \overline{u_1}^2 - \rho V_x V_r \beta_p A_p n$$

- Momentum correction ractor

$$\beta = \frac{1}{AV^2} \int_A u^2 dA$$

- Continuity equation

$$\overline{u_1} A + n V_p A_p = \overline{u_2} A$$

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Model Development

- Apparent friction factor

$$f_T = -\left(\frac{p_2 - p_1}{\Delta x}\right) / \frac{\rho \overline{u}^2}{2d}$$

- Wall friction factor

$$f_w = (8 \tau_w) / (\rho \overline{u}^2)$$

- Perforation density $\varphi = n / \Delta x$
- Definition $\phi = V_x / \overline{u}$

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Model Development

- Apparent friction factor expression

$$f_T = f_w + 2d \cdot (\frac{\beta_2 - \beta_1}{\Delta x}) + 2d\varphi \cdot \frac{q_{in}}{Q} \cdot \left[\beta_1 + \beta_2 - \phi\beta_P + \left(\frac{n}{4} \cdot (\beta_1 - \beta_2) \cdot \frac{q_{in}}{Q} \right) \right]$$

Let

$$C_n = \left[\beta_1 + \beta_2 - \phi\beta_p + \left(\frac{n}{4} \cdot (\beta_1 - \beta_2) \cdot \frac{q_{in}}{Q} \right) \right]$$

and neglect the second term,

$$f_T = a N_{Re}^{\ b} + C_n \cdot 2d\varphi \cdot \frac{q_{in}}{Q}$$

T

Model Development

- CFD simulation results by Yuan

Correlation to predict flow developing length

$$L_d/d = a \log (V_{in}/V) + b$$

where,

$a = 3.790\times10^{-4}(N_{Re}/1000)^2 + 5.213\times10^{-3}(N_{Re}/1000)^2 + 0.753$

$b = 8.173\times10^{-4}(N_{Re}/1000)^2 + 2.593\times10^{-3}(N_{Re}/1000)^2 + 5.139$

how does it compare to slot spacing?

$a\uparrow$, $Re\uparrow$, $u\uparrow \Rightarrow \frac{L_d}{d}\uparrow$

$b\uparrow$, $Re\uparrow$, $u\uparrow$

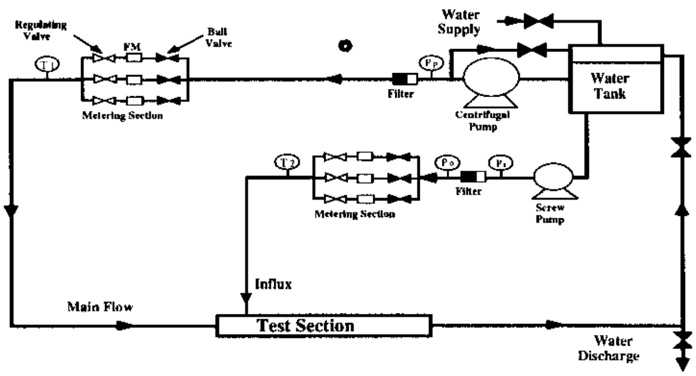
smaller V_{in} smaller $\frac{L_d}{d}\downarrow$

Model Development

Remarks about the CFD simulation

- Flow developing length is not constant.
- It increases with V_{in}/V and N_{re}.

Experimental Program



Schematic description of the test facility

THE UNIVERSITY of TULSA — Experimental Program

- Ten test sections
  - Multiple slot cases (4)
  - Multiple perforation cases (6)
- Parameters to be investigated
  - Completion shape (perforation/slot liner)
  - Perforations/slots density
  - Perforation/slots phasing

THE UNIVERSITY of TULSA — Test Matrix for Slotted Cases

Slot Liners		Phasing	
Density	360	180	90
18 slots/4ft	*	*	•
12 slots/4ft		•	•
24 slots/4ft		•	*

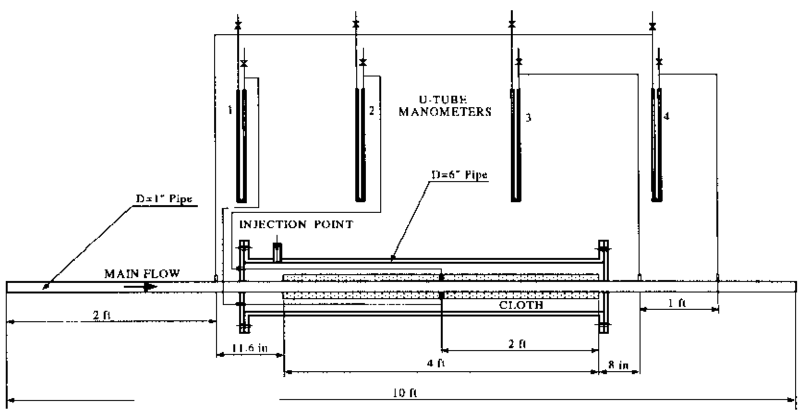
* already investigated
• to be investigated

Test Matrix for Perforated Pipes

Perforation Density	Phasing 360	180	90
5 shots/ft	*	•	•
10 shots/ft	•	*	•
20 shots/ft	•	*	•

* already investigated
• to be investigated

Experimental Program



Schematics of the test section and manometer connections

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Experimental Program

- 500 ~ 600 tests for the multiple perforations and slots cases
- Injection to main flow rate ratio of 1/50, 1/100
- 1/200, 1/500, 1/1000 and in some cases 1/2000
- Reynolds number: 5000 ~ 70000

