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Network modeling and experimental investigation of flow, dissolution, precipitation and fines migration in porous media

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NETWORK MODELING AND EXPERIMENTAL INVESTIGATION OF FLOW, DISSOLUTION, PRECIPITATION AND FINES MIGRATION IN POROUS MEDIA.

by

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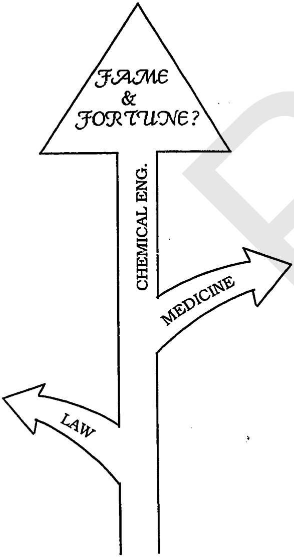

THE ROAD NOT TAKEN

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that, the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I -
I took the one less traveled by,
And that has made all the difference.

- Robert Frost -

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To my loving parents and sister.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

The phenomena of flow, dissolution, precipitation and particle entrapment in porous media is encountered in several industrial applications. Primary among these are geothermal/geochemical and enhanced oil recovery operations. During geochemical operations, for example, the primary interest is to dissolve valuable minerals present in the porous media or formation. Fluid is injected into the porous media where it dissolves several minerals. The fluid traverses the mineral zone and exits through a "production well". This fluid is then subjected to chemical treatment where the required valuable mineral is recovered. It is common practice to reuse the fluid for further mineral recovery. However, if this fluid contains unrecovered minerals in a supersaturated state, then precipitation can occur during reinjection. This precipitate then plugs up the pores in the formation leading to a well shut down.

During enhanced oil recovery, the principal motivation is to improve oil production by enhancing the formation conditions. One of the commonly used technique is Matrix Acidizing. Here acid is injected into the formation to dissolve parts of the porous matrix. This reduces the resistance to fluid flow enabling the oil to flow out relatively more easily. Sometimes, however, dissolution is followed by precipitation of certain minerals which can plug up the formation. It then becomes essential to identify the conditions under which precipitation will occur, the extent of damage caused, and the regions where damage will be concentrated.

Another application is during waterflooding operations for enhanced oil recovery. Water is pumped through an injection well into the formation to push the oil out. The injected water generally contains particles of different sizes and depending on the pore size distribution, these particles can get trapped in the pore throats. An important question to be addressed here is : "What is the optimum amount of prefiltration necessary to prevent significant damage to the formation?" While it is cheaper to filter only the larger particles, the filtrate if injected, may still contain enough large particles to cause a sufficient amount of permeability reduction. On the other hand, filtering of all particles would be extremely expensive. In order to determine an optimum cut-off size, an in-depth understanding of fines migration and capture is necessary.

The phenomena of flow, reaction and particle entrapment in porous media also provides several intellectual challenges. It involves the understanding of chemical engineering fundamentals such as, transport phenomenon, chemical reaction engineering, solids transport, and surface and colloid sciences. Furthermore it is necessary to apply these fundamentals within a heterogeneously complex, disordered, porous media. For example, when considering the flow of particulate suspension through a porous media, it is important to take into account the particle size distribution, the pore size distribution and the surface and the colloidal conditions which affect the rate of particle deposition. Additionally, if chemical reactions occurs between the aqueous species and the formation minerals, their reaction rates and reaction products need to be considered in the analysis. Developing a model which accounts for all the above mentioned factors is therefore of a great fundamental interest and significance.

While it is important to take into account pore level heterogeneities when modeling processes in porous media, the results predicted by the model should be relevant on a macroscopic scale. The reason for this is as follows. A good test to verify model predictions is to compare it with experimental data. Since experimental data is generally macroscopic in nature, the need for model predictions to be "macroscopic" is obvious. Throughout this research work, experiments and modeling have progressed simultaneously, one serving as a means of testing the other.

When performing flow experiments in porous media, two macroscopic variables which are of primary importance, and are generally measured, are the overall core permeability and the effluent concentration as a function of time. The effluent concentration can either be the particle concentration for injection of suspensions, or the hydrogen ion concentration for injection of reactive fluids. Other rock parameters which can be quantified are the pore throat size distribution, the porosity, the permeability, and the mineral composition.

This research takes a systematic, in-depth look at two major causes of formation damage in porous media:

a) Due to injection of non-reactive suspensions

b) Due to injection of a reactive fluid, leading to precipitation.

The prime goal of this research is to develop a versatile model which can predict the permeability response and the effluent concentration history for processes undergoing flow, dissolution, precipitation and fines migration in porous media.

A network model was selected to represent the porous matrix. This model takes into account the pore level heterogeneities and has interconnectivity properties similar to that of the porous media. The process of particle capture by purely mechanical means (straining or sieving) is first simulated within the network model. Certain fundamental concepts used in this modeling are then incorporated into a sophisticated simulator which takes into account both straining as well as capture of relatively smaller particles by several forces (deep bed filtration, DBF). Comparison of model predictions with experimental observations of other researchers shows excellent agreement.

Having gained an in-depth knowledge of inert particle deposition, the more complex phenomenon of flow, dissolution and precipitation is studied next. The flow system considered for this research is limestone and ferric chloride. One of the factors for selecting this system is that the deposition of iron scale during matrix acidizing of limestone formations has caused significant damage to oil wells. Besides its practical importance, this system is a clean model system and several flow imaging techniques (such as Wood's alloy castings and Neutron Radiography) can be used to study the evolution of the pore structure. This system is then modeled using the previously described network representation of the porous media. Model predictions for this and other systems are compared with other theories and experimental data.

The dissertation is a collection of individual papers. In Chapter 2, an overview of porous dissolution reactors is presented (Fogler and Rege, 1985). Detailed description of several models used in the literature is reported here in the form of a review. This chapter provides an understanding of the advantages and limitations of previous approaches in studying flow and reaction in porous media. Chapter 3 describes the network model approach in detail (Rege and Fogler, 1987). Its application to simulating the capture of relatively larger particles by straining is then postulated and compared with experimental data. Several case studies are undertaken with varying pore size and particle size distributions. The effect of these parameters on formation damage is emphasized. The theories of deep bed filtration are reviewed in Chapter 4 (Rege and Fogler, 1988). The network model for straining is modified to include the capture of relatively smaller particles (or emulsion drops) due to colloidal and surface forces. The differences between formation damage caused by emulsion drops and solid particles are predicted in this chapter. Case studies performed herein, also give an insight into the evolution of the filter coefficient with time. In Chapter 5, the network model is further modified to include flow, reaction and particle deposition (Rege and Fogler, 1988). Several innovative ideas, based on first principles, have been incorporated into the network model. In this chapter, results from other theories, such as the "equilibrium model", and experimental data are compared with the currently developed model.