A Parametric Study of Sandstone Acidizing Using a Fine-Scale Simulator

by

Tao Xie, M.IT

Thesis
Presented to the Faculty of the Graduate School
Of the University of Texas at Austin
In Partial Fulfillment
Of the Requirements
For the Degree of

Master of Science in Engineering

The University of Texas at Austin

May, 2004
A Parametric Study of Sandstone Acidizing Using a Fine-Scale Simulator

APPROVED BY
SUPERVISING COMMITTEE

__________________________
A. D. Hill

__________________________
Ding Zhu
Dedication

to

my wife Chun

without her encouragement and patience

this accomplishment would not have been possible
Acknowledgements

I would like to express my most sincere acknowledgement to my supervisor Dr. A.D. Hill and Dr. D. Zhu for their guidance, help and encouragement throughout this research. I will always remember their patience and kindness. It was a beneficial and enjoyable experience for me to under their supervision.

It has also been a great pleasure working with my fellow graduate students: Chunlou Li, Maysam Pournik, and Naga Potluri. Special thanks to Dr. Kenji, Furui, for his time to help me with using GiD software. Many people in the department of Petroleum Engineering and Geosystems helped me concentrate my study: Cheryl Kruzie, Roger Terzian, Glen Gaum, and Reynaldo Casanova.

Finally, I would like to extend my utmost thanks to my wife and my parents for their persistent support and understanding during my studies.
A Parametric Study of Sandstone Acidizing Using a Fine-Scale Simulator

by

Tao Xie, M.S.E.
The University of Texas at Austin, 2004
Supervisor: A. Daniel. Hill

Sandstone acidizing is a group of complex chemical reactions process. Some of previous researches express that it is possible to generate wormhole in sandstone. If the optimal conditions for sandstone wormholing is found, the success rate of sandstone acid treatment will be largely improved from the current success rate which is about 50%-70%.

A fine-scale sandstone acidizing simulator was developed to simulate the heterogeneity of properties in sandstone. To make the wormholing analysis easily and clearly, a 3D Visualization Program (UT3DVIS) is used to display a 3D image for numerical acidizing results.
The parametric study demonstrate that to generate wormholes in sandstone, mineral heterogeneity is the most important factor. High temperature and high HF concentration are also helpful for wormholing. Low acid injection rate is advantage to wormholing for heterogeneous sandstone. However, too low an injection rate can cause face dissolution, and increase the operation cost. There is an optimal Damkohler number to generate channels or wormholes for a sandstone acidizing case.

Precipitation will cause heavy damage in sandstone acidizing treatments if the acidizing reaction front is uniform in the core. However, if there is a main acid flow channel in the core, the precipitates will block the other parts of the core, and force more acid to converge into the channel. Therefore, precipitation is helpful to generate wormholes or high permeability channels in heterogeneous sandstone rather than being a solely negative factor in sandstone matrix acidizing.
TABLE OF CONTENTS

List of Tables ......................................................................................... ix

List of Figures ....................................................................................... x

Chapter 1: Introduction ............................................................................ 1

1.1 Sandstone Acidizing ......................................................................... 1

1.2 Previous Wormholing Researches in Sandstone ................................. 3

1.3 Optimal Sandstone Wormholing Conditions ..................................... 7

1.4 Visualization of Numerical Simulation of High HF Concentration
   Sandstone Acidizing ........................................................................... 8

Chapter 2: Fine Scale Simulation for Acidizing in Heterogeneous Sandstone .................................................................................. 10

2.1 Previous Sandstone Acidizing Models ............................................. 10

2.2 Fine-scale Sandstone Acidizing Model ........................................... 12

2.3 Generation of Heterogeneous Field ............................................... 14

Chapter 3: Visualization Result of Sandstone Fine-scale Acidizing

Simulation .............................................................................................. 16

3.1 Converting Program for 3D Visualization ...................................... 16
   i. Background Introduction ............................................................ 16
   ii. Introduction of GiD Files ......................................................... 18
3.2 Multiple Methods to Detect the Wormhole Existence in the Core from the Simulation Result Data

i. Initial Porosity .........................................................29

ii. Porosity Profile ........................................................29

iii. Delta Porosity ..........................................................31

iv. HF Acid Concentration ..............................................31

v. Si(OH)<sub>4</sub> Concentration .........................................33

vi. Velocity of Acid flow ...............................................35

vii. Permeability and Pressure .........................................37

viii. Slow-reacting Mineral Concentration and Fast-reacting Mineral Concentration .............................................40

ix. Maximum Delta Porosity vs. Average Delta Porosity for each YX plane .................................................................40

x. Maximum HF Concentration vs. Average HF Concentration for each YZ plane ......................................................44

3.3 Summary .................................................................44

Chapter 4: Parametric Study for Sandstone Channeling/Wormholing .......47

4.1 Introduction ..............................................................47
4.2 Reaction Temperature ..............................................................49
4.3 Acid Injection Rate ..............................................................53
4.4 Mineral Distribution Correlation.............................................60
4.5 HF Acid Concentration ..........................................................64
4.6 Different Fast-reacting Mineral ..............................................66
4.7 A Sample Channeling Map ...................................................72
4.8 Summary ..............................................................................74

Chapter 5: Conclusions and Recommendations .............................76

Nomenclature .............................................................................79

Bibliography ..............................................................................81

Vita .............................................................................................85
List of Tables

3-1. A Sample of GiD Mesh File .........................................................20
3-2. A Sample of GiD Mesh File .........................................................22
3-3. Properties and Treatment Data Summary of Uta19 .....................28
4-1. Uta19 Base case Input Data File ..................................................48
List of Figures

1-1  Wormholing test for Bandera sandstone (Lamb, 1985)..................4
1-2  Wormholing test for Berea sandstone (Lamb, 1985).....................5
1-3  HF concentration effects on injection surfaces of South America sandstone cores (Kalfayan and Metcalf, 2000).............................6
3-1  3D graphics of initial porosity distribution for Uta19 base case........17
3-2  The construction of the core in fine-scale sandstone acidizing simulator.................................................................24
3-3  The operation menu in GiD platform........................................25
3-4a Porosity distribution..............................................................30
3-4b The grid blocks with higher porosity......................................30
3-5a Delta porosity distribution......................................................32
3-5b The grid blocks with higher delta porosity...............................32
3-6a HF concentration distribution.................................................34
3-6b The grid blocks with higher HF concentration..........................34
3-7a The YZ plane view from the inlet of the core for precipitation......36
3-7b The three dimension view of the core for precipitation..............36
3-8a The grid blocks with higher flow velocity in X direction.............38
3-8b  The grid blocks with higher velocity in three directions.................38

3-9a  Permeability distribution..............................................................39

3-9b  The grid blocks with higher permeability.......................................39

3-10a  The grid blocks with lower fast-reacting mineral concentration.........41

3-10b  The grid blocks with lower slow-reacting mineral concentration........41

3-11  The maximum delta porosity and average delta porosity for each YZ
      plane........................................................................................................43

3-12  The maximum $C_{HF}$ and average $C_{HF}$ for each YZ plane...............45

4-1  The impacts of temperature and different fast-reacting minerals to
      maximum delta porosity and maximum porosity.................................52

4-2a  The grid blocks with higher porosity at 422°K.................................54

4-2b  The grid blocks with higher porosity at 343°K................................54

4-3a  The grid blocks with higher delta porosity at 422°K.........................55

4-3b  The grid blocks with higher delta porosity at 343°K.........................55

4-4  The impact of acid injection rate to maximum porosity and maximum
      delta porosity..........................................................................................57

4-5a  The grid blocks with higher porosity at acid injection rate of 1ml/min...58

4-5b  The grid blocks with higher porosity at acid injection rate of
      20ml/min............................................................................................58

4-6a  The grid blocks with higher delta porosity at acid injection rate of
      1ml/min...............................................................................................59
4-6b The grid blocks with higher delta porosity at acid injection rate of 20ml/min.

4-7a The grid blocks with higher porosity at injection rate 2.5 ml/min for random initial porosity distribution.

4-7b The grid blocks with higher porosity at injection rate 20 ml/min for random initial porosity distribution.

4-8a The grid blocks with higher $C_{HF}$ at injection rate 2.5 ml/min for random initial porosity distribution.

4-8b The grid blocks with higher $C_{HF}$ at injection rate 20 ml/min for random initial porosity distribution.

4-9 The impact of $C_{HF}$ to maximum porosity and maximum delta porosity.

4-10a The grid blocks with higher delta porosity at 1wt% $C_{HF}$.

4-10b The grid blocks with higher delta porosity at 12wt% $C_{HF}$.

4-11a The grid blocks with higher porosity at 1wt% $C_{HF}$.

4-11b The grid blocks with higher porosity at 12wt% $C_{HF}$.

4-12 The break through time for two cases which fast-reacting mineral is clay and fasting reacting mineral is feldspar.

4-13a The grid blocks with higher porosity for feldspar as fast-reacting mineral at 422°K.
4-13b The grid blocks with higher porosity for feldspar as fast-reacting mineral at 343°K

4-14 A Channeling map for Uta19 case
Chapter 1: Introduction

1.1 Sandstone Acidizing

Sandstone matrix acidizing has been applied in oil, gas and injection wells for many years to stimulate the production rate. The goal of sandstone matrix acidizing is to remove formation damage in the near wellbore area and restore the natural permeability of the reservoir by injecting the acidizing fluid into the reservoir below fracturing pressure. Sandstone is a complicated composite of many minerals exhibiting various morphologies. The HF reaction rate differs widely from mineral to mineral. Some precipitation is inevitable when HF reacts with silicate minerals, especially at high temperature condition. Failure to consider this problem can lead to poor treatment result and, in some case, severe formation damage.\(^1\) That is the main problem to limit the success of sandstone acidizing.