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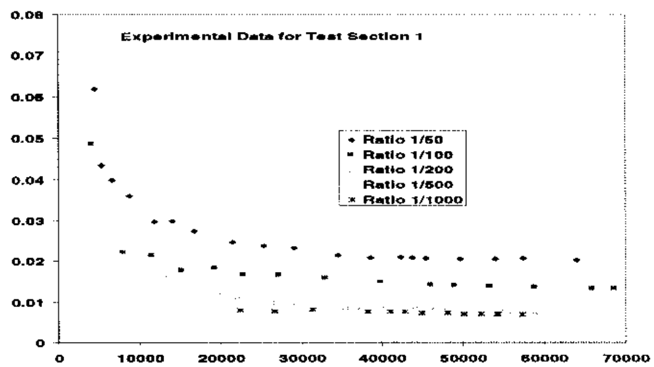
Results and Discussions

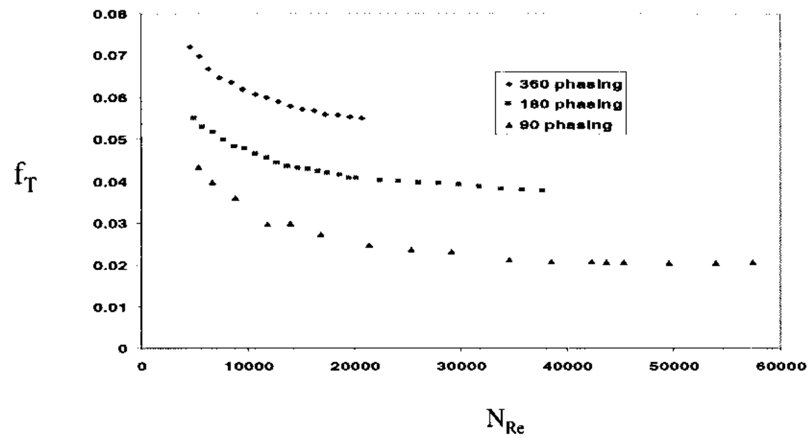
f_T



N_{Re}

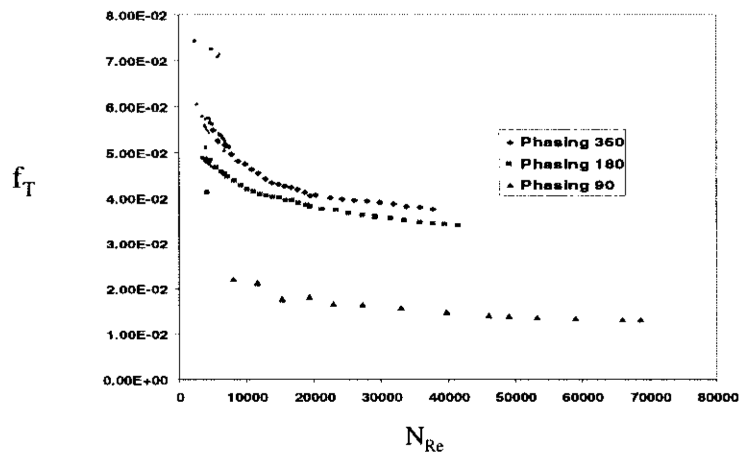
Experimental data for test section 1(18 slots with 90° phasing)

Results and Discussions



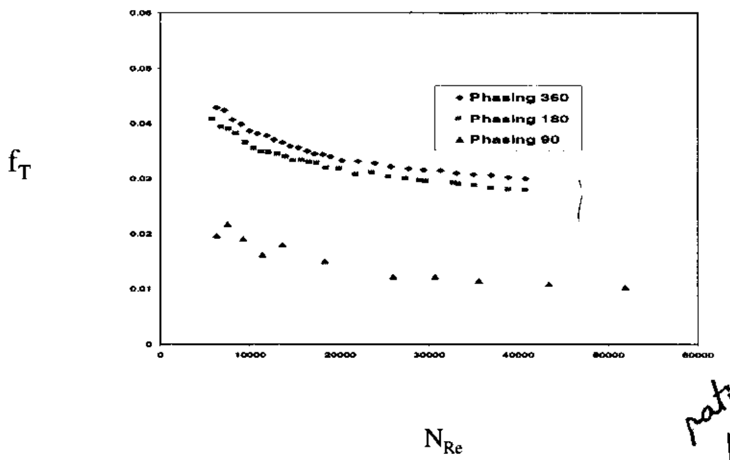
f_T vs. N_{Re} for different phasings (φ = 18 slots/4 ft and ϕ = 1/50)

Results and Discussions



f_T vs. N_{Re} for different phasings (φ = 18 slots/4 ft and ϕ = 1/100)

Results and Discussions



f_T vs. N_{Re} for different phasings (φ = 18 slots/4 ft and ϕ = 1/200)

Results and Discussions

- Friction factors increase with the increase of influx/main velocity ratio. However, the increase of friction factor is negligible at high influx/main velocity ratio.
- Slot distribution affects friction factors; the friction factor decreases with decreasing phasing (at fixed completion density).

Results and Discussions

- The friction factor difference between 180° phasing and 90° phasing is more significant at higher influx/main velocity ratio.

Future Tasks

- Data acquisition for the remaining test sections.
- Analyze experimental data for both the perforated pipes and the slotted pipes.
- Develop a general friction factor expression.

