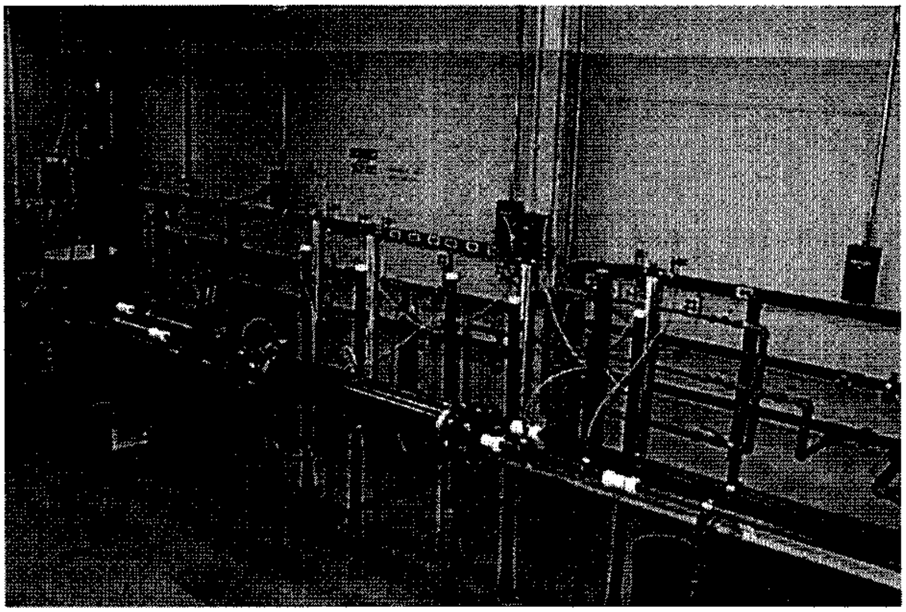
Executive Summary

The newsletter has been shortly delayed because of the events concerning our JIP this summer. Effective August 1998, Drs. Erdal Ozkan and Cem Sarica left the University of Tulsa to accept new positions at the Colorado School of Mines and The Pennsylvania State University, respectively. Their involvement with the JIP, however, will continue as was planed initially based on the contractual agreements between the University of Tulsa and the corresponding universities. Another development this summer was that Mr. Yula Tang, the research assistant with the JIP, passed the Ph.D. qualifying exam in September (congratulations Yula). He will now be able to devote his full concentration on the JIP studies. Weipeng has also completed his first semester at TU (and that was a very good semester). During the summer, both Yula and Weipeng took a Differential Equations course working at the same time on their JIP problems. In this newsletter, you will find their progress reports.



Test Facilities at The University of Tulsa

Since the kick-off meeting in February 1998, the JIP studies have been in progress according to the schedule. We now have five members. In addition to DOE, Amoco, and Phillips; Unocal/Spirit 76 and the Mineral Management Services decided to join the JIP. We are expecting more members as they continue with their company evaluation and approval processes. We have started the modification of the experimental facility to obtain data to develop the wellbore friction factor correlations. Weipeng spent some time with the facility to gain experience and start acquiring data. Dr. Sarica and Weipeng have worked on the design and schedule of the experiments to be conducted. New test sections have been ordered to start the experimental phase of the study. The details of the experimental work conducted thus far can be found in Weipeng's progress report.

On the reservoir studies part of the JIP, most of our effort concentrated on the literature survey and background studies. We have reviewed the related literature during the spring and summer months. Yula worked on the special mathematical techniques to be used in the solution of the reservoir flow problem. These techniques include, integral transforms, Green's Functions, and the Method of Sources and Sinks. He also gathered background on Bessel Functions, the Principle of Superposition, and the Method of Images. Yula has gained confidence in the special mathematical techniques by reviewing and solving problems such as partially penetrating vertical wells, fractured and horizontal wells,

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Reservoir Performance Modeling and Comprehensive Model

By Yula Tang

Projected Completion Dates

Literature Survey	Completed
Related Theory Study	Completed
Derivation of Reservoir Flow Equations for Horizontal Well Completion	January, 1999
Combination of Wellbore and Reservoir Performance	August, 1999
Numerical Algorithm and Solution	January, 2000
Program Design for Optimal Completion	August, 2000
Final Report	December, 2000

Objective

The overall objective of this 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 and developing correlations to integrate the effects of fluid ingress through small openings on the surface of a horizontal well into the standard horizontal pipe flow equations.