HF is usually used in sandstone matrix acidizing because HF is the only common acid that dissolves siliceous particles sufficiently. Walsh et al\(^2\) reported that an essential feature of even a well-designed sandstone treatment is the dissolution of aluminosilicates with the attendant precipitation of some form of amorphous acid Si(OH)\(_4\). To minimize matrix unconsolidation and precipitation, acid concentration and the ration of HCl/HF should be carefully considered in the
acid treatment design. Since the mid-1990s the use of HCl/HF at a weight ratio of 9 to 1 has been extensive in field operations to minimize precipitation during sandstone acidizing. The precipitation reaction is one of the main causes of HF acid treatment failures. Failure to properly chose an HF acid blend based on mineralogy and temperature can cause precipitation in the range of 6-24 in. from the wellbore.\(^3\) Compared with carbonate matrix acidizing, the success rate of acidizing in sandstone is still surprisingly low, typically around 50%.

The reactions between HF and siliceous material are very intricate, and the damage from precipitation depends on various factors such as concentration ratio of HCl/HF, mineralogy of formation, acid injection rate, and reaction temperature etc. Sandstone acid treatment design cannot be defined by an exact set of rules and expectations to control the precipitation. Moreover, the impact of precipitation on damage is not uniform for different cases. Under some specific conditions, precipitation may only block a part of the formation, and force the acid flow through another part of the formation to form a main acid flow channel in the formation. Therefore, it should be subjected to an open mind and an understanding that there is not necessarily one “right” answer when it comes to solving the precipitation problem of sandstone matrix acidizing. For example, if we can generate wormholes or a high permeability channel in sandstone during the acid treatment, the problem of damage caused by precipitation could be bypassed.
1.2 Previous Wormholing Research in Sandstone

Being different from carbonate acidizing, it is rare to generate wormholes in sandstone acidizing because of the low reaction rate between HF and quartz, the main component in the sandstone. Many people doubt the possibility to generate wormholes in sandstone acidizing. However, Lamb\(^4\) did several sandstone acidizing experiments using high HF concentrations (12 wt% HCl, 12wt% HF) in 1985 with Bandera sandstone and Berea Sandstone respectively, and observed that there were obvious wormholes in the cores for both two sandstones (Figure 1-1 and Figure1-2). The experiments were performed at 150\(^{\circ}\)F, and the amount of injected acid was 6-8 pore volumes.

Another laboratory core flow test study reported that high HF concentration could create wormholes was done by Kalfayan and Metcalf\(^5\) at 265 \(^{\circ}\)F for South America sandstone. In their core flow test, 6wt% and 9wt% HF was used. They observed that there were some channels or “wormholes” (Figure 1-3) from the injection side core face. Based on the laboratory tests, the well treatment increased production rate from 2,100 BOPD to over 4,000 BOPD. Kalfayan and Metcalf also expressed that slow acid injection rate (longer acid residence time or contact time) was a positive factor to generate wormholes in sandstone.

Thomas\(^6\) reported that at high temperature condition, it is possible to generate wormholes in sandstone. The wormholing in sandstone depends on core
Figure 1-1. Wormholing test for Bandera sandstone (Lamb, BP, 1985)
Figure 1-2. Wormholing test for Berea sandstone (Lamb, BP, 1985)
Figure 1-3. HF concentration effects on injection surfaces of South America sandstone cores: HF 6% (top) and HF 9% (bottom) (Kalfayan and Metcalf, SPE 63178, 2000)
permeability, HF concentration, preflush type, and heterogeneity of the core. Wehunt\textsuperscript{7} also stated that wormholing in sandstone is due to the heterogeneity of core samples and high temperature.

From the above studies, it is clear that wormholing or high permeability channeling can exist in sandstone acidizing under certain conditions. But there is not yet a theoretical study to predict the conditions that generate wormholes in sandstone. It is the impetus for us to develop a fine-scale sandstone acidizing simulation model, which includes various factors that affect the results of sandstone acidizing, such as heterogeneity of the formation, treatment temperature, acid concentration, acid injection rate, initial porosity distribution, and so on. The goal of this study is to develop a theoretical model with a numerical simulation model to study the possibility of generating wormholes for a particular sandstone acidizing, and to find the optimal acid treatment design for sandstone wormholing.

1.3 Optimal Sandstone Wormholing Conditions

From the previous studies of sandstone wormholing acidizing, we could find that high temperature, high concentration of HF, acid injection rate, and heterogeneity of formation are the four key factors among the many others for wormholing in sandstones. For most acidizing cases, heterogeneity of the formation and temperature are fixed, but we can design acid concentration and
acid injection rate in the acid treatment to find the optimal condition for wormholing. From the previous research results, we know that the higher temperature and the lower acid injection rate, the easier it is for wormholes to develop. On the other hand, to consider the time and cost, high acid injection rate is preferred by field operations. Moreover, low acid injection rate is a potential factor causing unconsolidation on the of the formation.\(^5\)

For the convenience in sandstone wormholing design, it is necessary to find a range of wormholing conditions for a particular case. The easy way is to create a wormholing map for a specific case by an extensive simulation study over a range of condition. With the wormholing maps, we can easily identify whether wormhole could be generated for specific case, and if it could, design the acidizing treatment with the most effective treatment results. In Chapter 4, a case study of sandstone wormholing is presented.

### 1.4 Visualization of Numerical Simulation of High HF Concentration Sandstone Acidizing

A fine-scale sandstone acidizing simulator model has been developed by Li\(^8\) to focus on the study of wormholing in sandstones. In this model, there are 8000 grid blocks to compose a test core, and a numerical simulator developed to predict the properties of acidizing results for each grid block. A C++ visualization program was developed to display the three dimensional simulation
results on the GiD platform\textsuperscript{8}. The output displays include permeability, porosity, HF concentration, precipitation concentration, velocity of acid front, and porosity change at each grid block as a function of injected pore volume (injection time). A porosity change plot is a useful tool to easily detect if a wormhole is formed in the core sample after acid injection. High permeability trends can be tracked by the porosity change plot. With these 3D plots, conditions that are likely generate wormholes in sandstone acidizing can be easily identified. Chapter 3 discusses the 3D visualization plots in detail.
Chapter 2: Fine Scale Simulation of Acidizing in Heterogeneous Sandstones

2.1 Previous Sandstone Acidizing Models

Because of the complex mineral composition of sandstone, it is difficult to develop an exact theoretical model to simulate the reactions in a sandstone acidizing process. To simplify the complex reactions, the one acid, two-mineral model had been accepted in the industry for years before the two acids, three minerals model was developed by Bryant.

In the one acid, two-mineral model, quartz is treated as the slow-reacting mineral because it reacts relatively slowly with HF, while clay minerals and feldspars are treated as the fast-reacting minerals. The HF/HCl acid and sandstone system can be approximated as the following two dissolution reactions:

\[ \text{n}_1 \text{HF} + \text{Mineral 1} \rightarrow \text{p}_1 \text{H}_2\text{SiF}_6 + \text{fluorides of Al, etc} \]  \hspace{1cm} (1)

\[ \text{n}_2 \text{HF} + \text{Mineral 2} \rightarrow \text{p}_2 \text{H}_2\text{SiF}_6 \]  \hspace{1cm} (2)

where Mineral 1 is the lumped fast-reacting minerals and Mineral 2 is the lumped slow-reacting minerals.

Although the two lumped minerals model was used as the “standard” model for convenience, Bryant\textsuperscript{10,11} used the data from Lindsay’s experiments\textsuperscript{12} to
test the “standard” model and found that it did not adequately describe mud acid/sandstone interactions, especially when temperature is high. To improve the two lumped minerals model, Bryant\textsuperscript{10} proposed a new two-acid and three-mineral model for sandstone acidizing. Compared with the old model, the improved model add the third reaction which is ubiquitous in the sandstone acidizing process

\[
n_3H_2SiF_6 + \text{Mineral 1} \rightarrow p_3 SiO_2 + n_3 Si(OH)_4 + \text{fluorides of Al, etc}
\]

where SiO\textsubscript{2} is expressed as quartz. Moreover, Bryant asserts that the reactions are self-limiting because the silica gel will coat the clay surface.

da Motta et al\textsuperscript{13} introduced a four parameter model. Different from Bryant’s model, da Motta’s model does not include the production of quartz, and the silica gel can be dissolved by the HF rather than coating the surface of clay. The chemical reactions in da Motta’s model are described as follow:

\[
\begin{align*}
    v_1 & \quad HF + \text{minerals 1} \rightarrow v_5 H_2SiF_6 + \text{fluorides of Al} \\
    v_2 & \quad HF + \text{minerals 2} \rightarrow v_6 H_2SiF_6 + \text{fluorides of Al} \\
    v_3 & \quad HF + Si(OH)_4 \rightarrow v_7H_2SiF_6 + H_2O \\
    v_4 & \quad H_2SiF_6 + \text{minerals 1} \rightarrow v_8 Si(OH)_4 + \text{fluorides of Al}
\end{align*}
\]

With this four parameters model, da Motta explains the experiments by Cheung and Van Arsdale, and by Crowe as follows:

\textit{Silica gel may result in the damage at the initial acidizing treatment time. After a few pore volumes of acid injection, the}
permeability keeps increasing as more acid is injected, because the following HF can dissolve silica gel.