Projected Completion Dates

◆ Data Acquisition Program	Completed
◆ Experimental Instrument Calibration	Completed
◆ Test Section Design and Construction	Completed
◆ Data Acquisition	May, 1999
◆ Data Analysis and Modeling	August, 1999
◆ Final Report	August, 1999

Optimization of Horizontal Well Completion

Reservoir Performance Modeling

and Comprehensive Model

Yula Tang

Projected Completion Dates

Literature Survey.. Completed
Related Theory Study.. Completed
Derivation of Reservoir Flow Equations
for Horizontal Well Completion... In Progress
Combination of Wellbore and Reservoir Performance.......................... August 1999
Final Report.. December 1999

Objective

The productivity of a horizontal well depends on the reservoir flow characteristics, while the reservoir flow characteristics are functions of reservoir parameters and wellbore geometry as well as the hydraulics of the wellbore. To obtain a comprehensive horizontal well performance model, the influence of well completion on both wellbore and reservoir flow performances should be taken into account. Therefore, the objectives of this study are as follows.

1. Develop a reservoir performance model that considers the effect of flow convergence toward slots and perforations on the surface of the well.
2. Couple wellbore and reservoir flow models to build a comprehensive model that considers the interaction between the horizontal well and the reservoir through small openings on the surface of the well.
3. Develop efficient algorithms to numerically evaluate the complex analytical expressions.
4. Develop a user-friendly software for horizontal well completion design.
5. Investigate various completion scenarios to develop completion guidelines as to the optimization of horizontal-well performance.

Literature Survey

In 1990, Dikken[1] emphasized the importance of wellbore pressure losses for openhole completed horizontal wells for the first time. He, however, used the assumption of uniform specific productivity to couple the wellbore and reservoir flows. This assumption, in fact, neglects the influence of wellbore hydraulics on the reservoir performance. Therefore, it cannot predict the correct flux and pressure profiles along the well length.

In 1993 and 1995, Ozkan and Sarica et al.[2,3] used the physical coupling conditions (pressure and flux continuity at the well surface) to obtain a solution to compute the performances of openhole completed horizontal wells.

In 1994, Yildiz & Ozkan[4] studied the performance of selectively completed horizontal wells (i.e., only some segments of the well are open to flow with the arbitrary distribution of the open segments and skin). They derived a general Laplace space solution describing the transient pressure responses. The flow rate distribution was obtained as a result of a matrix inversion. They also derived the asymptotic solutions for different time periods. In their model, the wellbore pressure losses were neglected (the assumption of an infinite-conductivity wellbore).

In 1990, Ahmed, Horne, and Brigham[5] presented an analytical solution for flow into a vertical well via perforations using Green's functions. This solution contains products and series of Bessel functions and their derivatives. An array of eigenvalues is computed from an implicit equation (they failed to obtain an explicit equation for the eigenvalues) and then they are used in the computation of the solution. Although they visualized perforations as surface sources, they treated them as line sources. They also used a coordinate transformation to simplify the integration over the complex perforation geometry. The coordinate transformation used in their work has potential applications to the integrations we will encounter in our project.

Spivak and Horne[6] studied the transient pressure responses due to production from a slotted liner completed vertical well by using the source function method in 1982. They modeled the slots as line sources of finite length. However, their simplifying assumptions are not applicable for general slot distributions.

Hazenberg and Panu[7] investigated flow into perforated drain tubes. The problem considered in their work bears similarities to the horizontal well problem and has potential of yielding a simplified solution.

In 1998, Yildiz and Ozkan[8] presented a 3-D analytical model for the analysis of transient flow toward perforated vertical wells. In their model, the perforations are presented as line sources. They used the Laplace transform for the time variable and the Fourier transform for the space variables. A pseudo-skin expression was derived from the long-time solution to estimate the inflow performance. The treatment of perforations in this paper gives us a good reference to solve the perforated horizontal well problem.

In 1991, Landman[9] studied the optimization of perforation distribution for horizontal wells. His model couples Darcy's equation into each perforation in an infinite reservoir and uses 1-D momentum equation for pipe flow to model wellbore hydraulics. Thus the perforated well is treated like a pipe manifold with T-junctions representing the perforations along the wellbore. Although this paper provides useful information about the effect of perforation distribution on horizontal well performance, the reservoir flow model used in this study, is approximate and thus, the results should be regarded accordingly.

In 1991, Perez and Kelkar[10] studied two-phase pressure drop across perforations on a vertical well. They assumed steady flow with constant pressure at the outer edge of the crushed zone and used a horizontal-micro-well model. They combined non-Darcy flow with the mass-conservation of oil and gas, and used relative permeability curves to solve the saturation and pressure drop. In 1998, Ates and Kelkar[11] presented two-phase flow equations for gravel packed completions and an alternative solution for pressure drop across perforations. This method is easy to use for the calculation of additional pressures drop across the perforations and gravel packs. These two studies should help us if, in the future, we extend our project into two-phase flow conditions.

In 1996, Gonzalez and Camacho[12] developed a model to investigate the performance of a horizontal well under two-phase flow conditions. Their model essentially follows the one presented by Landman[9]. They used the producing gas-oil ratio to relate pressure and saturation at each perforation. They also used Xiao's[13] mechanistic model to determine the flow pattern and Su and Gudmundsson's[14] modified friction factor.

Progress

Since last October, I have made the following progress.

1. Literature Survey

I have obtained further understanding of the theories and methods used in the literature. Some of these studies might be important references for our work.

2. Background

By taking the advanced well testing course, I became more familiar with the well test analysis theory, the method of sources and sinks and its application to complex reservoir boundaries, numerical methods, and the use of the inverse Laplace transform procedure. This semester, I am also taking the "computer application to petroleum engineering" course, which will make me familiar with C++ and interface building. These should be very beneficial for me to develop the user-friendly software for our project.

