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PHYSICS OF FLUID SPREADING ON ROUGH SURFACES

K. M. HAY AND M. I. DRAGILA

Abstract. n the vadose zone, fluids, which can transport contaminants, move within unsaturated rock fractures. Surface roughness has not been adequately accounted for in modeling movement of fluid in these complex systems. Many applications would benefit from an understanding of the physical mechanism behind fluid movement on rough surfaces. Presented are the results of a theoretical investigation of the effect of surface roughness on fluid spreading. The model presented classifies the regimes of spreading that occur when fluid encounters a rough surface: i) microscopic precursor film, ii) mesoscopic invasion of roughness and iii) macroscopic reaction to external forces. Theoretical diffusion-type laws based on capillarity and fluid and surface frictional resistive forces developed using different roughness shape approximations are compared to available fluid rise on roughness experiments. The theoretical diffusion-type laws are found to be the same apparent functional dependence on time; methods that account for roughness shape better explain the data as they account for more surface friction.

Key Words. roughness, wetting, capillarity

1. Introduction

The movement of fluids in unsaturated rock fractures is an involved subject, requiring an understanding of multiphase fluid dynamics and fluid interaction with soil and porous media as well as the use of complex modeling systems. However, before one can model the big picture of multiphase flow in a rock fracture system it is important to understand the basic physics that describes types of fluid movement and interaction with boundaries. In a fractured rock system, the rock surface can be porous, moist, chemically heterogeneous and rough. In this manuscript the focus will be the movement of a wetting fluid over a rough surface. Glass is commonly used to model rock when investigating characteristics of droplet movement in rock fractures. It has been observed that the speed of droplets moving down between smooth glass parallel plates is significantly different than the speed down rough glass plates and rock fractures. The physical mechanism behind fluid movement on rough surfaces is not yet well understood.

A wetting fluid is pulled into roughness by capillarity. What are the physical mechanisms that drive and resist this movement? An analytical diffusion-type law is developed that provides an explanation and a way to quantify the physical mechanisms that drive fluid invasion into roughness. The theory is based on the balance between capillary and fluid and surface frictional resistive forces. Relationships derived have the same apparent functional dependance on time as available experiments of fluid rise on roughness. The more accurate the geometry of the roughness shape, the better explain the data.

There is a large body of experimental and theoretical literature that clearly shows a rough surface affects fluid movement. Wenzel [1] observed that surface roughness caused a hydrophobic fluid to behave as if it were more hydrophobic and a hydrophilic fluid to behave as if it were more hydrophilic. Wenzel also suggested that the structure of the surface had a greater effect on the static contact angle than the chemistry. Bico *et al.* [2] suggest that a surface can be designed to tune it's wetting properties. They observe the dynamic behavior of the gas-liquid-solid interface for a hydrophilic fluid on a rough surface and derive a spreading diffusion law based on the change in energy that accompanies movement of the contact line. Cazabat and Cohen Stuart [3] explored the effects of surface roughness experimentally. They found that drops on rough surfaces spread faster than drops on smooth surfaces. While the macroscopic cap of the drop on a rough surface follows a gravity-dominated behavior, a thin fluid front rushes away from the macroscopic edge, spreading *into* the roughness by capillarity. Eventually fluid in the macroscopic drop relaxes onto the fluid film that invaded the roughness.

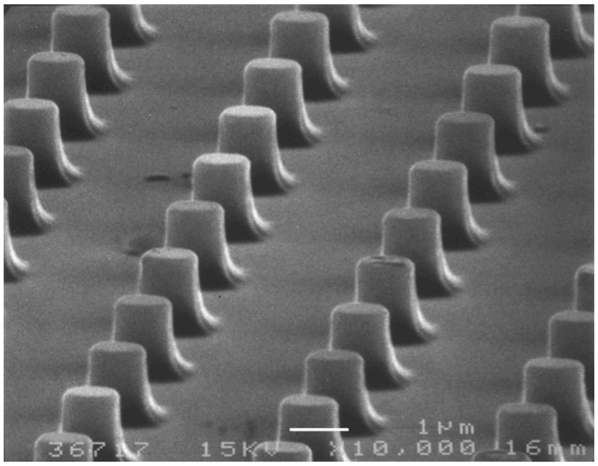

FIGURE 1. Microstructure with regular micronic cylindrical spikes used for the experiment [2].

The model for the invasion process incorporates the capillary driving mechanism suggested by experimentalists and theoreticians in this field [2], [3]. The expression derived uses an idealized geometry for the rough surface that coincides with the micropatterned surface used in experiments by Bico *et al.* [2] (Figure 1). The goal of the mathematical model is to predict the wetting behavior on a surface, given the basic surface structure and to eventually describe larger multiphase systems involving rock surfaces [4].

2. Theory

The model presented classifies three regimes of spreading: precursor film, roughness invasion and reaction to external forces (Fig. 2). It is known that a microscopic *precursor film* precedes a fluid that is in contact with a solid. Movement of the precursor film is governed by molecular diffusive transport of vacancies from the tip of the film to the edge of the macroscopic meniscus [5]. It is assumed here that the precursor film must also occur on rough surfaces and this will be considered the first regime of spreading. During the second regime of spreading on a rough