Moreover, da Motta believes that the reaction between fluosilicic acid and clays can increase the mineral dissolution power of the HF acid system.

### 2.2 Fine-scale Sandstone Acidizing Model

All of the previous sandstone acidizing models assumed that the properties of the core were homogenous. However, the sandstone wormholing studies report that the heterogeneity of the core is one of the key points for generating wormhole in sandstone. Based on the da Motta’s four-parameter model, Li applied a three tier reaction model in the sandstone wormholing simulation model. The primary tier reactions include HF with fast reacting mineral and HF with slow reacting mineral. The reactions can be written as

\[
v_1 HF + \text{minerals 1} \rightarrow v_5 H_2SiF_6 + \text{fluorides of Al}
\]

\[
v_2 HF + \text{minerals 2} \rightarrow v_6 H_2SiF_6 + \text{fluorides of Al}
\]

The secondary tier reaction is fluosilicic acid with fast reacting mineral and it can be written as

\[
v_4 H_2SiF_6 + \text{minerals 1} \rightarrow v_8 \text{Si(OH)}_4 + \text{fluorides of Al}
\]

The third tier reaction of HF dissolving silica gel is

\[
v_3 HF + \text{Si(OH)}_4 \rightarrow v_7 H_2SiF_6 + H_2O
\]
where minerals 1 is the fast-reacting mineral and minerals 2 is the slow-reacting mineral.

The physical model used in the Li’s model is a cylindrical core with 2 inches in length and 1 inch in diameter. To simulate heterogeneous properties in the sandstone core, Li divides the whole core into 100 grids along the X direction, and in each YZ plane, there are 80 grid blocks. Thus, there are a total of 8000 grid blocks for the whole core. The properties for each grid block, such as permeability, porosity, mineralogy etc, can be input individually to simulate the heterogeneity of the sandstone core. Therefore, each grid block is an independent unit, and the acid convection dependents on the pressure gradient in the conjunctive grid blocks.

Crowe\(^1\) stated that the silica gel precipitation may coat the surface of fast-reacting mineral, so sandstone acidizing is a self-limiting process. In the fine-scale sandstone acidizing simulator, there is no self-limitation for the acidizing reaction because the silica gel will be dissolved by following HF, especially at high HF concentration and high temperature conditions. Therefore, the fast-reacting mineral will easily be dissolved completely with HF. To simplify the chemistry reactions, Li ignores the reaction between HCl and aluminosilicates. This model also simplifies various types of precipitation to silica gel only. Although the model is an approximation for sandstone acidizing, its fine-scale
heterogeneous feature provides us a much better tool to study wormholing in sandstone acidizing.

The results of the sandstone acidizing simulation provide the information of porosity, permeability, pressure, acid concentration, mineral concentration, and flow velocity in each grid block. However, based only on this information, it is not easy to analyze the acidizing results. To monitor the wormholing process, we also develop a 3D visualization graphics program with C++. This visualization program can display the core with 8000 meshes in a three dimensional graphics. 3D visualization helps us to understand the simulation result more clearly and easily. The description of the method of using 3D Visualization Graphics for wormholing analysis is in Chapter 3.

2.3 Generation of Heterogeneous Field

Lamb\textsuperscript{4} and Thomas\textsuperscript{5} assert that sandstone wormholing depends highly on the heterogeneity of the core. Contrasting to the previous sandstone acidizing models, the fine-scale sandstone acidizing simulation model focuses on the effect of heterogeneity of the core on the acidizing result. The heterogeneous properties include porosity, permeability, and mineralogical composition. In this model, we can assign different values of porosity and mineral composition to each grid, and then calculate the permeability from the porosity and morphology. These values are first generated randomly with the mean value for all 8000 grids equal average
to the porosity or the average mineralogy composition for the core. For the core with a diameter of one inch and a length of 2 inches, the standard deviation was set to be 0.03 to generate a random normally distributed porosity for the system. The mineral composition distribution was assumed to be a uniform distribution, and the range of values is set as 5% difference from the average value.

Porosity, mineral content, and other variables in geoscience are usually not randomly distributed in space. Instead, they are usually spatially correlated. To simulate correlated porosity distribution and mineral content distribution, we used the Fast Fourier Transform (FFT) simulator. FFT is developed by J.W. Jennings\textsuperscript{15} with the University of Texas at Austin. This program can generate a group of numbers with 3D correlation. To run the FFT simulator, an input parameter file is needed. Parameters include the variogram type, the variogram sill, the correlation direction, and the correlation length in x, y, and z directions respectively. The results from running FFT simulator is a group of correlated numbers which are corresponding to the input parameters. A C++ program is needed to convert these numbers to the initial porosity or the initial mineral component for each grid block in the fine-scale sandstone acidizing simulator. In Chapter 4, we will discuss several specific cases of the simulation study, and each has a different heterogeneity.
Chapter 3: Visualization Results for Fine-Scale Acidizing Simulation

3.1 Converting Program for 3D Visualization

i. Background Introduction

The fine-scale sandstone acidizing simulator calculates porosity, permeability, pressure, concentration of HF, concentration of H$_2$SiF$_6$, concentration of Si(OH)$_4$, concentration of slow-reacting mineral, concentration of fast-reacting mineral, and the velocity of acid flow for each grid block in the core. To present the data more effectively, so that wormholes or wormholing trend can be detected directly and clearly, a special tool or method that can convert the numerical results to visual result is needed. A C++ program (3D Visualization Program) is used to display 3D graphics of the numerical simulation results. The 3D graphics are displayed using platform of GiD$^8$, which is a 3D engineering visualization software. Figure 3-1 is an example for the initial porosity in 3D graphical format. The value of initial porosity is scaled by colors. In this case, the initial porosity is correlated in the X direction, and there is a high initial porosity XZ plane in the middle of the core. In the GiD platform, graphical image can be rotated in any direction. Moreover, we also can select to display
Figure 3-1. 3D display of initial porosity distribution for Uta19 base case.
only the grid blocks that have a property value in a desired range. It is very helpful to detect if there is a wormhole in the core.

ii. Introduction of GiD Files

GiD is a graphics program, used to define and prepare the data for numerical simulation, as well as to visualize the results of numerical simulation. It is developed by the International Center for Numerical Methods in Engineering (CIMNE). This program generates meshes (for finite elements, finite differences or other methods), and transfers geometric data. An essential characteristic of GiD is that it is not specialized to any particular problem. Any user can make its own particular “problem type”, in such a way that GiD recognizes the syntax of its own particular simulation program.

GiD includes two sections, a preprocessor or a postprocessor. In our study, we only use the postprocessor to display the simulation results. Postprocessing consists of analysis of the results in such a way that it is very easy to interpret them. It is possible to visualize by colors, level curves, labels, vectors, graphics, animations, etc. To display an image in the GiD postprocessor, two files are needed, GiD Mesh file and GiD Result file. Both of these two files need to follow the GiD syntax exactly, including the file name and content format.
The name of a GiD Mesh file must have a double-suffix name as “.flavia.msh”. The Mesh file describes the geometric structure for the object which will be displayed in GiD postprocessor. In our study, we need to set MESH type as “block”; DIMENSION as “3”; ELEMTYPE as “Hexahedra”; and NNODE (number of nodes) as “8” in the first line of the Mesh file. Table3-1 is a sample for GiD Mesh file. Since there are 8000 grid blocks in the fine-scale sandstone acidizing simulator, and each grid block has eight nodes to create a cube, we need to assign the ID number and values of the coordinates in X, Y, and Z direction to each of 64000 nodes in the GiD Mesh file. After assigning the coordinates to each node, we still need to construct each grid block by 8 nodes in the GiD Mesh file. In this module, each grid block need to be assigned its own ID number and the ID numbers of its 8 nodes in a special order (anti-clockwise for the four nodes in the down plane first, then anti-clockwise for the other four nodes in the up plane).