3. Coupling Precedure for the Wellbore and Reservoir and the Reservoir Pressure Response

I have started to study the procedure to couple the wellbore with the reservoir and the reservoir pressure responses for horizontal wells.

(1) The Coupling Procedure

Combining the reservoir flow equation with the wellbore flow equation, we can solve the flux distribution and wellbore pressure. The reservoir pressure drop equation for perforated or slotted-liner completed horizontal wells will be different from that for open-hole completed horizontal wells because of the convergence of flow into small openings instead of the entire surface of the well. The wellbore flow equation also needs to be modified to incorporate the friction factor expressions derived for specific completion configurations.

(2) Pressure Response for Slotted-Liner Completed/ Perforated Horizontal Wells

For slotted-liner completed horizontal wells, each slot can be treated as a micro-horizontal line source and the pressure drop can be obtained by using the method of sources and sinks and Newman's product. The total pressure drop is obtained by the superposition of the pressure drops for individual slots.

For perforated horizontal wells, perforations are represented by partially penetrating inclined line source wells. We derive the inclined line-source well solution in the Laplace domain. We start with the point source solution and integrate it along the axis of the perforation. Again, the total pressure drop is obtained from the individual perforation solutions by superposition.

(3) Pseudo-skin Factor

We have considered the transient flow problems so far. Our idea in doing this is as follows: Because the convergence of flow toward the wellbore openings will take place in the near vicinity of the well, the outer portions of the reservoir including the boundaries will not be affected by the existence of the openings. Therefore, if we derive the pseudo-skin expressions by comparing the transient pressure solutions of the open-hole completed and slotted-liner completed (or perforated) horizontal wells, then the same pseudo-skin factors can be incorporated into the bounded reservoir solutions for open-hole completed horizontal wells. This would represent the solution for a slotted-liner completed (or perforated) horizontal well in a bounded reservoir. Thus, what remains to be done right now is to derive the long-time (pseudo-radial flow) approximations of the transient flow solutions we have and define the pseudo-skin factors. This will not yield ~~look~~ simple expressions because the~~y~~ pseudo-skin factors should be functions of flux and perforation/slot distributions. To obtain simplified pseudo-skin expressions, we will make reasonable assumptions about the flux and perforation/slot distributions.

Future Work

In the near future, I will perform the following study.

1. Derive the completion pseudo-skin expressions and incorporate them into various bounded reservoir solutions available for openhole completed horizontal wells. Obtain simplified pseudo-skin expression under certain assumptions
2. Couple the reservoir and wellbore flow models and develop the computational algorithm.
3. Modify the existing Fortran code (that is for open-hole completed horizontal wells) for the perforated/slotted-liner completed horizontal wells using C++.
4. Investigate various completion scenarios to develop completion guidelines.

References

1. Dikken, B. J.: "Pressure Drop in Horizontal Wells and Its Effect on Production Performance," *JPT* (Nov. 1990) 1426-1433.
2. Ozkan, E., Sarica, C., Haciislamoglu, M., and Raghavan, R.: "Effect of Conductivity on Horizontal Well Pressure Behavoir," *SPE Advanced Technology Series*, Vol. 3, No. 1 (March 1995) 85-94.
3. Ozkan, E., Sarica, C., Haciislamoglu, M., and Raghavan, R.: "The Influence of Pressure Drop along the Wellbore on Horizontal Well Productivity," paper SPE 25502 presented at the SPE Production Operation Symposium, Oklahoma City, OK, March 21-23, 1993.
4. Yildiz, T., Ozkan, E.: "Transient Pressure Behavior of Selectively Completed Horizontal Wells," paper SPE 28388 presented at the SPE 69th Annual Technical Conference and Exhibition held in New Orleans, LA, U.S.A., Sept. 25-28, 1994.
5. Ahmed, G., Horne, R. N., and Brigham, W.E.: "Theoretical Development of Flow into a Well through Perforations," DOE/BC/14126-25 (1990).
6. Spivak, D., and Horne, R. N.: "Unsteady-State Pressure Response due to Production with a Slotted Liner Completion," paper SPE 10785 presented at the 1982 SPE California Regional Meeting, San Francisco, CA, March 24-26, 1982.
7. Hazenberg, G., and Panu, U. S.: "Theoretical Analysis of Flow Rate into Perforated Drain Tubes," *Water Resources Research*, Vol.27, No.7, 1411-1418 (July 1991).
8. Yildiz, T., Ozkan, E.: "Pressure-Transient Analysis for Perforated Wells," paper SPE 49138 presented at the 1998 SPE Annual Technical Conference and Exhibition held in New Orleans, LA, Sept. 27-30, 1998.

9. Landman, M. J., Goldthorpe, W. H.: "Optimization of Perforation Distribution for Horizontal Wells," paper SPE 23005 presented at the SPE Asia-Pacific Conference held in Perth, Western Australia, Nov. 4-7, 1991.
10. Perez, G., Kelkar, B. G.: "A New Method to Predict Two-Phase Pressure Drop Across Perforations," SPE Production Engineering (Feb. 1991) 93-101.
11. Ates, H., Kelkar, B. G.: "Two-Phase Pressure Drop Predictions Across Gravel Pack," SPE Production & Facilities (May 1998) 104-108.
12. Gonzalez, J. A., Camacho, R.: "A Horizontal Well Model Considering Multiphase Flow and The Presence of Perforations," paper SPE 36073 presented at the Fourth Latin American and Caribbean Petroleum Engineering Conference held in Port of Spain, Trinidad & Tobago, April 23-26, 1996.
13. Xiao, J., Shoham, O.: "Evaluation of Interfacial Friction Factor Prediction Methods for Gas/Liquid Stratified Flow", paper SPE 22765 presented at the 66th Annual Technical Conference and Exhibition held in Dallas, TX, October 6-9 (1991).
14. Su, Z. and Gudmundsson, J. S.: "Friction Factor of Perforation Roughness in Pipes," paper SPE 26521 presented at the 68th Annual Technical Conference and Exhibition held in Houston, TX, October 3-6 (1993).