In accordance with the JIP goals, the objectives of my study are to 1) develop a reservoir performance model which considers the effect of flow convergence toward slots and perforations on the surface of the well; 2) couple the wellbore and reservoir 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) perform the sensitivity analysis and optimize well completion design study; 5) finally develop a user-friendly software for horizontal well completion design.

Presently, I am working on the development of an analytical model for flow in the reservoir with well completion restrains (flow convergence toward perforations or slots). First, we will develop a model for a single opening using the source function approach. Then we will construct the solution for multiple openings considering the variations in the density, phasing, and patterns by using the superposition principle. We will also develop some asymptotic approximations to compare our results. The asymptotic approximations should be useful to provide a first estimate before detailed computations and to derive simplified completion pseudoskin expressions.

Problem Statement

Since the early 1980s, a wide variety of successful applications for horizontal wells have been reported. Horizontal wells have been attractive alternatives to produce thin reservoirs, naturally fractured reservoirs, reservoirs with gas and water conning problems, offshore environments, as well as to improve oil recovery by using enhanced recovery techniques such as steam injection. The appreciation of the favorable conditions and optimization of well completion are among the key factors to guarantee an economic production with horizontal wells. There are four major types of completion used for horizontal wells. They are 1) openhole completion, 2) slotted liner in open hole, 3) slotted linear in open hole with blank sections and ECPs, and 4) cased cemented and perforated completion.

Openhole completion (Type 1) is the simplest and the least expensive horizontal well completion technique. This completion is appropriate in competent formations (such as Austin Chalk). It provides the maximum contact with the reservoir but it does not permit re-entry for measurement or workover purposes. Similarly, if sand control is an issue or selective completion of the well is a requirement because of water or gas coning problems, openhole completion is not a viable option.

Types 2 and 3 are used for completion in unconsolidated formations. The slot widths are small enough (typically in the range of 0.5 to 1.5 mm) to allow sand grains to bridge across them, preventing the influx of any but the finest material. Wire-wound screens with much narrower slot widths are also used to prevent finer sand grains, although they are more expensive than simple slotted liners.

Type 4, the cased and perforated completion, on the other hand, is a selective completion technique that provides the necessary downhole conditions for controllable production, workover, and stimulation. It is, however, the most expensive and the most difficult completion technique.

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. Although some studies[1-7] have investigated the effects of completion parameters on wellbore hydraulics, no study is available in the literature on the effect of well completion on reservoir flow behavior. To obtain a comprehensive horizontal-well-performance model, however, the influence of well completion on both wellbore and reservoir flow performances should be taken into account.

Generally, the reservoir performance can be obtained by an analytical or numerical approach. One of the most important differences between the reservoir performances of horizontal and vertical wells is the flux distribution along the wellbore. For a fully penetrating vertical well, it is normally assumed that the pressure drop in the wellbore is negligible (infinite-conductivity-well assumption) and the flux distribution is uniform along the well. This assumption is justified based on 1) the short interval along which the wellbore communicates with the reservoir, 2) plane radial flow resulting from complete penetration of the pay thickness, and 3) resulting symmetry of flow lines. The assumptions of uniform flux and infinite conductivity, however, may be inappropriate for horizontal wells. In fact, wellbore pressure loses contribute more the 20% of the total pressure drawdown for long and high-flow-rate horizontal wells. In addition, the flux along the wellbore is non-uniformly distributed because the streamlines around the wellbore are not circular but rather elliptic. Actually, the flux entering the wellbore at a given point on the well surface is determined by the interplay between the reservoir and the wellbore.