The GiD Result file assigns the property values to all grid blocks which were defined in the GiD Mesh file. The name of GiD Result file must have a double-suffix name as “.flavia.res”, and its primary file name must be the same as that of the GiD Mesh file. The GiD Mesh file and the GiD Result file should be stored in the the same directory. For our study, the value for any property is the same inside a grid block. Therefore, we can define each grid block as a Gauss point, and assign values of the properties to these Gauss points. In the GID
Table 3-1. A sample of a GiD Mesh File

<table>
<thead>
<tr>
<th>MESH &quot;block&quot; DIMENSION 3 ELEM TYPE Hexahedra NNODE 8 COORDINATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 -3.06964e-010 4.05312e-009 0.762</td>
</tr>
<tr>
<td>2 -3.06964e-010 0.254 0.762</td>
</tr>
<tr>
<td>3 0.0508 0.254 0.762</td>
</tr>
<tr>
<td>4 0.0508 4.05312e-009 0.762</td>
</tr>
<tr>
<td>5 -3.06964e-010 4.05312e-009 1.016</td>
</tr>
<tr>
<td>6 -3.06964e-010 0.254 1.016</td>
</tr>
<tr>
<td>... ... ... ... ... ... ... ...</td>
</tr>
<tr>
<td>63993 5.0292 2.286 1.524</td>
</tr>
<tr>
<td>63994 5.0292 2.54 1.524</td>
</tr>
<tr>
<td>63995 5.08 2.54 1.524</td>
</tr>
<tr>
<td>63996 5.08 2.286 1.524</td>
</tr>
<tr>
<td>63997 5.0292 2.286 1.778</td>
</tr>
<tr>
<td>63998 5.0292 2.54 1.778</td>
</tr>
<tr>
<td>63999 5.08 2.54 1.778</td>
</tr>
<tr>
<td>64000 5.08 2.286 1.778</td>
</tr>
</tbody>
</table>

END COORDINATES

<table>
<thead>
<tr>
<th>ELEMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1 2 3 4 5 6 7 8</td>
</tr>
<tr>
<td>2 9 10 11 12 13 14 15 16</td>
</tr>
<tr>
<td>... ... ... ... ... ... ... ... ... ... ... ... ... ...</td>
</tr>
<tr>
<td>7999 63985 63986 63987 63988 63989 63990 63991 63992</td>
</tr>
<tr>
<td>8000 63993 63994 63995 63996 63997 63998 63999 64000</td>
</tr>
</tbody>
</table>

END ELEMENTS
Result file, we can define the GaussPoints as “block elements” and ElemType as Hexahedra "block"; Number Of Gauss Points as “1”; Natural Coordinates as “internal”. We also can set the name and the range of scale for RESULTRANGESTABLE, which can classify the values of a specified property into different ranges. The Table 3-2 is a sample of GiD Result file. To define a property, we need to set the name of that property, the type of the value, and the result range table. Then we assign the value of that property to each grid block. After that, we can define another property. If the value type is a vector, three values, which represent the values in X, Y, and Z direction, need to be assigned to one grid block.

iii. **3D Visualization Program Development**

A 3D Visualization Program (UT3DVIS) was developed in C++ language, which takes the results from the fine-scale sandstone acidizing simulator as the input file. Based on the data from the simulation results file, it generates the GiD Mesh file, GiD Result file, and a text file which includes the information for wormholing detection. Both GiD files are follow the GiD syntax, and can be opened in the GiD postprocessor to display the acidized core as a 3D image.

In UT3DVIS, 8000 grid blocks are rebuilt with the same dimension to imitate the test core in the fine-scale sandstone acidizing simulator. There are 100
Table 3-2. A sample of a GiD Result File

<table>
<thead>
<tr>
<th>GaussPoints &quot;block elements&quot; ElemType Hexahedra &quot;block&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number Of Gauss Points: 1</td>
</tr>
<tr>
<td>Natural Coordinates: internal</td>
</tr>
<tr>
<td>End GaussPoints</td>
</tr>
<tr>
<td>RESULTRANGESTABLE &quot;B-TABLE&quot;</td>
</tr>
<tr>
<td>- 0.2 : &quot;:-0.2&quot;</td>
</tr>
<tr>
<td>0.2 - 0.3 : &quot;0.2 -0.3&quot;</td>
</tr>
<tr>
<td>0.3 - 0.4 : &quot;0.3 -0.4&quot;</td>
</tr>
<tr>
<td>0.4 - 0.48: &quot;0.4 -0.48&quot;</td>
</tr>
<tr>
<td>0.48 - : &quot;0.48 - &quot;</td>
</tr>
<tr>
<td>END RESULTRANGESTABLE</td>
</tr>
<tr>
<td>RESULTRANGESTABLE &quot;V-TABLE&quot;</td>
</tr>
<tr>
<td>- 1 : &quot;: -1&quot;</td>
</tr>
<tr>
<td>1 - 2 : &quot;1 -2&quot;</td>
</tr>
<tr>
<td>2 - 3 : &quot;2 -3&quot;</td>
</tr>
<tr>
<td>3 - 4 : &quot;3 -4&quot;</td>
</tr>
<tr>
<td>4 - 5 : &quot;4 -5&quot;</td>
</tr>
<tr>
<td>5 - : &quot;5 - &quot;</td>
</tr>
<tr>
<td>END RESULTRANGESTABLE</td>
</tr>
<tr>
<td>RESULT &quot;Porosity Profile&quot; &quot;Acidizing Mode3&quot; 1 Scalar OnGaussPoints &quot;block elements&quot;</td>
</tr>
<tr>
<td>RESULTRANGESTABLE &quot;B-TABLE&quot;</td>
</tr>
<tr>
<td>ComponentNames &quot;Porosity&quot;</td>
</tr>
<tr>
<td>Values</td>
</tr>
<tr>
<td>1 0.0992499</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>8000 0.124012</td>
</tr>
<tr>
<td>End Values</td>
</tr>
<tr>
<td>RESULT &quot;Velocity&quot; &quot;Acidizing Mode3&quot; 1 Vector OnGaussPoints &quot;block elements&quot;</td>
</tr>
<tr>
<td>RESULTRANGESTABLE &quot;V-TABLE&quot;</td>
</tr>
<tr>
<td>Values</td>
</tr>
<tr>
<td>1 9.12668e-005 -1.82525e-005 -1.8253e-005</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>8000 0.000450828 0 0</td>
</tr>
<tr>
<td>End Values</td>
</tr>
</tbody>
</table>

...
layers in the X-direction of the core, and each layer contains 80 grid blocks. Each grid block is assigned a unique ID number, and the location for a specified grid block depends on the coordinates of its eight nodes. Figure 3-2 presents a picture of a core which consists of 8000 grid blocks (64000 nodes). All information about the coordinate of the nodes is stored in the GiD Mesh file, which is created by the UT3DVIS.

After construction of the core, it is necessary to assign the values of all properties to each grid block in the core. Although the whole core can be heterogeneous, for each individual grid block unit, it is homogenous inside the cube for all properties. Thus, every grid block is an individual Gauss point, and all the data for a grid block can be directly assigned to the corresponding Gauss point. The velocity of the acid flow rate is assigned as a vector value, while all other properties are assigned as scalar values for the grid block. To monitor the process of wormholing, initial porosity (the porosity before acid injection) and delta porosity (the porosity change due to acidizing) are added to the GiD operation menu in UT3DVIS besides other properties which are generated by the fine-scale sandstone acidizing simulator. Figure 3-3 is a sample of the GiD operation menu to select the desired property in the GiD platform. All information about the values of properties is stored in the GiD Result file which is also created by UT3DVIS.
Figure 3-2. The construction of the core which is consisted by 8000 grid blocks.
There are 100 layers in X direction for the core. In for each YZ plane layer, there are 80 grid blocks.
Figure 3-3. The operation menu in the GiD Platform
UT3DVIS also generates a text data file to provide the data for each YZ plane layer. The data include maximum HF concentration, average HF concentration, maximum delta porosity, and average delta porosity for each YZ plane layer. Plotting these data vs the index of YX plane, it helps us to determine whether there is a main channel for acid flow in the core.

iv. **UT3DVIS Manual**

Before running UT3DVIS, we need store the fine-scale sandstone acidizing simulator result file into the same directory that UT3DVIS is in. After running UT3DVIS, the GiD Mesh file, the GiD Result file, and a text information file will be created in the same directory.

To display the 3D image in the GiD platform, open the GiD program and convert the process to postprocessor (Click the seventh icon on the up button bar). Then open either GiD Mesh file or GiD Result file which is created by UT3DVIS.

To rotate the graphic, click the fifth icon on the left button bar first, then press the left button of the mouse and drag the mouse in any direction.

To display the values of a specified property for all 8000 grid blocks, click the “view result” menu on the main menu bar, then go to “Contour Fill”, and select the desired property. Figure 3-3 is an example for property menu selection.

To select the grid block with the value of a specified property in a desired
range, click the “Options” menu on the main menu bar, select the desired property, then go to “Contour” and click the “Define Limits” menu.

To store the current image to an image file, click the fifth icon on the top button bar.

3.2 Multiple Methods to Detect Wormhole Existence in the Core from the Simulation Result Data

It is difficult to directly judge whether there is a wormhole in the core, or if there is, how long it is and how it extends in the core, from the numerical data of the simulation results. However, using 3D visualization graphics in the GiD platform, we can display only the grid blocks that have a value of a property in a desired range. In other words, we can display only the grid blocks with high permeability, or high delta porosity, or any other properties that would help us to detect the wormhole trend. By rotating a 3D picture freely, it also allows us to view all information in the core during the acidizing process easily, and to detect the existence of wormholes or main acid flow channels in the core.

To demonstrate the functions of 3D visualization graphics, one sample case, Uta19, is used in this chapter is Uta19 experiment. Experiment Uta19 was implemented under high HF concentration condition for sandstone wormholing study\textsuperscript{19}. In experiment Uta19, the core used is a two-inch long and one inch in diameter Berea sandstone. The average porosity of the core is 0.18; the volume
fraction of fast minerals is 0.15; the volume fraction of slow mineral is 0.82; the volume fraction of carbonate is 0.03; the experimental temperature is 122°F (In the simulation Uta19 base case, we set temperature is 422°F, which is easier to generate wormholes). The acid injection rate is 2.5 ml/min, and the volume injected is 20 pore volume. The original rock sample has visible streaks. To simulate the laminated construction in the sandstone, we artificially set that there is a high initial porosity XZ plane in the middle of the core in the simulation. The mineralogy distribution is homogeneous in Uta19 case.

The following is the description of how the simulation results to detect wormholes Uta19 base case. The properties and treatment data of Uta19 are summarized in Table 3-3.

