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EXPERIMENTAL STUDY OF TWO-PHASE FLOW IN ROUGH FRACTURES

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ABSTRACT

Two-phase (air-water) flow experiments were conducted in horizontal artificial fractures. The fractures were between glass plates (1 x 0.5 m) artificially roughened by gluing a layer of glass beads of Imm diameter. Three rough fractures were studied: one with the two surfaces in contact, and two without contact. Videotape observations revealed flow structures similar to those observed in two-phase flow in pipes, with structures depending upon the gas and liquid flow rates. The data of flow rates, pressure gradients and saturations were interpreted using the generalized Darcy's law. Relative permeabilities curves were found to be similar to classical curves in porous medium, but not unique functions of saturations. The sum of gas and liquid relative permeabilities were found to be less than one at all saturations.

INTRODUCTION

Two-phase flow in fractured rocks occurs in recovery of petroleum or natural gas, recovery of coalbed methane, exploitation of geothermal energy, and isolation of radioactive waste. Models to predict two-phase flow in fractures are therefore of practical interest, but little is known of the laws governing such flow.

The approach most commonly taken to model two-phase flow in a single fracture is to treat the fracture as a 2-dimensional porous medium, and write Darcy's law for each phase. For horizontal flow:

$$V_{LS} = -\frac{K_0 K_{rL}}{\mu_L} \nabla P_L \qquad (1)$$

$$V_{GS} = -\frac{K_0 K_{rG}}{\mu_G} \nabla P_G \qquad (2)$$

where V is velocity, μ is viscosity, P is pressure, K_0 is the intrinsic permeability and K_r the relative permeability. Subscripts L and G represent liquid and gas respectively, and subscript S represents superficial velocity (also called Darcy velocity). The relative permeability factors account for the fact that each phase interferes with the flow of the other, and (at least in porous media) the K_{rL} and K_{rG} functions are strongly dependent upon phase saturation.

For lack of data, it is generally assumed for modeling purposes that in fractures the relative permeability to each phase is equal to its saturation; that is, each phase does not interfere with the flow of the other, and $K_{rL} + K_{rG} = 1$. This assumption is based upon the experimental work of Romm (1966), in which oil and water were confined to different regions of a smooth fracture by controlling the wettability of the fracture surfaces; and upon analysis of field data from geothermal reservoirs (Pruess et al 1983, 1984). But theoretical analysis and numerical simulations by Pruess and Tsang (1990) showed that in a rough fracture, significant phase interference would occur, and this was confirmed by the experimental work of Persoff et al. (1991) and Fourar et al. (1991,1992).

Roughness of the fracture walls is important in single phase flow because it increases friction and causes streamlines to be crooked even in laminar flow. In two- (or multi-) phase flow, wall roughness causes the aperture to vary from point to point in the fracture. Regions of smaller aperture (like smaller pores in porous medium) are more attractive to the wetting phase, and generally constitute the flow path for that phase. In this work we conducted two-phase flow experiments in rough fractures with openings of order of 1 mm. The data are interpreted using Darcy's model.

APPARATUS

A schematic view of the apparatus is shown in Fig. 1. The fracture consisted of two horizontal glass plates, 1 m long and 0.5 m wide. The plates were artificially roughened by gluing a single layer of 1 mm glass beads to each plate. Three sets of experiments were done: one with the rough surfaces in contact (h1) and two with the surfaces spaced apart (h2 and h3). For all the fractures, steel bars were tightened in place to prevent the glass from bulging at high flow rates.

The flow injector consisted of 500 stainless steel tubes of 1 mm o.d. and 0.66 mm i.d. Air and water were injected through alternating tubes to achieve uniform distribution of flow at the inlet. Air was injected at constant pressure, and its volumetric flow rate, corrected to standard pressure, was measured by an inline rotameter. Water was injected by a calibrated pump. At the outlet of the fracture, gas escaped to the atmosphere and water was collected in a decanter and recycled.