For a perforated vertical well, a large number of numerical simulation studies have been performed by using the finite difference or finite element methods. The numerical simulation of a perforated vertical well is feasible because of the symmetric pattern of perforations and flow convergence lines. Therefore, it suffices to consider one of the repetitive elements of the completion interval. In addition, the effect of wellbore hydraulics need not be considered.

The numerical simulation of horizontal well completions, however, poses significant complexities. The main problem is that the numerical simulation needs to be performed over the entire wellbore instead of a single completion interval because of asymmetry. As we mentioned above, the flux distribution along a horizontal wellbore is non-uniform. Thus, the overall well productivity cannot be deduced or simply computed from the performance of a single representative completion interval (because there is no repetitive scheme of flow convergence lines toward the openings on well surface). When the entire length of the completion interval is modeled, on the other hand, the CPUs requirement for the numerical computations usually becomes excessively long. Another difficulty in numerical simulation of horizontal well completions is to construct the grid transition from the very fine slot size to the large reservoir grid size.

The complexities of the numerical simulation of horizontal well completions make analytical models extremely attractive despite the inherent difficulties of the analytical solutions. Because of the 3D nature of the horizontal well flow problem, the Green's function or the source function approach can provide an efficient analytical solution. At the first step, a general solution for the performance of a single perforation/slot needs to be derived. Then, the overall performance of the well can be obtained by using the method of superposition. The analytical approach not only has the capability to incorporate the complex reservoir/wellbore interaction, but also has the advantage of exploring the intrinsic characteristics of the problem itself.

Background

Dikken[1] emphasized the importance of wellbore pressure losses for an openhole horizontal well 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 drawdown along the well length. Ozkan *et al.*[2] and Ozkan *et al.*[3] used the physical coupling conditions (pressure and flux continuity at the well surface) to obtain a solution to compute the horizontal well performance.

The influence of reservoir flow convergence toward small openings on the surface of a horizontal well, however, has not been investigated in the literature. Penmatcha, *et al.*[4] suggested to use the vertical-well perforation-pseudo-skin expressions for horizontal wells. This approach cannot be readily justified because of non-uniform flux distribution and selective completion along a horizontal wellbore.

The Green's and source function approaches have often been used to develop solutions to 3D flow problems in porous media. Although Carslaw and Jaeger[5] had used Green's functions in the solution of heat conduction problems, this approach had not been widely practiced in reservoir engineering until Gringarten and Ramey[6] introduced the use of source and Green's functions for the solution of transient flow problems in porous media. They presented tables of instantaneous Green's function and source functions that can be used with the Newman's product method to generate solutions for a wide variety of reservoir flow problems. This approach creates uniform-flux well solutions. The infinite-conductivity well solutions need to be approximated by using the uniform-flux source functions (the source volume is divided into a number of elements, each having uniform flux, and then the flux distribution to yield uniform pressure in all segments is computed).

In 1974, Gringarten, Ramey, and Raghavan[7] applied the source and Green's functions approaches to analyze the transient pressure response of infinite-conductivity vertical fractures. In 1975, Gringarten and Ramey[8] presented the analytical solutions for both uniform-flux and infinite-conductivity, partially penetrating vertical wells. Spivak and Horne[9] studied the transient pressure response due to production with a slotted liner completion using source function method in 1982. They modeled the slots as line sources of finite length. Clonts and Ramey[10] presented a pressure transient solution for uniform-flux horizontal drainholes in anisotropic reservoirs of finite thickness by using Green's functions and Newman's product method.

In 1990, Ahmed, Horne, and Brigham[11] presented an analytical solution for flow into a vertical well via perforations using Green's functions. Their solution assumed 3D, steady-state, single-phase flow in a homogeneous porous medium. The perforations were treated as line sinks. This solution contains products and series of Bessel functions and their derivatives. First, an array of eigenvalues is computed from an implicit equation and then they are used in the computation of the solution.