Optimization of Horizontal Well Completion

Reservoir Performance Modeling and Comprehensive Model

Yula Tang
The University of Tulsa

Contents

Objectives

- Model the reservoir flow to slots/perfs on wellbore (convergence & pseudo-skin).
- Couple reservoir model with wellbore hydraulic model (comprehensive model).
- Develop guidelines to optimize horizontal well completion performance.

Literature Survey

Methodology for Horizontal Well Performance

- Dikken's method to couple reservoir to openhole well (1990).
- Ozkan *et al.'s* physical coupling procedure for openhole well (1993, 1995).
- Yildiz *et al.'s* approach on selectively completed horizontal wells (1994).

Literature Survey

Flow Convergence to Perforations / Slots

- Ahmed *et al.'s* analytical solution for steady state flow to perforated vertical wells (1990).
- Spivak *et al.'s* study on slotted liner, vertical well (1982).
- Hazenberg *et al.'s* study on perforated drain tubes (1991).

Literature Survey

Pseudo-Skin Due to Perforations

- Yildiz, *et al.*, pressure transient analysis for perforated vertical wells (1998).
- Landman *et al.*'s manifold model for perforated horizontal wells (1991).

Literature Survey
Two-Phase Flow Through Perforations

- Perez, *et al.*, two-phase pressure drop across perforations (1991).
- Ates *et al.*'s two-phase pressure drop across Gravel Pack (1998).
- Gonzalez *et al.'s* study on multiphase flow through perforated horizontal wells (1996).

Background
Analytical Techniques & Methods

- The method of source and sinks, Green's functions.
- Superposition theorem, Duhamel's principle, Newman's product method.
- Laplace transform, convolution, Stehfest' inverse transform.
- The coupling method for comprehensive horizontal well performance.

Background
The Method of Source and Sinks

For 1-D flow, the pressure response due to a instantaneous withdrawing of Q(bbl) of fluid at x', and at time of τ, is

$$\Delta p_x(x,x',t,\tau) = \Delta p_s \frac{dx'}{2\sqrt{\pi\eta_x(t-\tau)}} \exp[-\frac{(x-x')}{4\eta_x(t-\tau)}]$$

where, ΔP_s is the strength of the source (psi)

$$\Delta P_s = \frac{5.615Q}{Adx'\phi C_t}$$

Background
The Method of Source and Sinks

For 3-D flow, the pressure response in an infinite media due to a continuous removal of flux q' from a sink volume (V) starting from time of τ, is

$$\Delta p(x,y,z,t) = \int_0^t \int_V \frac{5.615q'}{dx'dy'dz'\varphi C_t} \Delta p_{sx} \Delta p_{sy} \Delta p_{sz} dV d\tau$$

where, Δp_{sx}, Δp_{sy}, and Δp_{sz} are the pressure responsesalong x, y, and z axes, respectively, for unit strength sources; e.g.

$$\Delta p_x(x,x',t,\tau) = \frac{dx'}{2\sqrt{\pi\eta_x(t-\tau)}} \exp[-\frac{(x-x')^2}{4\eta_x(t-\tau)}]$$

Solutions
Coupling Procedure for Open Hole Horizontal Well

Assume:

1. **A line source well**
2. **non-uniform flux(q_h) along the line source**

The Reservoir flow equation is given by

$$\frac{kh[p_i - p_h(t,x)]}{141.2qB\mu} = \frac{1}{L_h}\int_0^t\int_0^{L_h} q_{hD}\, p_u'(t-\tau, x-x')dx'd\tau$$

p_u': derivative of dimensionless pressure drop for unit rate (obtained by the method of sources and sinks)

Solutions
Coupling Procedure for Open Hole Horizontal Well

The wellbore flow equation is given by

$$\frac{kh[p_h(t,x) - p_{wf}]}{141.2qB\mu} = \frac{4\pi}{C_{hD}L_h}\{x - \int_0^x\int_0^{x'} \frac{D\, q_{hD}dx''dx'}{L_h N_{\mathrm{Re},t} f_t}\}$$

where, $N_{Re:}$ **Reynolds Number**

$$D = N_{Re}^2 \frac{df}{dN_{Re}} + 2N_{Re}f$$

f: **Friction Factor**

Solutions

Coupling Procedure for Completed Horizontal Well

Reservoir flow equation for slotted-liner completion is

$$\frac{kh[p_i - p_h(t,x)]}{141.2qB\mu} = \int_0^t \{\sum_{i=1}^{N} \int_{x_i}^{x_i+l} \frac{\tilde{q}_i(t-\tau)}{qB} p_{u,i}'(t-\tau, x-x')dx'\}d\tau$$

Reservoir flow equation for perforating completion is

$$\frac{kh[p_i - p_h(t,x)]}{141.2qB\mu} = \int_0^t \{\sum_{i=1}^{N} \int_0^{l_p} \frac{\tilde{q}_i(t-\tau)}{qB} p_{u,i}'(t-\tau, x, \rho)d\rho\}d\tau$$

Solutions

Coupling Procedure for Completed Horizontal Well

Wellbore flow equation for an open-hole completed horizontal well:

$$\frac{kh[p_h(t,x) - p_{wf}]}{141.2qB\mu} = \frac{4\pi}{C_{hD}L_h}\{x - \int_0^x \int_0^{x'} \frac{D\, q_{hD} dx'' dx'}{L_h N_{\mathrm{Re},t} f_t}\}$$

The wellbore flow equation needs to be modified to incorporate the friction factor expressions for the specific completion configurations.

