



## Mechanism of wormholing and its optimal conditions: A fundamental explanation

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### ABSTRACT

Acid stimulation is commonly used in carbonate reservoirs, which can be either matrix acidizing or acid fracturing. In both treatments, wormholes can form. In matrix acidizing, wormholing is favorable because the damaged region can be bypassed. In acid fracturing, wormholing is not desired because it can increase fluid loss, which can limit conductive fracture length. Three major processes are involved for wormholing: convection, diffusion and surface reaction. A thorough understanding of these processes is necessary for engineering design.

In this paper, we fundamentally explore wormholing mechanisms starting from pore growth. A wormhole forms when larger pores grow in cross-sectional area at a rate that greatly exceeds the growth rate of smaller pores due to surface reaction. This happens when pore growth follows a particular mechanism, which is discussed in this paper. We developed a model to predict wormhole growth behavior. The model uses the mode-size pore in a pore size distribution - the pore size that appears most frequently in a distribution - to predict the growth of the pore. By controlling the acid velocity inside of it, we can make larger pores grow much faster than other smaller pores, thus reaching the most favorable condition for wormholing. This also results in a balance between overall acid/rock reaction and acid flow.

By understanding the wormholing mechanism, engineers can select proper treatment fluids and pumping rate for acid stimulation design.

### 1. Introduction

When acid flows into a rock, it reacts with its minerals and changes its pore structure. The macro properties like porosity and permeability of the rock change accordingly. To describe this phenomenon more precisely, [Schechter and Gidley \(1969\)](#) studied the changes of pore structure and pore size distribution due to surface reaction. They set up a porous medium model with pores represented by capillaries distributed randomly. Pore enlargement is described by a pore growth function and the change of pore size distribution is described by a pore evolution function. They concluded that it is the larger pores that determine the response of rocks to acid attack for high surface reaction rates, and this response is sensitive to the distribution of these larger pores.

The effectiveness of this model was verified experimentally with retarded acid injected into a sintered glass disk ([Guin et al., 1971](#)). Excellent agreement was obtained for permeability increase between experiments and model prediction. Furthermore, the pore evolution equation was solved by a simulation procedure using Monte Carlo

techniques ([Guin and Schechter, 1971](#)). Besides pore enlargement, the collisions between neighboring pores were also accounted for in this simulation. They found that for diffusion-controlled reactions (high surface reaction rate), wormholes tend to form, and acid preferentially flows through these channels. It is best explained by the enlargement of larger pores and collisions between them. This process is independent of the distribution of small pores since they receive little acid.

Network modeling was developed to simulate wormhole initiation and formation ([Hoefner and Fogler, 1988](#)). The network consists of nodes connected by bonds of cylindrical tubes. To represent real rock, the pore size distribution was repeatedly simulated until good agreement with an experimentally determined distribution was obtained. The bond growth rate was studied for both diffusion-limited and reaction-limited cases. They found that if the bond growth is limited by diffusion, a dominant wormhole can form; if the bond growth is limited by surface reaction, permeability increases very little and no channel forms.

A convection-diffusion equation was solved to explore wormholing mechanisms ([Buijse, 2000](#)). In his research, the equation is setup for a

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cylindrical pore. The acid/rock reaction is incorporated as the boundary condition. Finite reactivity is used to study the transition from being reaction-controlled to being diffusion-controlled. The author analyzed two extremes, one is reaction-controlled limits, and the other is diffusion-controlled limits. Through analysis, the author identified that optimal wormholing occurs only in diffusion-controlled reaction. In the later part of this research, the author directly treated the pore as a wormhole. The conditions for pores growing into a wormhole are not discussed. [Fredd \(2000\)](#) solved the convection-diffusion equation in a wormhole and obtained the acid concentration profile inside the wormhole. His work is based on an existing wormhole and also did not reveal how the wormhole forms.

[Wang et al. \(1993\)](#) focused on the largest pore naturally existing in a rock. A transition pore area was defined, and that was used to distinguish the growth mechanisms of small pores and large pores. If the area of a pore is larger than this transition pore area, this pore grows rapidly, and a wormhole can form. She then developed a model to predict optimal acid fluxes based on this principle. The advantage of her work is that she explored the wormholing mechanism from the pore scale, but the pore growth mechanism is not fully illustrated. [Huang et al. \(2000a\)](#) utilized this theory and developed a matrix acidizing treatment chart.

Recent experimental study show that permeability and porosity are concepts too large to describe wormhole initiation and propagation ([Etten et al., 2015](#)). Instead, pore size distribution has direct relationship with optimal conditions ([Zakaria et al., 2015](#); [Ziauddin and Bize, 2007](#)). [Dubetz et al. \(2016\)](#) studied pore size distributions for 8 different types of carbonate rocks through a micro-CT scanner. He compared the corresponding optimal conditions of each type of rock with mean pore size and median pore size. It is found that the optimal breakthrough pore volume increases with increasing mean pore size through a logarithmic function. The optimal acid flux increases with increasing median pore size through a power law function. His research reveals the importance of understanding pore size distribution and pore growth when designing acid treatments.