As we noted before, one of the objectives of our study is to develop simplified completion pseudoskin expressions for horizontal wells. The source and Green's function approaches are known to be particularly useful to obtain asymptotic expressions of the exact solutions. The asymptotic expressions should lead to the completion pseudoskin expressions in our case. We must also note a relevant study to obtain a completion pseudoskin expression that has been published in the hydrology literature. Hazenberg and Panu[12] 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.

All of the above studies provide the basis for our study. The success of the source and Green's functions approaches in developing analytical solutions for perforated or slotted-liner-completed vertical wells indicate their potential for the solution of the problem under consideration.

Current Status

I started to work on this project in March of this year. Since then, I have built the basic knowledge on the Laplace transformation, superposition theorem, the method of images, and the source and Green's functions methods. As part of these preparations, I have read some of the classic papers and derived the equations for basic source and Green's functions. I also developed some experience on vertical fracture, horizontal well, and partially penetrating well solutions. Finally, I reviewed the existing solutions for slotted liner completed vertical wells. I took a course in order to improve my understanding of the basic and important concepts of partial differential equations. Meanwhile, I had to prepare for the Ph.D qualification exam this summer. I have also collected some references (papers and books) for this study. In summary, I have prepared myself to work on the project goals.

Future Work

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

1. Derive the pressure response solutions for slotted liner completed horizontal wells

First, I will start by constructing the pressure response equations for a unit wellbore section with varying slot density, phasing, and pattern. Then, I will consider the reservoir pressure response for the entire horizontal wellbore by using the superposition principle, based on individual wellbore section pressure response.

After obtaining the analytical solution for the reservoir with the effect of flow convergence toward slots or perforations, I will couple it with the wellbore model. With this coupled model, we will be able to obtain the productivity index of the well and the additional pressure drawdown and overall skin factor due to completion.

Because of the complexity of the analytical expressions, we should need to formulate efficient numerical algorithms. This will constitute a significant part of my study.

2. Derive the approximate expression of pseudoskin due to convergence

One of our objectives in this study is to develop an alternative, simple expression for the effect of flow convergence to the completion opening. After this, we will study further to delineate the conditions under which this approximation will be valid.

We will use two approaches in our derivations. The first approach is to obtain the asymptotic expressions from the rigorous solutions. The second is the approach presented in Reference 12. In this approach, we will assume that the flux is uniform and the wellbore friction is negligible. We will divide the flow into two different zones. The outer zone will be assumed unaffected by the completion. The inner zone will be the flow convergence zone where flow is affected by the distribution of the slots and is three dimensional.

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, Mar. 21-23, 1993.
4. Penmatcha, R., Fayers, J., and Aziz, K.: "Skin Factor Calculations for Vertical, Deviated, and Horizontal Wells (Task 2)," DOE/BC/14862-10, Productivity and Injectivity of Horizontal Wells, Annual Report for the Period of March 10, 1994 to March 9, 1995, Stanford University, Stanford, CA (July 1995).
5. Carslaw, H.S., and Jaeger, J.C.: *Conduction of Heat in Solids*, Oxford at the Clarendon Press (1959).
6. Gringarten, A.C., and Ramey, H.J., Jr.: "The Use of Source and Green's Functions in Solving Unsteady-Flow Problems in Reservoirs," *SPEJ* (Oct. 1973) 285-296.
7. Gringarten, A.C., Ramey, H.J., Jr, and Raghavan, R.: "Unsteady-State Pressure Distributions Created by a Well with a Single Infinite-Conductivity Vertical Fracture," *SPEJ* (Aug., 1974) 347-360.
8. Gringarten, A.C., and Ramey, H.J., Jr.: "An Approximate Infinite Conductivity Solution for a Partially Penetrating Line-Source Well," *SPEJ* (April., 1975) 140-148.
9. 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.
10. Clonts, M.D., and Ramey, H.J., Jr.: "Pressure Transient Analysis for Wells with Horizontal Drainholes," paper SPE 15116 presented at the 56th SPE California Regional Meeting, Oakland, CA, April 2-4, 1986.
11. Ahmed, G., Horne, R.N., and Brigham, W.E.: "Theorical Development of Flow into a Well through Perforations," DOE/BC/14126-25 (1990).
12. 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).