Solutions

Slotted-Liner Completed Horizontal Well

For *i*-th slot, we have

$$\Delta p_i = \int_0^t \int_{x_{wi}-0.5l_i}^{x_{wi}+0.5l_i} \left(\frac{5.615 q_i}{\varphi C_t dx' dy' dz'} \Delta p_{sx} \Delta p_{sy} \Delta p_{sz}\right) dx' d\tau$$

$$\Delta p_{sx} = \frac{dx'}{2\sqrt{\pi\eta(t-\tau)}} \exp\left[-\frac{(x-x')^2}{4\eta(t-\tau)}\right]$$

$$\Delta p_{sy} = \frac{dy'}{2\sqrt{\pi\eta(t-\tau)}} \exp\left[-\frac{(y-y')^2}{4\eta(t-\tau)}\right]$$

The same for Δp_{sy}, but Δp_{sz} is different

Solutions

Slotted-Liner Completed Well

$$\Delta p_{sz} = \frac{dz'}{2h}\left[\theta_3\left(\frac{z-z'}{2h}, \frac{\eta(t-\tau)}{h^2}\right) + \theta_3\left(\frac{z+z'}{2h}, \frac{\eta(t-\tau)}{h^2}\right)\right.$$

where, θ_3 is the third kind of theta function.

Define the following dimensionless variables

$$p_D = \frac{kh\Delta p}{141.2 q\mu}, \quad t_D = \frac{t\eta}{h^2}, \quad q_{Di} = \frac{q_i l_i}{q}$$

$$r_D = \frac{r}{h}, \quad z_D = \frac{z}{h}, \quad l_{id} = \frac{l_i}{h}$$

Solutions

Slotted-Liner Completed Horizontal Well

The Pressure drop equation for the *i-th* slot becomes

$$\Delta p_{Di} = \frac{\pi}{4 l_{iD}} \int_0^{t_D} \frac{q_{iD}(\tau)}{\sqrt{t_D - \tau}} \exp\left(-\frac{y_D - y_{iD}}{4(t_D - \tau)}\right) \cdot$$

$$\left[erf\left(\frac{x_{wiD} - x_D + 0.5 l_{iD}}{\sqrt{4(t_D - \tau)}}\right) - erf\left(\frac{x_{wiD} - x_D - 0.5 l_{iD}}{\sqrt{4(t_D - \tau)}}\right)\right] \cdot$$

$$\left[\theta_3\left(\frac{z_D - z_{iD}}{2}, t_D - \tau\right) + \theta_3\left(\frac{z_D + z_{iD}}{2}, t_D - \tau\right)\right] d\tau$$

Solutions

Slotted-Liner Completed Horizontal Well

For M slots, we have

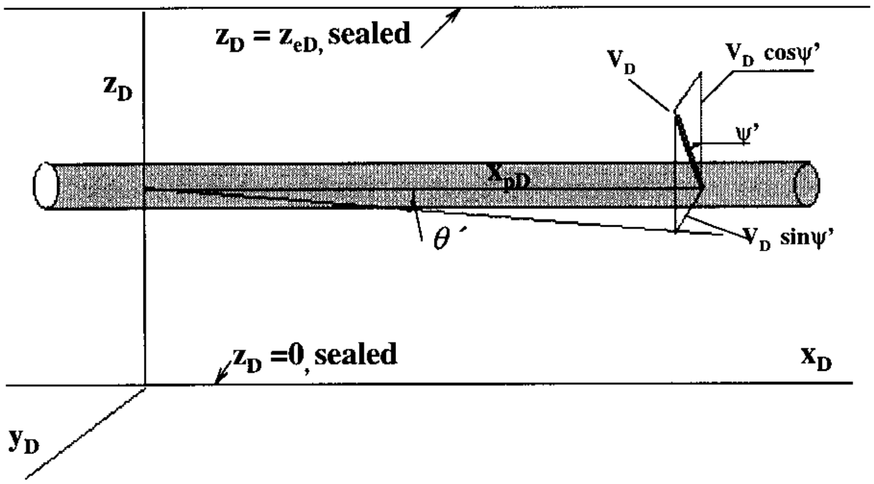
each perforation acts as a single horizontal well

$$\Delta p_{\bar{w}} = \sum_{i=1}^{M} \Delta p_{Di} \quad and \quad \sum_{i=1}^{M} q_{iD} = 1$$

superposition

By taking Laplace transform, and combining the wellbore flow equation, q_{iD} and wellbore pressure can be solved.