Pore growth modeling laid the foundation for wormhole modeling. The next section introduces our research on the wormholing mechanism related to pore growth by use of a pore growth function.

## 2. Mechanism of wormholing

### 2.1. Overall chemical reaction

The overall chemical reaction in this study involves acid diffusion to the rock surface and acid/rock surface reaction. An acid concentration gradient exists in the diffusional boundary layer, as shown in [Fig. 1](#).

When the chemical reaction in the diffusional boundary layer is at steady state, the rate of acid diffusing to the pore surface equals the rate of surface reaction. We can describe the boundary condition using [Eq. \(1\)](#) below.

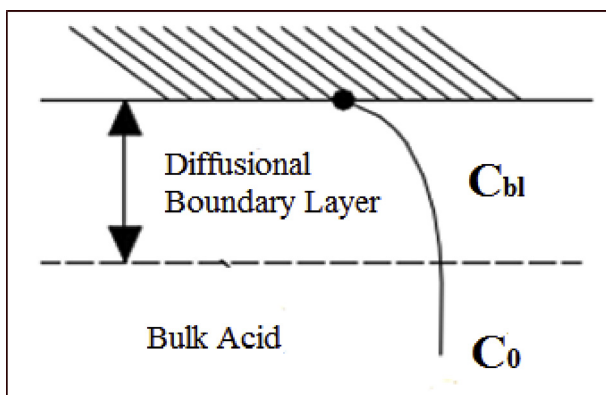


Fig. 1. Overall chemical reaction inside a pore.

$$D \left( \frac{\partial C_{bl}}{\partial n} \right) = E_f C_s^m \quad (1)$$

where  $D$  is the acid diffusion coefficient,  $C_{bl}$  is the acid concentration in the diffusional boundary layer,  $n$  is the outward normal,  $E_f$  is the surface reaction rate constant,  $C_s$  is the surface acid concentration and  $m$  is the reaction order.

The boundary condition can be written in another form with dimensionless variables, by introducing  $C_D = C/C_0$  and  $N = n/L$ . Then the boundary condition becomes

$$\frac{D}{E_f L C_0^{m-1}} \left( \frac{\partial C_{D-bl}}{\partial N} \right)_{y=0} - C_{D-s}^m = 0 \quad (2)$$

where  $C_0$  is the acid bulk concentration,  $L$  is the diffusional boundary layer thickness,  $C_{D-bl}$  is the dimensionless acid concentration in the diffusional boundary layer,  $C_{D-s}$  is the dimensionless surface acid concentration and  $y$  is the unit normal to the pore wall.

The diffusional boundary layer thickness  $L$  can be obtained by solving acid convection diffusion equation inside the boundary layer. However, this parameter can be reduced by introducing a mass transfer coefficient  $K$ , which is the ratio between the diffusion coefficient  $D$  and the diffusional boundary layer thickness  $L$  ([Levich Veniamin, 1962](#)).

$$K = \frac{D}{L} \quad (3)$$

Levich V.G (1962) also derived the equation to calculate the mass transfer coefficient  $K$  as shown by [Eq. \(4\)](#).

$$K = 1.2819 \left( \frac{\bar{v}_p}{r_p L_p} \right)^{1/3} D^{2/3} \quad (4)$$

where  $\bar{v}_p$  is the average acid velocity in the pore, which is averaging the parabolic velocity profile in the pore, as shown in [Fig. 2](#);  $r_p$  is the pore radius, and  $L_p$  is the pore length.

To determine if a reaction is diffusion limited or surface reaction limited, the relative importance of  $K$  and  $E_f C_0^{m-1}$  needs to be analyzed. [Eq. \(5\)](#) shows that the amount of acid diffusing to the pore surface (left side) is equal to the amount of acid reacting with the pore surface (right side).

$$K(C_0 - C_s) = E_f C_0^{m-1} C_s \quad (5)$$

By eliminating  $C_s$ , we can then get an overall reaction rate equation and overall reaction rate coefficient.

$$r = \kappa C_0 \quad (6)$$

$$\kappa = \frac{K E_f C_0^{m-1}}{K + E_f C_0^{m-1}} \quad (7)$$

In [Eq. \(7\)](#), if  $K \gg E_f C_0^{m-1}$ , the surface reaction rate is slow and is the limiting step of the overall reaction, and  $\kappa = E_f C_0^{m-1}$ . If  $K \ll E_f C_0^{m-1}$ , the diffusion rate is slow and is the limiting step of the overall reaction, and  $\kappa = K$ . To better understand this equation, a plot of it is shown in [Fig. 3](#), with  $K = 1 \text{ cm/s}$ .

We can see from [Fig. 3](#), if  $E_f C_0^{m-1}$  and  $K$  are within around 100 times difference, both surface reaction rate and convective diffusion rate play roles in the overall reaction rate. The overall reaction depends

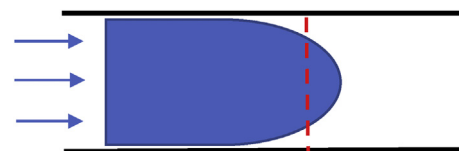


Fig. 2. Acid flow velocity profile in a pore. The velocity profile is parabolic, and the average velocity is denoted as the red dash line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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