Executive Summary (Continued)

wells in bounded reservoirs. He is presently working on the solution of fluid flow toward a slotted liner completed vertical well. This is the last step before he starts modeling and solving the convergence of fluid flow toward a slotted liner completed horizontal well.

During the next phase of the JIP (until we meet for our advisory board meeting in February), we are planning to complete the first set of the experiments to improve the existing friction factor correlations. On the reservoir studies part, our goal is to derive an asymptotic solution to help understand the structure of the solution that takes into account the flow convergence toward slots or perforations. We are also expecting to make progress on the development of the rigorous reservoir flow model.■

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

By Weipeng Jiang

Projected Completion Dates

Data Acquisition Program	Completed
Experimental Instrument Calibration	Completed
Test Section Design	Completed
Test Section Construction	September, 1998
Data Acquisition	December, 1998
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. Extensive experimental work will be 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.

Background

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 petroleum industry started to investigate horizontal wellbore hydraulics in the late 1980's. A new friction factor correlation for horizontal wellbores was proposed by Asheim et al.[1] which included accelerational pressure losses due to continuous fluid influx along the wellbore. They assumed that the injected fluid entered the main flow with no momentum in the axial direction. The experimental work by Kloster[2] concluded that the friction factor vs. Reynolds number relationship for perforated pipes with no injection from the perforation did not show the characteristics of regular pipe flow. The friction factors were 25-70% higher than those of regular commercial pipes. He also observed that small injections through perforations reduced the friction factor.

Yuan[3] and Yuan et al.[4] have investigated the flow behavior in perforated horizontal wells and horizontal wells completed with slot liners. By using the principles of mass and momentum conservation, a general horizontal well friction factor expression was developed for both the perforated horizontal wells and horizontal wells completed with slot liners. Horizontal well friction factor correlations for limited completion geometries were developed by applying experimental data to the general friction factor expression. It was observed that the friction factor of a perforated pipe with fluid injection can be either smaller or greater than that of a smooth pipe, depending on influx to main flow rate ratios.

The results of above studies prove that the shape and the distribution of the openings on the pipe wall can significantly influence the flow behavior in horizontal wells. Each completion geometry displays different flow characteristics. However, because the available data consider either single opening or limited multiple opening cases, the influence of the shape and the area of the openings has not been thoroughly investigated. Therefore, there is a real need to investigate the completion geometry effects thoroughly.

Experimental Program

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

Experimental Tests

Ten new test sections were designed in order to investigate the effects of slot/perforation density and phasing. Each test section will be made up of a 10-ft long, 1 in. diameter horizontal pipe with a 4-ft long test section. Experiments will be conducted under steady state flow conditions with Reynolds number ranging between 5,000 and 60,000.

The following parameters will be 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. 10 out of the 17 combinations, which are denoted by "•" in the tables, require the new test sections.

Data Analysis & Modeling

In this JIP, the general model developed by Yuan et al.[4] (1996) will be adopted to analyze the acquired data.