Solutions
Perforated Horizontal Well



Solutions
Perforated Horizontal Well

Laplace domain

The fundamental (point-source) solution is

$$\bar{\gamma}=\frac{1}{2\pi z_{ed}}\{K_0(\sqrt{u}R_D)-\sum_{k=-\infty}^{\infty}I_k(\sqrt{u}\,r_D)\frac{I_k(\sqrt{u}\,x_{PD})K'_k(\sqrt{u}\,r_{ed})}{I'_k(\sqrt{u}\,r_{ed})}\cos k(\theta-\theta')+$$

$$2\sum_{n=1}^{\infty}\cos n\pi\frac{z_D}{z_{ed}}\cos n\pi\frac{z_{wD}+V_D\cos\psi'}{z_{ed}}[K_0(\sqrt{u+\frac{n^2\pi^2}{z_{eD}^2}}\,\tilde{w})-\sum_{k=-\infty}^{\infty}I_k(\sqrt{u+\frac{n^2\pi^2}{z_{eD}^2}}\,r_D)\cdot$$

$$\frac{I_k(\sqrt{u+\frac{n^2\pi^2}{z_{eD}^2}}\,x_{PD})K'_k(\sqrt{u+\frac{n^2\pi^2}{z_{eD}^2}}\,r_{eD})}{I'_k(\sqrt{u+\frac{n^2\pi^2}{z_{eD}^2}}\,r_{eD})}\cos k(\theta-\theta')]\}$$

Solutions
Perforated Horizontal Well

where, $u = \text{Laplace variable}$,

$\theta' = \arctan(V_D \sin(\psi') / x_{PD})$,

$R_D = r_D^2 + x_{PD}^2 - 2\, r_D x_{PD} \cos(\theta - \theta')$.

Then, the pressure response for single perfloration is

$$\overline{\Delta p} = \frac{\bar{\tilde{q}}\,\mu}{k_r l_s} \int_0^{Lp} \bar{\gamma}(V_D)\,dV$$

Solutions
Perforated Horizontal Well

For N_p perforations, we have

$$\overline{\Delta p} = \frac{1}{u} \sum_{i=1}^{N_p} \frac{\bar{\tilde{q}}_{iD}}{L_{piD} \sin\psi_i'} \int_0^{L_{piD} \sin\psi_i'} \bar{\gamma}(\alpha)\,d\alpha$$

Combining the wellbore flow equation, q_{iD} and the wellbore pressure can be solved.

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Solutions

Methodology for Pseudo-Skin

- **Fact**

  Convergence toward the openings takes place only in the near vicinity of the well; far-away reservoir will not be affected.

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Solutions

Methodology for Pseudo-Skin

- **Method**
  1. **Assume an infinite reservoir.**
  2. **Obtain pseudo-skin expressions by comparing the long-time solutions for open-hole and slotted-liner completed or perforated wells.**
  3. **Add pseudo-skin to bounded reservoir solutions for open-hole horizontal wells to obtain the corresponding solutions for perforated or slotted-liner completed wells.**

Solutions

Methodology for Pseudo-Skin

- **Alternative Method**
  Derive simplified pseudo-skin expressions by making reasonable assumptions about the flux and the opening distribution

- **Long-Time Solutions**
  It is more convenient to derive the solutions in the Laplace domain to obtain long-time, asymptotic approximations.

Future Work

- Derive pseudo-skin expressions.
- Incorporate them into various bounded reservoir solutions available for open hole horizontal well.
- Obtain simplified forms under certain assumptions.
- Develop algorithms for the numerical computation of the wellbore and reservoir flow equations

change to other terminology

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Future Work

- **Obtain analytical solution by coupling reservoir model with wellbore model.**
- **Modify the existing Fortran code (that is for open hole) for the perforated/slotted-liner completions using C++.**
- **Investigate various completion scenarios to develop completion guidelines.**

previous flow regime - pseudo-skin expressions during pseudo-radial flow

Optimization of Horizontal Well Completion

JIP

Future Studies

Cem Sarica* & Erdal Ozkan**

***The Pennsylvania State University**

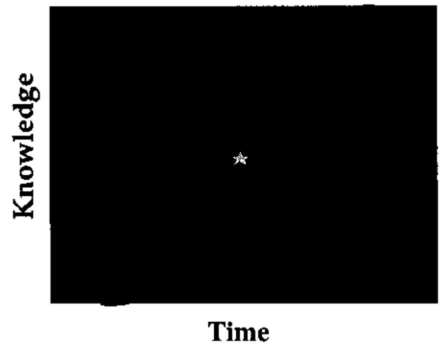
****Colorado School of Mines**

Introductory Remarks

- **Time to reflect and plan ahead**
- **Scope of this study**
  - **Progress as planned**
- **Has every aspect of horizontal well completion been adequately addressed?**

Where are we?

- Single Phase Liquid and Gas Flows
  - Considerable amount of knowledge



Single Phase

- Rigorous Coupling of Wellbore and Reservoir
- Completed Wells
  - Significant Progress
  - But Not Complete

Single Phase ...

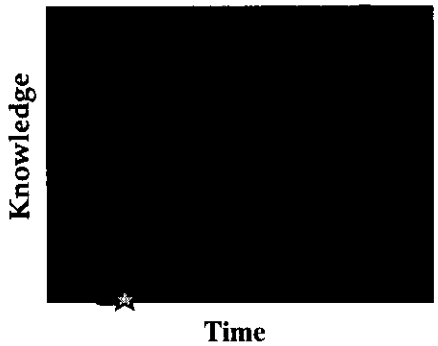
- Pre-Packed Screens
- Scale up
  - Larger Diameter Pipes
- Flow in Perforations
- Performance Evaluation and Monitoring
  - Production Logging
  - Well Testing

Multiphase Flows

- Examples
  - Oil-Water
  - Oil-Gas
  - Oil-Water-Gas
  - Solids in Fluids (e.g. sand)