Table 3-3. Properties and Treatment Data Summary of Uta19 base case

<table>
<thead>
<tr>
<th>Properties and Treatment Data</th>
<th>Uta19</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>2</td>
<td>inch</td>
</tr>
<tr>
<td>Core diameter</td>
<td>1</td>
<td>inch</td>
</tr>
<tr>
<td>Average initial porosity</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Volume fraction of fast reacting mineral</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Volume fraction of slow reacting mineral</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Volume fraction of carbonate</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Concentration of HCl</td>
<td>6</td>
<td>wt%</td>
</tr>
<tr>
<td>Concentration of HF</td>
<td>6</td>
<td>wt%</td>
</tr>
<tr>
<td>Acid injection rate</td>
<td>2.5</td>
<td>ml/hr</td>
</tr>
<tr>
<td>Experimental temperature</td>
<td>422</td>
<td>°F</td>
</tr>
<tr>
<td>Injected pore volume</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
i. **Initial Porosity**

Initial porosity is the values of porosity for in each block before acid injection. In the fine-scale sandstone acidizing simulator, these values are randomly generated with a certain degree of correlation, and are assigned to the grid blocks respectively. The program allows the user to generate the initial porosity in the core randomly (with no any correlation), with correlation (linear correlation) in one dimension, or with correlation (laminated correlation) in two dimension. The 3D picture of initial porosity for Uta19 case with an YZ plane layer in the middle of the core having higher initial porosity than other grid blocks, is shown in Figure 3-1.

ii. **Porosity Profile**

If there is a wormhole or a high porosity channel in the core, the grid blocks that have high porosity value should be connected and extend from the inlet side to some distance or to the outlet side of the core. In the 3D acidizing result graphics, we can set a minimum cut-off value for porosity, and only display the grid blocks with porosity that is higher than the minimum cut-off value. If these high porosity blocks are connected in the acid flowing direction in the core, we believe that there is a wormhole or a high porosity channel in the core after the acidizing. In Figure 3-4a, the picture displays the porosity distribution for all block grids for Uta19. In Figure 3-4b, the picture displays the block grids with a
Figure 3-4a. Porosity distribution.

Figure 3-4b. The grid blocks with higher porosity ($\phi > 0.4$)
porosity that is higher than 0.4 after acidizing. It is obvious that there is a high porosity channel going through the whole core. From this picture, we can conclude that there is a high porosity channel in the core which is created by the acidizing process.

iii. **Delta Porosity**

Delta porosity is another property for wormhole detection. Delta porosity for a grid block is the difference between the initial porosity and the porosity after acidizing. It can be positive if the porosity increases due to the dissolution of the mineral, it also can be negative if the porosity decreases because the volume of precipitation is larger than the volume of the dissolved mineral in grid block. Delta porosity shows us whether the high porosity comes from acidizing or comes from the initial porosity distribution. Figure 3-5a is the delta porosity distribution for the whole core in Uta19 case, and figure 3-5b displays the grid blocks in which the delta porosity is higher than 0.18. Comparing with Figure 3-4b, the high porosity channel and high delta porosity channel are in the same place in the core. Therefore, the high porosity channel is generated by acidizing rather than by the initial porosity distribution in this case.

iv. **HF Acid Concentration**

The distribution of HF acid concentration in the core provides information
Figure 3-5a. Delta porosity distribution.

Figure 3-5b. The grid blocks with higher delta porosity ($\Delta \phi > 0.15$)
about the appearance of high permeability channels in the core. Since the injected fluid prefers going through the grid blocks that have higher permeability than others, we can display the grid blocks with high HF concentration to represent the high permeability channel. Moreover, the acid converging into the high permeability channel will continue increasing the porosity in these grid blocks, and consequently, the permeability will keep increasing. This phenomenon is a self-feeding process, and will be helpful for wormholes to develop. Figure 3-6a is the HF acid concentration distribution for Uta19 case, and Figure3-6b displays the grid blocks with the higher HF concentration. We can see that there is a main acid flow channel in the Uta19 case. Comparing with previous the figures (Figure 3-4b and Figure3-5b), the HF concentration channel is also at the same location as the high porosity channel in the core. It means the porosity of the main channel would increase continually if more acid were injected into the core.

v. **Si(OH)₄ Concentration**

Si(OH)₄ is a precipitate that is found during the sandstone acidizing process. Whether the precipitation is a positive factor or a negative factor for the sandstone wormholing is a disputable question. Since UT3DVIS can provide the precipitation distribution in the core during the acidizing process, it helps us to discover the role of precipitation in sandstone wormholing. Figure 3-7a and
Figure 3-6a. HF concentration distribution.

Figure 3-6b. The grid blocks with higher HF concentration ($C_{HFD} > 0.01$)
Figure 3-7b show the precipitate distribution for Uta19. We see that the high precipitate concentration zones exist in inlet surface of the core except where the main acid flow channel is, and further they also surround the high porosity channel through the whole core length. In a sandstone acidizing process, Si(OH)$_4$ is a product of the reaction between H$_2$SiF$_6$ and the fast-reacting mineral. Since the front of Si(OH)$_4$ is farther than the HF front from the acid flow inlet, Si(OH)$_4$ will be dissolved by the flowing HF. The HF flowing in the X direction from the inlet side to the outlet makes Si(OH)$_4$ remain in the grid blocks that are contiguous to the high porosity grid block in YZ plane. Precipitations make more and more HF flow converge to the high permeability / high porosity grid blocks, and form a main acid flow channel in the core. This enhances high porosity / high permeability channel development. Therefore, we believe that precipitation has a positive effect on heterogeneous sandstone wormholing.

vi. **Velocity of Acid Flow**

UT3DVIS can display the velocity of acid flow in each grid block with a vector value. Acid flow velocity can be disassembled into three scalar values for the velocity in the X, Y, and Z directions respectively ($|V_{XD}|$, $|V_{YD}|$, and $|V_{ZD}|$), or can be displayed as a scalar value of the magnitude of the velocity in a given direction ($|V_{D}|$). The scalar velocity in the X-direction shows the fast flow of acid
Figure 3-7a. The YZ plane view from the inlet of the core for precipitation

Figure 3-7b. The three dimension view of the core for precipitation
in the injection direction, and hence indicates where the high permeability channel is. Figure 3-8a displays the high acid flow velocity (the magnitude of the velocity is higher than injection rate, for which the dimensionless value is 1) in the X direction. Figure 3-8b displays the magnitude of the high velocity in three directions. It is obvious that there is a high acid velocity channel in the core. The high velocity channel is coincident with the high porosity channel which we displayed before.

vii. **Permeability and Pressure**

In general, permeability is the most important parameter to assess the result of acidizing. In fine-scale sandstone acidizing simulator, permeability is calculated from the porosity value using the Panda and Lake\textsuperscript{17} model for each grid block. Pressure is calculated from acid injection rate and the permeability is by Darcy’s law. Therefore, for each grid block, the values of permeability and pressure only depend on the porosity value in that grid block for a fixed acid injection rate. In UT3DVIS, permeability and pressure can be displayed for each grid block in addition to the porosity for wormholing analysis. Figure 3-9a displays the permeability distribution of the whole core for Uta19 case. Figure 3-9b displays the high permeability grid blocks. We find that there is a high permeability channel in the core whose location is same as the high porosity channel.
Figure 3-8a. The grid blocks with higher flow velocity in X direction ($|V_{XD}| > 1$)

Figure 3-8b. The grid blocks with higher velocity in three directions ($|V_{D}| > 1$)
Figure 3-9a. Permeability distribution.

Figure 3-9b. The grid blocks with higher permeability (K>1)
viii. **Slow-reacting Mineral Concentration and Fast-reacting Mineral Concentration**

UT3DVIS can display the concentration of slow reacting mineral (quartz) and the concentration of fast-reacting for each grid block. From analysis of the concentration of fast-reacting mineral, we can get information about whether the acidizing process is completed, and we can also detect the existence of a main channel of acid flow in the core. In Figure 3-10a, we find that the fast-reacting minerals have been completely dissolved in the main acid flow channel. In the grid blocks which are around the main acid flow channel, the concentration of fast-acting mineral is less than half of the initial value. In this case, if we inject more acid continuously, the diameter of main acid flow channel may increase. In Figure 3-10b, the concentration of slow-reacting mineral is only slightly less than the initial value in the main acid flow channel. It indicates that the reaction between quartz and HF does not help the wormholing generation in Uta19 case, even at high temperature conditions.

ix. **Maximum Delta Porosity vs. Average Delta Porosity for each YZ plane layer**

Besides generating three-dimension images of the sandstone acidizing results, UT3DVIS creates a data file from the simulation result. This data file includes four columns of data, which are maximum delta porosity, average delta porosity,
Figure 3-10a. The grid blocks with lower fast-reacting mineral concentration ($C_F < 0.5 C_{FD}$).

Figure 3-10b. The grid blocks with lower slow-reacting mineral concentration ($C_S < 0.95 C_{SD}$)
porosity, maximum HF concentration, and average HF concentration for each YZ plane respectively. With these data, we can conduct a numerical analysis for sandstone wormholing.