Consider an incompressible fluid flowing isothermally along a uniformly perforated pipe of a cross-section A. The area of each perforation is A_p. Fluid is injected through the perforations into the main flow stream uniformly as illustrated by Figure 3. The mo-

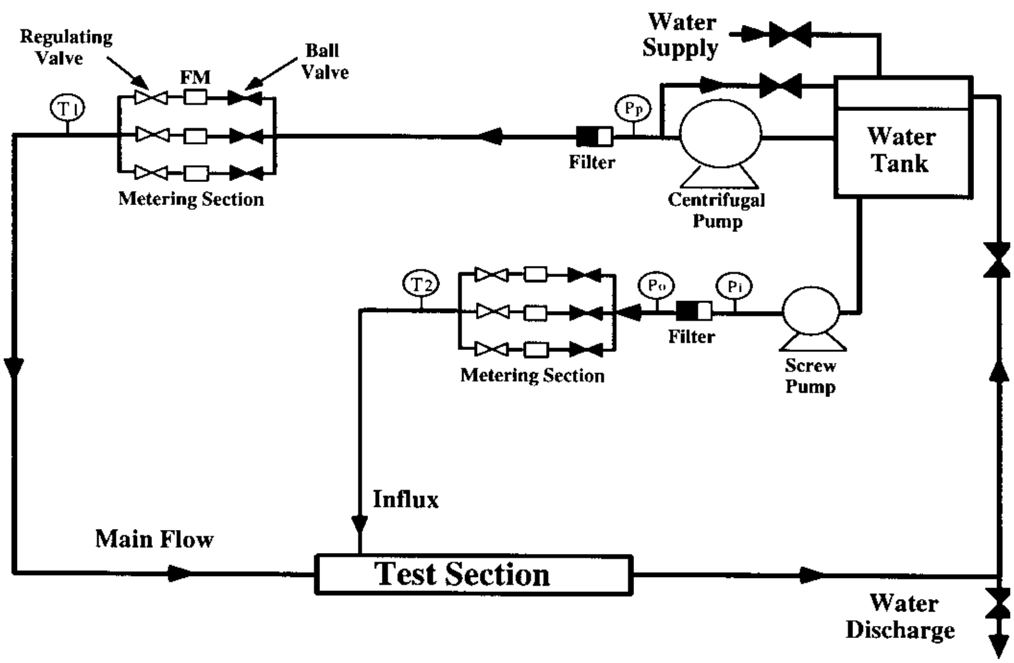

Figure 1 - Schematic Description of the Test Facility

mentum balance for the control volume in the axial direction is,

$$p_1 A - p_2 A - \tau_w \cdot \pi d \cdot \Delta x = \beta_2 \rho \bar{u}_2^{\,2} - \beta_1 \rho \bar{u}_1^{\,2} - \rho V_x V_r \beta_p A_p n \quad (1)$$

p_1 and u_1 are the pressure and average velocity at the inlet of the control volume, and p_2 and u_2 are the pressure and average velocity at the exit. n is the number of perforations along the distance Δx.

For the three terms on the left hand side of the above equation, we assume that average properties completely define the flow field. The first two terms on the right hand side of the equation use the average velocities by introducing momentum correction factors, β_1 and β_2, which are defined by the following equation,

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

where u and V are the velocity distribution and the average velocity in cross section A, respectively.

The last term of Eq. 1 represents the acceleration of flow resulting from fluid injection. When the injected fluid enters the main flow stream through the perforations, the streamlines change directions. Each local mean velocity is tangent to the streamlines and can be divided into two components, V_r and V_x as shown in Figure 3. Fluid is transported into the main flow with a radial velocity component V_r, while retaining some axial momentum from velocity component V_x. V_r is equal to V_p due to continuity. β_p is the momentum correction factor for the influx stream and V_x will be discussed later.

For multiple injection points, it is convenient to use average properties. The average velocity over Δx is u and is defined as follows,