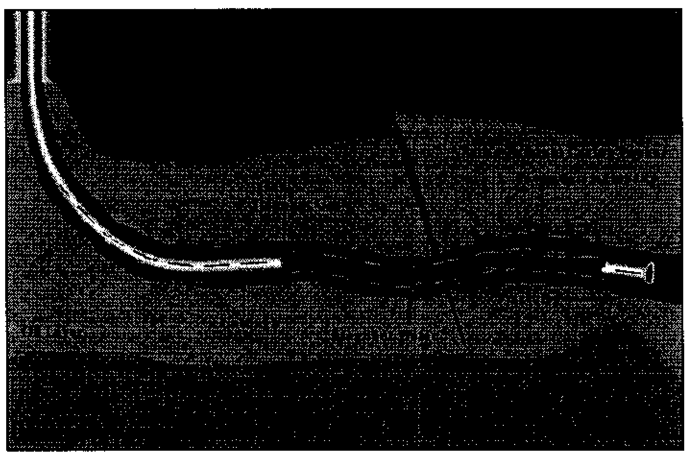
Where are we? …

- Multiphase Flows …
  - Very Limited Information Available



Multiphase Flows

- Very Common and Complex

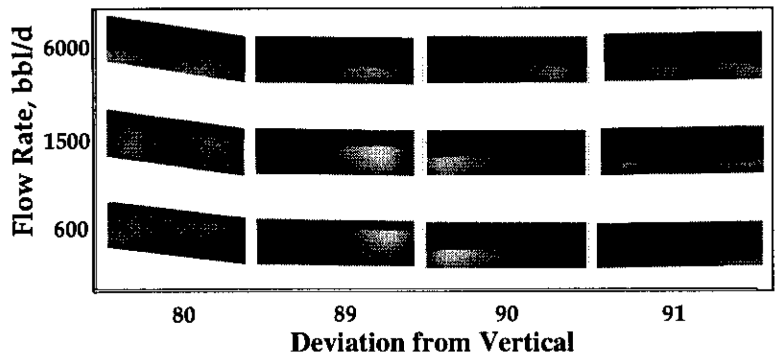


Courtesy of Schlumberger Oil Field Services

Multiphase Flows ...

- Slight inclinations can result in significant changes.

Water-Oil Stratified Flows in 5.5 in. Casing (50% Water Cut)



Courtesy of Schlumberger Oil Field Services

Multiphase Flows ...

- Can Be Considered as Disturbed Pipe Flow
- Limited Experimental Data
- No Reliable Predictive Tools
  - Pipe flow models are adapted

Multiphase Flows ...

- **Performance Prediction**
  - **Production Profile Predictions Along Wellbore**
    - **Water and Gas Breakthrough Locations**
  - **Design of Efficient Completion Program**

Multiphase Flows ...

- **Operational Concerns**
  - **Water accumulation in lower spots**
    - **Oil - Water Slugging**
  - **Phase separation**
  - **Sand accumulation or production**
  - **Back flow (from wellbore to reservoir)**
  - **???**

Need

- Increase productivity and profitability
  - Improving Current and/or Developing New Operational Practices
- Require better knowledge of fluid flow through completions and its interaction with wellbore and reservoir

Possible Future Studies

- Future research directions in horizontal well completion optimization
  - Single Phase Flow
  - Multiphase Flow

Single Phase

- Experimental Studies
  - Pre-packed Screens
  - Larger Pipe Diameters
  - Flow in Perforations
    - Perforation Density and Phasing Effects
    - Movement of Solids
    - Effectiveness (Perforation Damage)

Single Phase ...

- Software Development Studies
  - General Purpose 3-D Numerical Simulator
    - Every possible completion geometry

Multiphase Flow

- Experimental Studies
  - Acquire data for
    - Range of flow rates and inclination angles typical of horizontal wells
    - Various completion geometries
  - Investigate characteristics of flow
    - Distribution of Phases
    - Natural Separation of Phases
  - Develop constitutive relationships
    - Practical and Readily Usable in Software Development

Multiphase Flow ...

- Software Development
  - Analytical Studies
    - Single Phase Flow in Reservoir - Multiphase Flow in Wellbore
    - Multiphase Flow both in wellbore and reservoir.
  - Numerical Simulation
    - Development of 3D Multiphase Flow Simulator
      - Two-Phase flow numerical reservoir simulator is currently being developed for open hole completion geometry.

Where do we go from here?

- Continue with single phase studies
- Initiate multiphase studies
- Both

Platform

- Multi Institutional Project
- Joint Industry Project
- Consortium
- Other suggestions?

Optimization of Horizontal Well Completion

Business Report

Mohan Kelkar
The University of Tulsa

Member Companies

- Amoco
- Department of Energy
- Mineral Management Service
- Phillips
- Unocal

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1998 Budget Revenues

Membership Dues	$60,000
AWU Student Funds	34,600
Total 1998 Budget Revenues	$94,600

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1998 Budget Expenditures

Salaries	$ 43,000
Indirect Costs	4,704
Tuition	15,734
Fringe Benefits	1,655
Facilities and Equipment	858
Meeting Expenses	780
Total Expenditures	$66,731

1999 Projected Budget Revenues

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Carry Forward from 1998	$27,869
Anticipated Membership Dues	60,000
AWU Student Funds	34,600
Total 1999 Budget Revenues	$122,469

1999 Projected Budget Expenditures

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Salaries	$ 59,600
Indirect Costs	14,250
Tuition	6,920
Fringe Benefits	7,750
Facilities and Equipment	31,449
Miscellaneous	2,500
Total Expenditures	$122,469

Future

- Expand the scope of the JIP.
- Extend the JIP two additional years.
- Seek additional members to support the proposed research.