For each YZ plane, there are 80 grid blocks. The average delta porosity can be expressed as:

$$\Delta \Phi_{av} = \frac{\sum_{i=1}^{80} \Delta \Phi_i}{80}$$

Figure 3-11 is the plot of the maximum delta porosity and the average delta porosity for each YZ plane in Uta19 case. In the plot, we can find that average delta porosity is negative for all 100 YZ planes while the maximum delta porosity is around 0.2 for all layers. This means the overall delta porosity is below zero, or the average porosity is decreased. But the maximum delta porosity is around 0.2 in the X direction. This indicates that on each YZ plane there exist some grid blocks in which porosity increased while porosity in other grid blocks decreased. It provides proof that there is a main channel for acidizing in the core, and the precipitation is a positive factor for generating wormhole because precipitation blocks other part of the core and forces the acid flow to converge to the main channel.
Figure 3-11. The maximum delta porosity and average delta porosity for each YZ plane.
x. **Maximum HF Concentration vs. Average HF Concentration for each YZ plane**

For each YZ plane, the average HF concentration can be expressed as:

\[
C_{av} = \frac{\sum_{i=1}^{80} C_i}{80}
\]

Figure 3-12 is a plot of maximum HF concentration and average HF concentration for each YZ plane in the Uta19 case. From this plot, the maximum HF concentration is much higher than the average HF concentration for the same layer through the whole core. It proves that there is a main channel for acid flow in the core, which matches our analysis using the 3D visual graphics.

### 3.3 Summary

UT3DVIS is a multifunctional tool for sandstone wormholing analysis. It can provide objective visual pictures for sandstone wormholing simulation from the tedious data files generated from the numerical simulator. It also can be used to do numerical analysis of the simulation result to find channeling in sandstone acidizing. We can utilize the result of UT3DVIS to determine whether wormholing will occur under a specified condition. As the consequence, we can generate an optimal wormholing condition map for any specific sandstone acidizing case, which could be uses as a guideline for sandstone acidizing
Figure 3-12. The maximum HF concentration and average HF concentration for each YZ plane
treatment design for that case. In Chapter 4, we will discuss the impact of simulation parameters on wormholing, and demonstrate a sample of the channeling map for a specific case.
Chapter 4: Parametric Study for Sandstone

Channeling / Wormholing

4.1 Introduction

Sandstone acidizing is a complex chemical reaction process. It includes multiple tiers of reactions for various reactants. The acidizing result is affected by various factors. In fine-scale sandstone acidizing simulator, these factors are input parameters. In this chapter, a base case (Uta19) is used to study the effect of these parameters on sandstone channeling / wormholing. Table 4-1 lists all the parameters in the input file.

To study the impact of the parameters in a sandstone acidizing process, we can classify these parameters into three groups. The first group is the fixed parameter group. In this group, all parameters have a fixed value in the simulation and the experiment. The parameters in this group include core length, core diameter, density of acid, density of minerals, grid numbers, viscosity of HF, operation time, time step, dissolving powers, and specific surface area of slow-reacting mineral. Their impacts on the acidizing process are not considered in this study. The second group of parameters includes initial porosity (with heterogeneity distribution), temperature, volume fraction of fast mineral (with
Table 4-1. Uta19 Base case Input Data File

<table>
<thead>
<tr>
<th>Parameter</th>
<th>uta19</th>
</tr>
</thead>
<tbody>
<tr>
<td>core length</td>
<td>2 inch</td>
</tr>
<tr>
<td>core diameter</td>
<td>1 inch</td>
</tr>
<tr>
<td>Nx grid number</td>
<td>100</td>
</tr>
<tr>
<td>Ny grid number</td>
<td>10</td>
</tr>
<tr>
<td>porosity</td>
<td>0.18</td>
</tr>
<tr>
<td>outlet pressure</td>
<td>1 atm</td>
</tr>
<tr>
<td>flow rate (ml/hr)</td>
<td>2.5 ml/hr</td>
</tr>
<tr>
<td>temperature</td>
<td>422 K</td>
</tr>
<tr>
<td>operation time</td>
<td>60 minute</td>
</tr>
<tr>
<td>time step</td>
<td>5 second</td>
</tr>
<tr>
<td>Specific area for fast reacting mineral</td>
<td>4.19E+08 m²/m³ (for Kaolinite)</td>
</tr>
<tr>
<td>Specific area for slow reacting mineral</td>
<td>300000 m²/m³</td>
</tr>
<tr>
<td>reaction rate constant E0 (fast-HF)</td>
<td>0.33 kg-mole (for Kaolinite)</td>
</tr>
<tr>
<td>reaction rate constant E0 (slow-HF)</td>
<td>2.32E-08 kg-mole mineral/(m²·sec·(kg-mole HF/m³) acid)</td>
</tr>
<tr>
<td>dissolving power (mass) (fast-HF)</td>
<td>0.486 Mass of rack dissolved/mass of acid reacted</td>
</tr>
<tr>
<td>dissolving power (mass) (no meaning)</td>
<td>1</td>
</tr>
<tr>
<td>dissolving power (mass) (slow-HF)</td>
<td>0.5</td>
</tr>
<tr>
<td>density of fast reacting mineral</td>
<td>2600 kg/m³ (density of Kaolinite)</td>
</tr>
<tr>
<td>density of slow reacting mineral</td>
<td>2650 kg/m³</td>
</tr>
<tr>
<td>reaction rate constant E0 (silica gel-HF)</td>
<td>9.86E-06 calculating from Van’t Hoff law</td>
</tr>
<tr>
<td>reaction rate constant E0 (fast-H₂SiF₆)</td>
<td>2.06E+00 for Kaolinite</td>
</tr>
<tr>
<td>Specific area for silica gel</td>
<td>2.00E+06 m²/m³</td>
</tr>
<tr>
<td>density for silica gel</td>
<td>740</td>
</tr>
<tr>
<td>dissolving power (mass) (silica gel-HF)</td>
<td>0.8</td>
</tr>
<tr>
<td>dissolving power (mass) (fast-H₂SiF₆)</td>
<td>2.47</td>
</tr>
<tr>
<td>concentration of HCl</td>
<td>6 wt%</td>
</tr>
<tr>
<td>concentration of HF</td>
<td>6 wt%</td>
</tr>
<tr>
<td>viscosity of HF</td>
<td>0.89 cp</td>
</tr>
<tr>
<td>density of acid</td>
<td>1075 kg/m³</td>
</tr>
<tr>
<td>volume fraction of fast mineral</td>
<td>0.15 (Assuming are Kaolinite)</td>
</tr>
<tr>
<td>volume fraction of slow mineral</td>
<td>0.82</td>
</tr>
</tbody>
</table>
heterogeneity distribution), volume fraction of slow mineral, and specific surface area for fast-reacting mineral. In this group, all parameters could have different values from case to case, but we cannot change the value in the acidizing design for a particular case. They are objective parameters in the simulation. The third group includes HF concentration, acid injection rate, and acid injection pore volumes. We can adjust these parameters in the acid treatment design, so they are subjective parameters in the simulation.

In this chapter, we will discuss the impact of the parameters in the second group and third group individually. For any individual parameter study, we keep the other parameters constant, and only change the one which we are focusing on to make sure that the difference in the result is caused by that specific parameter.

4.2 Reaction Temperature

Some previous research has reported that more precipitation would be generated at high temperature, which is a potential damage factor for homogenous sandstone acidizing treatment.\textsuperscript{10} On the other hands, others believed that HF acid might effectively remove damage from sandstone at high temperature.\textsuperscript{7} In heterogeneous sandstones, we believe that high temperature will have a positive impact on acid stimulation, since the precipitation is helpful in some way to form main acid flow channels.
In the fine-scale sandstone acidizing simulator, there are four different chemical reactions which are classified into three tiers. To predict the result of acidizing process, we need to know the reaction rate for each reaction

$$r = kc_A^\alpha c_B^\beta \ldots$$

Where \( r \) is the reaction rate, \( k \) is the reaction rate constant, and \( c_A \) and \( c_B \) are the concentrations of the reactants. \( \alpha \) and \( \beta \) are reaction order coefficients which are constants for a particular reaction. The values for \( \alpha \) and \( \beta \) can be obtained from experiments. The initial reactant concentration can be set as dimensionless values. The reaction rate constant, \( k \), is a function of temperature:

$$k = A \exp\left(-\frac{E_o}{RT}\right)$$

Where preexponential factor \( A \) and activation energy \( E_o \) are the constants for an idiographic chemical reaction.

The approximate law of van’t Hoff states that the reaction rate constant will increase to about 2~4 times while the temperature increases 10°K for most chemical reactions. That is

$$\frac{K_{T+10}}{K_T} = 2 \sim 4$$
From Bryant’s research, we know the reaction rate of the secondary reaction is slow if temperature is below 120 °F, and it will become very fast at the high temperature, especially for the reaction between fluosilicic acid and Kaolinite. Since we already have the reaction rate constants at room temperature from the empirical values for all four chemical reactions in the simulation, we can calculate the reaction rate constant at high temperature from van’t Hoff’s approximate law for each reaction respectively. For the reaction between fluosilicic acid and Kaolinite, we set the ratio of $K_{T+10}/K_T$ is 4 because the reaction rate for this reaction increases much higher than other reactions when temperature increase, and the ratio of $K_{T+10}/K_T$ is set as 2 for all other reactions in the simulator. The result of this hypothesis is matched the experimental data by the study of kinetics of the secondary reaction of HF on alumino-silicates.

Therefore, we can use vat’t Hoff’s approximate law to calculate the various reaction rate constants at different temperature, and find out the impact of temperature on sandstone wormholing or channeling.