$$\bar{u} = \bar{u}_1 + \bar{u}_2 \qquad (3)$$

A mass balance for the control volume is given by,

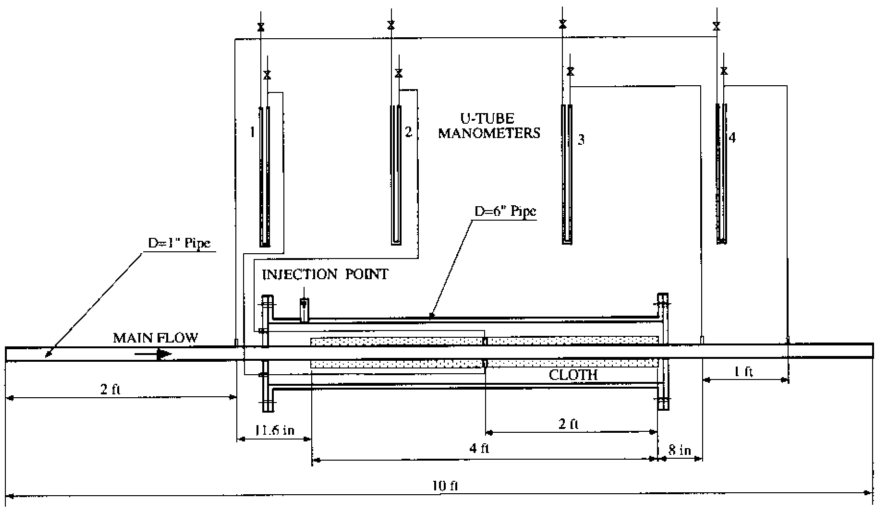

Figure 2 - Schematic of the Test Section and Manometer Connections

Table 1 : Test Section Matrix for Perforated Pipes. (Perforation Diameter: d = 1/8 inch)

	Phasing		
Perforation Density	360	180	90
Single Opening	X		
Perf. Density 1	X	•	•
Perf. Density 2	•	X	•
Perf. Density 3	•	•	X

Perforation Density 1: 5 shot per foot
Perforation Density 2: 10 shot per foot
Perforation Density 3: 20 shot per foot

Table 2 : Test Section Matrix for Slotted Lines. (Slot Liner Length: 2-in, Width: 1/16 inch)

	Slot Liners Phasing		
Slot Liners Density	360	180	90
Single Opening			
Multiple Slots 1	X	X	•
Multiple Slots 2		•	•
Multiple Slots 3		•	X

Multiple Slots 1: 18 slots in the 4 ft. test section
Multiple Slots 2: 12 slots per 4 ft. test section
Multiple Slots 3: 36 slots in the 4 ft. test section

$$\overline{u_1}A + n\,V_p A_p = \overline{u_2}A \tag{4}$$

The influx through each perforation is,

$$q_{in} = V_p A_p \tag{5}$$

The total volumetric influx rate is,

$$Q_{in} = nV_pA_p \tag{6}$$

Velocities u_1 and u_2 may be eliminated by employing Eqs. 3 and 4.

An apparent friction factor, defined as the ratio of the net imposed external forces to the inertial forces, can be given by,

$$f_T = -\left(\frac{p_2 - p_1}{\Delta x}\right) / \frac{\rho \overline{u}^2}{2d} \tag{7}$$

which is an average friction factor over a length Δx.

The wall friction factor f_w is defined as,

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

Let,

$$\overline{Q} = (\pi d^2 \overline{u})/4 \tag{9}$$

$$\phi = V_x / \overline{u} \tag{10}$$

$$\varphi = n / \Delta x \tag{11}$$

where *f* is perforation density.

An expression for the apparent friction factor can then be found by substituting Eqs. 6-11 into Eq.1, rearranging and simplifying,

$$f_T = f_w + 2d \cdot \left(\frac{\beta_2 - \beta_1}{\Delta x}\right) + 2d\varphi \cdot \frac{q_{in}}{\overline{Q}} \cdot \left[\beta_1 + \beta_2 - \phi\beta_p + \left(\frac{n}{4} \cdot (\beta_1 - \beta_2) \cdot \frac{q_{in}}{\overline{Q}}\right)\right] \tag{12}$$

Equation 12 implies that the apparent friction factor is a function of average Reynolds number, pipe roughness, influx to main flow rate ratio, velocity profile and perforation density.

Let,

$$C_n = \left[\beta_1 + \beta_2 - \phi\beta_p + \left(\frac{n}{4} \cdot (\beta_1 - \beta_2) \cdot \frac{q_{in}}{\overline{Q}}\right)\right] \tag{13}$$

Equation 12 then becomes,

$$f_T = f_w + 2d \cdot \left(\frac{\beta_2 - \beta_1}{\Delta x}\right) + C_n \cdot 2d\varphi \cdot \frac{q_{in}}{\overline{Q}} \tag{14}$$

The second term on the right-hand side of Eq. 14, $2d(\beta_2 - \beta_1)/\Delta x$ is caused by a change in the velocity profile in the x direction. Since no local velocity data will be acquired,

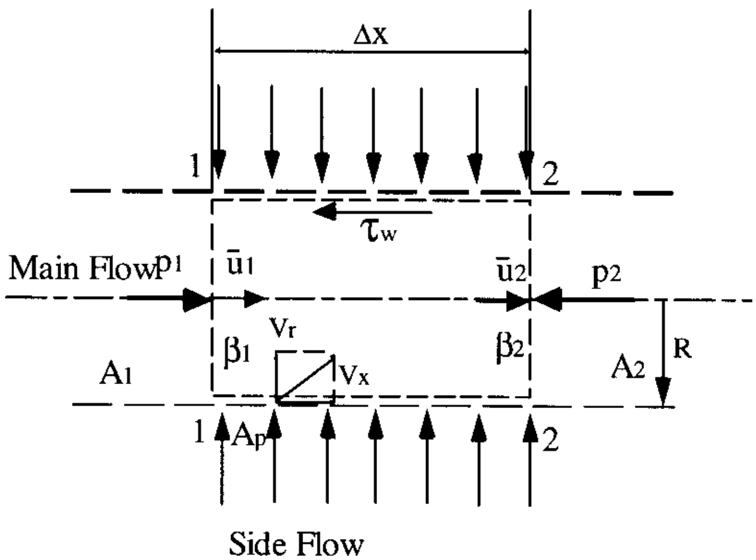

Figure 3 - Schematic of Horizontal Well Control Volume for Uniformly Distributed Injection

no attempt will be made to evaluate this term. However, this term is negligible in this project since the small rate of injection will not affect the velocity field significantly, except in the near wall region. Using Blasius Correlation for predicting friction factors: $f_w = aN_{Re}^b$, Eq. 14 can be expressed as,

$$f_T = aN_{\mathrm{Re}}^b + C_n \cdot 2d\varphi \cdot \frac{q_{in}}{Q} \tag{15}$$

In the above equation, C_n, a and b will be determined experimentally. Efforts will be made to express C_n, a and b in terms of d, f, N_{Re} and other independent parameters in order to get a friction factor correlation that can be used for any perforation/slot densities and phasings.

Status

Since the Advisory Board Meeting in January 1998, the following tasks have been accomplished.

- Review and improvement of the existing experimental procedure.
- Development of the data acquisition program. The LabView™ graphic language is used to write the program.
- Calibration of the instruments.
- Test section design and construction of several test sections.
- Data acquisition has begun since late September.

Future Tasks

Our future tasks include the following:

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

References

1. Asheim, H., Kolnes, J., and Oudeman, P.: " A Flow Resistance Correlation for Completed Wellbore," Journal of Petroleum Science and Engineering, 8 (1992), pp. 97-104.
2. Kloster, J.: "Experimental Research on Flow Resistance in Perforated Pipe," M.S. Thesis, Norwegian Institute of Technology, 1990.
3. Yuan, H.: "Investigation of Single Phase Liquid Flow Behavior in a Single Perforation Horizontal Well," M.S. Thesis, the University of Tulsa, 1994.
4. Yuan, H., Sarica, C., Brill, J., Miska, S.: " Investigation of Single Phase Liquid Behavior in Horizontal Wells," Trans. ASME, Vol. 119, pp. 20-25.

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