Thomas et al. reported a successful sandstone wormholing case under high temperature conditions. From our simulation result, we can use the maximum porosity value or maximum delta porosity value to represent the acidizing result. Figure 4-1 shows the plots for the maximum porosity value vs. temperature and the maximum delta porosity value vs. temperature for Uta19 case. From Figure 4-1, it can be seen that both maximum porosity and delta
Figure 4-1. The impacts of temperature and different fast-reacting minerals on maximum delta porosity and maximum porosity
porosity increase as the treatment temperature increases. Figure 4-2a and Figure 4-2b show a 3D image for grid blocks which porosity is higher than 0.4 at 422K and 343K respectively. Figure 4-3a and Figure 4-3b are the images for grid blocks which delta porosity is higher than 0.15 at 422K and 343K respectively. These plots show that higher porosity channel is easier to create at a higher temperature than at a lower temperature.

4.3 Acid Injection Rate

Damkohler number is a parameter that relates the reaction rate to the injection rate, defined as the ratio of the rate of acid consumption to the rate of acid convection. For the fast-reacting minerals, the Damkohler number is

\[
N_{Da,F} = \frac{(1 - \phi_0) V_F^0 E_{f,F} S_F^* L}{u}
\]

where, \( V_F^0 \) is the initial fast-reacting mineral volume fraction

\( E_{f,F} \) is the reaction rate constant for fast-reacting mineral

\( S_F^* \) is the specific surface areas for fast-reacting mineral

\( L \) is the core length

\( u \) is rate of acid convection.
Figure 4-2a. The grid blocks with higher porosity ($\phi>0.4$) at 422$^\circ$K

Figure 4-2b. The grid blocks with higher porosity ($\phi>0.4$) at 343$^\circ$K
Figure 4-3a. The grid blocks with higher delta porosity ($\Delta \phi > 0.15$) at 422°K

Fig 4-3b. The grid blocks with higher delta porosity ($\Delta \phi > 0.15$) at 343°K
As acid is injected into sandstone, a reaction front is established by the reaction between the HF and the fast-reacting minerals. The shape of this front depends on the Damkohler number of the fast-reacting mineral. If acid injection rate is high, Damkohler number will be low, and the front will be diffuse. On the contrary, low injection rate will result in a sharp reaction front.

To discover the impact of acid injection rate on sandstone channeling, we analyze the acidizing simulation results of two cases. One is a porosity distribution with a high correlation case (a high porosity layer in the middle of the core), which is an ideal channeling condition; the other is random porosity distribution case, which is not a likely condition for channeling. Figure 4-4 is the maximum porosity and maximum delta porosity plot with various acid injection rates for the correlated distribution case. We can see from Figure 4-4 that lower acid injection rate results in a higher porosity increase in the core. In Figure 4-5 (a and b) and Figure 4-6 (a and b), we compare the porosity values and delta porosity values in the main acid flow channel for a low acid injection rate case (1ml/min) and a high acid injection rate case (20 ml/min). It shows that at the lower acid injection rate, the porosity is higher in the channel. The reason is that the reaction between HF and mineral is reaction rate controlled, and slower acid injection rate makes the acid residence in time longer, so the acid reacts with the mineral more completely before it exits the core. In another word, slower injection rate means higher Damkohler number, and leaves a sharp reaction front.
Figure 4-4. The impact of acid injection rate to maximum porosity and maximum delta porosity
Figure 4-5a. The grid blocks with porosity higher than 0.3 at acid injection rate of 1 ml/min

Figure 4-5b. The grid blocks with porosity higher than 0.3 at acid injection rate of 20 ml/min
Figure 4-6a. The grid blocks with delta porosity higher than 0.15 at acid injection rate of 1 ml/min

Figure 4-6b. The grid blocks with delta porosity higher than 0.15 at acid injection rate of 20 ml/min
Moreover, slow acid injection rate may create more precipitation. If there is a main acid flow channel, precipitation will block the grid blocks around the main acid flow channel vicinity, and force acid to converge into the high porosity channel.

For the random porosity distribution case, Figure 4-7a shows that there still are several high porosity channels in the core if the injection rate is slow. These high porosity channels are more dispersed than the channels in the correlated porosity distribution case, and there is face dissolution at low injection rates. If the injection rate is high, there will be no high porosity channel. Therefore, sandstone channeling is not likely to happen, even with low injection rate, for randomly distributed initial porosity case. Moreover, slow injection rate will eventually results in face dissolution at the inlet of the core, rather than penetrates the acid through the core. It also creates unconsolidated surface at the inlet.

### 4.4 Mineral Distribution Correlation

Our study shows that mineral distribution is a strong factor in sandstone channeling and wormholing. If the porosity distribution has high correlation (for example, if there is a high initial porosity layer in the core), it is easier to generate a high porosity channel in the sandstone, and almost all injected acid will pass through this channel (Uta19, Figure 4-1 to Figure 4-6).
If the initial porosity distribution is not correlated, we may still find some porosity grid blocks connected together, therefore, there is a trend to form high permeability channels when acid injection rate is slow and temperature is high. Comparing with the channel in the correlation case, the high porosity channel is more dispersed, and the porosity increase is smaller (Figure 4-7a). On the other hand, if the injection rate is high, the high porosity channel cannot be created (Figure 4-7b).

From Figures 4-8a and 4-8b, which display the high HF concentration ($C_{HF} > 0.5$) distribution for the initial random porosity distribution cases, there are HF flow channels for both high acid injection rate case and low acid injection rate case. However, a slight high-porosity channeling trend only occurs in the slow injection rate case (Figure 4-7a). It indicates that without a strong correlated mineral distribution or strong correlated initial porosity distribution, the channeling / wormholing is not easy to occur, even though the HF acid is not homogeneously distributed in a random initial porosity distribution case. So the heterogeneity of the core is the dominant factor for sandstone channeling / wormholing, while the acid injection rate is a minor factor for sandstone channeling / wormholing.
Figure 4-7a. The grid blocks with porosity higher than 0.38 at injection rate 2.5 ml/min for random initial porosity distribution.

Figure 4-7b. The grid blocks with porosity higher than 0.38 at injection rate 20 ml/min for random initial porosity distribution.
Figure 4-8a. The grid blocks with dimensionless HF concentration higher than 0.5 at acid injection rate of 2.5 ml/min for random initial porosity distribution

Figure 4-8b. The grid blocks with dimensionless HF concentration higher than 0.5 at acid injection rate of 20 ml/min for random initial porosity distribution
4.5 **HF Acid Concentration**

Since the high HF concentration may cause problems such as unconsolidated sand or severe reprecipitation\textsuperscript{21,22}, in traditional sandstone matrix acidizing, lower-strength HF solutions are preferred to reduce the precipitation damage from spent acid and the risk of unconsolidation of the formation around the wellbore. However, for heterogeneous sandstone, the porosity is not uniform in the formation. Acid may flow through the path which has high porosity than the other parts of the sandstone. It will make these higher porosity paths have even higher porosity, and become high porosity channels in the core. The rate of mineral dissolution is depends on the reaction rate constant and concentration of HF:\textsuperscript{13}

\[-R_A = E_f C_{HF}^\alpha S_B\]

where 
- \(R_A\) is the rate of appearance of mineral A
- \(E_f\) is the reaction rate constant
- \(C_{HF}\) is the concentration of HF
- \(\alpha\) is the reaction order (\(\alpha > 0\))

Obviously, higher HF concentration results in more minerals being dissolved. Figure 4-9 shows that the maximum porosity and maximum delta
Figure 4-9. The impact of HF concentration to maximum porosity and maximum delta porosity
porosity increase as HF concentration increases. Although high HF concentration will result in more precipitation, the following HF can dissolve the precipitates again. Therefore, high HF concentration is necessary for channeling in sandstone acidizing. Figures 4-10a and 4-11a show that there is no high porosity channel created when 9wt% HCl; 1wt% HF is used for the case with the temperature at 343K, acid injection rate of 2.5 ml/min, and initial random porosity distribution. Figures 4-10b and 4-11b show that a high porosity channel will appear if the concentration for HCl and HF are both 12wt% for the same case in Figure 4-10a and Figure 4-11a.

4.6 Different Fast-reacting Mineral

There are commonly two kinds of fast-reacting mineral in sandstone, clay and feldspar. Although HF can dissolve both of these two minerals much faster than it dissolves quartz, these two minerals have different specific surface areas and different variabilities of reaction rate with temperature. If the temperature is not too high (below 323 K), we can ignore the difference of impact for the two fast-reacting minerals. However, clay may create more precipitation than feldspar at high temperature, because the reaction rate of clay in the secondary reaction increases much faster than that of feldspar at high temperature. Figure 4-12 is the through break pore volumes as a function of temperature using Uta19 data. When the fast-reacting mineral is clay, the through break pore volume is 3.05,
Figure 4-10a. The grid blocks with delta porosity higher than 0.1 at HF concentration of 1wt% 

Figure 4-10b. The grid blocks with delta porosity higher than 0.1 at HF concentration of 12wt%
Figure 4-11a. The grid blocks with porosity higher than 0.3 at HF concentration of 1wt%.

Figure 4-11b. The grid blocks with porosity higher than 0.3 at HF concentration of 12wt%.
Through break time for Uta19
acid injection rate= 2.5ml/min

Figure 4-12. The break though time for two cases in which fast-reacting mineral is clay and fast-reacting mineral is feldspar
which is longer than that when fast-reacting mineral is feldspar (through break pore volume is 1.64). The temperature is higher; the difference of the through break pore volume is larger. This is because the reaction between clay and acid is stronger than the reaction between feldspar and HF at high temperature. Therefore, we may need to consider the impact of the different properties for clay and feldspar on sandstone channeling/wormholing at high temperature.

To test the difference of clay and feldspar as fast-reacting mineral in sandstone acidizing at high temperature condition (>122°F), we ran two identical cases in sandstone wormholing simulation, except for setting clay as the fast-reacting mineral in the one case, and feldspar as the fast-reacting mineral in the other case. In Figure 4-1, the maximum porosity values and the maximum delta porosity values for the two cases are very close at various temperature conditions. At high temperature, from Figures 4-13a and 4-6b, in which the feldspar is set as the fast-reacting mineral, the high porosity channel is similar as those in Figures 4-2a and 4-2b, in which clay is set as the fast-reacting mineral. So, we believe that the difference of the properties for clay and feldspar do not make a strong impact on sandstone channeling/wormholing, even at high temperature condition. Because all fast-reacting mineral, no matter what it is clay or feldspar, will be dissolved completely in the acid flow channel after a sufficient amount of acid is injected. To predict the channeling generation in sandstone acidizing
Figure 4-13a. The grid blocks with porosity higher than 0.4 for feldspar as fast-reacting mineral at 422°K

Figure 4-13b. The grid blocks with porosity higher than 0.4 for feldspar as fast-reacting mineral at 343°K
conservatively, we may use the properties of feldspar for fast-reacting mineral in sandstone acidizing simulation as well.

### 4.7 A Sample Channeling Map

High HF concentration can create high porosity channels in sandstone. However, using an HF that has a concentration higher than 6 wt% may be limited by EHS (Environment, Health, and Safety) regulation in some locations. On the other hand, high acid injection rate is always preferred to reduce the operation cost. If the goal of acid treatment is to generate channels and wormholes in a particular case, we should use as aggressive of HF as EHS regulation allows, and as high acid injection rate as channeling could happen at the specified temperature. Therefore, to design a sandstone acid treatment for channeling, it is helpful to generate a temperature vs. acid injection-rate map, and mark the channeling condition on the map, by using the simulator. Figure 4-14 is a channeling map for the Uta19 case. The concentrations for HF and HCl are both 6wt%, the fast-reacting mineral is set as feldspar, and the initial porosity distribution is random (no correlation). From Figure 4-15, we find that as temperature increases, the range of injection rate that will possibly result in channels increases. Although low acid injection rate is helpful to create channel in sandstone, face dissolution will occur when acid injection rate is too low. To generate high porosity channels in the sandstone, there is an optimal Damkohler
Figure 4-14. A Channeling map for Uta19 case.
number for a particular sandstone acid treatment.

4.8 Summary

Sandstone acidizing is a complex process. It is not easy to generate wormholes in sandstone, because the main competent in sandstone, quartz, reacts with HF very slowly and cannot be dissolved completely. However, for heterogeneous sandstone, the penetration of acid through the core is not uniform. There can be a main acid flow channel in the core. Under some conditions, this main acid flow channel can result in high porosity / permeability channels, which we call sandstone channeling. If the channels develop sufficiently to become visible channels, sandstone wormholing occurs.

Mineral distribution correlation has a strong impact on channeling in sandstone. It is possible to get high porosity / high permeability channels in strongly correlated mineral distributions, such as laminated structures. The correlated heterogeneity of the mineral composition is the primary factor for sandstone channeling / wormholing. High temperature and high HF concentration are also helpful for channeling. Low acid injection rate is also an advantage for heterogeneous sandstone channeling. However, too slow on injection rate can result in face dissolution and increase the operation cost. There should be an optimal Damkohler number for a specified case. Although the properties of clay and feldspar are different at high temperature, the impact from
this difference on sandstone channeling is very small, even at high temperature. We can conservatively use the properties of feldspar as that of fast-reacting mineral to predict acidizing result. For a particular sandstone acidizing case, we can plot a temperature vs. injection rate channeling map to help design acidizing treatments.
Chapter 5: Conclusions and Recommendations

A fine-scale sandstone acidizing simulator has been developed. In this simulator, the core is divided into 8000 grid blocks to represent the heterogeneity of sandstone. It provides acidizing results for each grid block individually. A 3D visualization program converts the acidizing results to a 3D imagine, and creates a new data file for assisting analysis. The 3D picture can be rotated in any direction. The user can select to display only the grid blocks, having a specified property in a desired range. With the fine-scale sandstone acidizing simulator and UT3DVIS, it is easy to detect wormholes or high permeability channels in sandstone, and find the optimal condition to generate wormholes or high permeability channels in sandstone formations.

Based on the simulation result and the experiments by BJ Services Company, we didn’t find any real wormholing case in sandstone acidizing treatments so far. However, some high porosity / high permeability channels, with average porosity more than 0.4, can be created under some specified conditions. Almost all acid flows through these channels. We call this channel as pseudo-wormholing or tiny wormhole. Tiny wormholes also was found in the experiment from BJ Service Company and some other previous researches.5, 6
Although tiny wormholes is not easy to be observed by eyes as real wormhole is, high porosity channels result in large increasing in the average permeability of the formation. That is the same ideal result for stimulating the formation as wormholing.

To generate tiny wormholes in sandstone, mineral heterogeneity is the most important factor. It is easy to generate high porosity channels in strongly correlated mineral distribution sandstones, such as sandstones with a laminated structure. High temperature and high HF concentration are also helpful for channeling / wormholing. But too high an HF concentration is limited in use in some places by ESH regulations. Low acid injection rate is helpful to channeling / wormholing for heterogeneous sandstone. However, too low an injection rate can cause face dissolution, and increase the operation cost. There is an optimal Damkohler number to generate channels or wormholes for a specified sandstone acidizing case. To make a design for sandstone channeling / wormholing treatment, a temperature vs. injection rate channeling map with the maximum HF concentration which the EHS regulation allows is needed.

Precipitation will cause heavy damage in sandstone acidizing treatments if the acidizing reaction front is uniform in the core. However, if there is a main acid flow channel in the core, the precipitates will block the other parts of the core, and force more acid to converge into the channel. Therefore, precipitation is helpful to generate wormholes or high permeability channels in heterogeneous
sandstone rather than being a solely negative factor in sandstone matrix acidizing.

In this case, a good acidizing treatment design which can generate channels or wormholes in sandstone will improve the success of sandstone acidizing.
NOMENCLATURE

A  preexponential factor
C_A, C_B  reactants concentration
C_av  average dimensionless HF concentration for a YZ plane
C_i  HF dimensionless HF concentration for a grid block which index is i in a YZ plane
C_HF  HF concentration
C_HFD  dimensionless HF concentration
C_F  dimensionless fast-reacting mineral concentration
C_FD  dimensionless initial fast-reacting mineral concentration
C_S  dimensionless initial slow-reacting mineral concentration
C_SD  dimensionless initial slow-reacting mineral concentration
E_f  reaction rate constant
E_{f,F}  reaction rate constant for fast-reacting mineral
E_o  active energy
K  permeability (Darcy)
K_T  reaction rate coefficient at temperature T
k  reaction rate constant
L  core length
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{d,a,F}$</td>
<td>Damkohler number for fast-reacting mineral</td>
</tr>
<tr>
<td>$R_A$</td>
<td>rate of appearance of mineral A</td>
</tr>
<tr>
<td>$r$</td>
<td>reaction rate</td>
</tr>
<tr>
<td>$S^*_F$</td>
<td>Specific surface areas for fast-reacting mineral</td>
</tr>
<tr>
<td>$T$</td>
<td>reaction temperature</td>
</tr>
<tr>
<td>$V^0_F$</td>
<td>initial fast-reacting mineral volume fraction</td>
</tr>
<tr>
<td>$</td>
<td>V_D</td>
</tr>
<tr>
<td>$</td>
<td>V_{XD}</td>
</tr>
<tr>
<td>$u$</td>
<td>rate of acid convection</td>
</tr>
<tr>
<td>$X, Y, Z$</td>
<td>coordinate axes</td>
</tr>
<tr>
<td>$\alpha, \beta$</td>
<td>reaction order coefficients</td>
</tr>
<tr>
<td>$\phi$</td>
<td>porosity</td>
</tr>
<tr>
<td>$\Delta\phi$</td>
<td>porosity change</td>
</tr>
<tr>
<td>$\Delta\phi_{av}$</td>
<td>average porosity change for a YZ plane</td>
</tr>
<tr>
<td>$\Delta\phi_i$</td>
<td>porosity change of a grid block which index is i in a YZ plane.</td>
</tr>
</tbody>
</table>
Bibliography


VITA

Tao Xie was born in Chengdu, Sichuan, China on September 2, 1968, the son of Changyu Xiao and Yaoming Xie. After completing his work at Chengdu Sude High School, Chengdu, Sichuan, China in 1983, he entered Southwest Petroleum Institute in Nanchong, Sichuan, China, and received the Bachelor of Science in July, 1990. From September 1990 to April 1997, he worked as an engineer at Sichuan Chemical Machinery Inc. From April 1997 to Jun 1999, he was employed as a supervisor at Motorola Inc. He received the degree of Master of Internet Technology from The University of Georgia in May 2002. In August 2002, he entered The Graduate School at The University of Texas at Austin.

Permanent Address: 3465B Lake Austin Blvd
Austin, TX, 78703

This thesis was typed by the author