Nine liquid-filled pressure taps were cemented into holes drilled along the center line of the lower plate. Any pair of taps could be connected by valves to a differential transducer. This arrangement allowed measurement of non-uniform pressure gradients, but in the experiments the pressure gradient was always found to be uniform along the length of the fracture. The measured pressure gradient varied rapidly as the two taps were contacted by air or water, and only the time-averaged values were recorded.

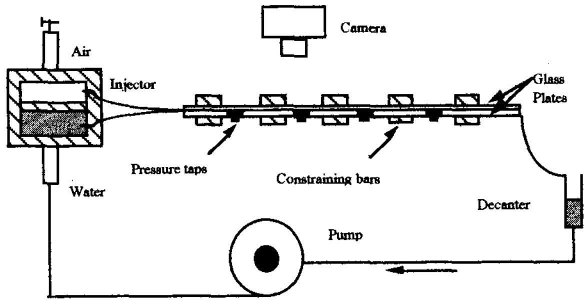

Fig. 1. Experimental apparatus

For each experiment, the fracture was initially saturated with water, and water was injected at a constant rate through the fracture. Air injection was started and increased stepwise through a range of flow rates. When steady state was reached for each flow rate, the pressure gradient and liquid saturation were measured. The fracture was Then resaturated with water and the experiment was repeated several times at different liquid flow rates.

Liquid saturation was measured by a volume-balance method. The water volume in the decanter was measured at the start of the experiment, with the fracture completely saturated with flowing water, and again when steady state had been reached at each air flow rate. Changes in the water volume in the decanter were then used to calculate a water balance, from which the liquid saturation in the fracture was determined.

RESULTS

Calculation of hydraulic aperture

The hydraulic aperture of each fracture was calculated from the single-phase liquid-flow data shown in Fig. 2. In this figure the data for the rough fractures plot as parabolas. Deviation from linearity indicates deviation from Darcy's law but does not necessarily indicate turbulent flow.

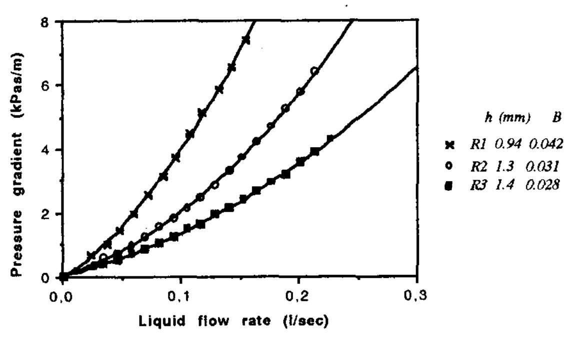

Fig. 2. Single-phase liquid flow

Such deviation has been observed in porous media (see reviews by Houper, 1974 and Temeng and Horne, 1988) and in rough fractures (Schrauf and Evans, 1986). The deviation from Darcy's law is attributed to inertial forces, which, at small Reynolds numbers, are negligible in comparison to viscosity forces. The relationship between pressure gradient and flow rate is then written (Schrauf and Evans, 1986):

$$\nabla P = -\frac{12\mu}{h^3}Q - B\frac{\rho}{h^3}Q^2 \qquad (3)$$

Where Q is the volumetric flow rate per unit width of the fracture, B is a dimensionless number, a measure of the roughness, and h is the hydraulic aperture. Values of h and B determined from the parabolas are shown in Fig. 2.

Two-phase flow structures

The flow structures observed in our experiments are similar to those observed in pipe flow. By varying gas flow rate at a given liquid flow rate, we have identified several structures: bubbles, fingering bubbles, complex, films, and drops. Their maps are presented in Figure 3. In these figures, the volumetric flow rate of liquid and gas have been converted to superficial velocities.

INTERPRETATION

To correlate our data of flow rates, pressure drop, and saturation, we have used the generalized Darcy law.

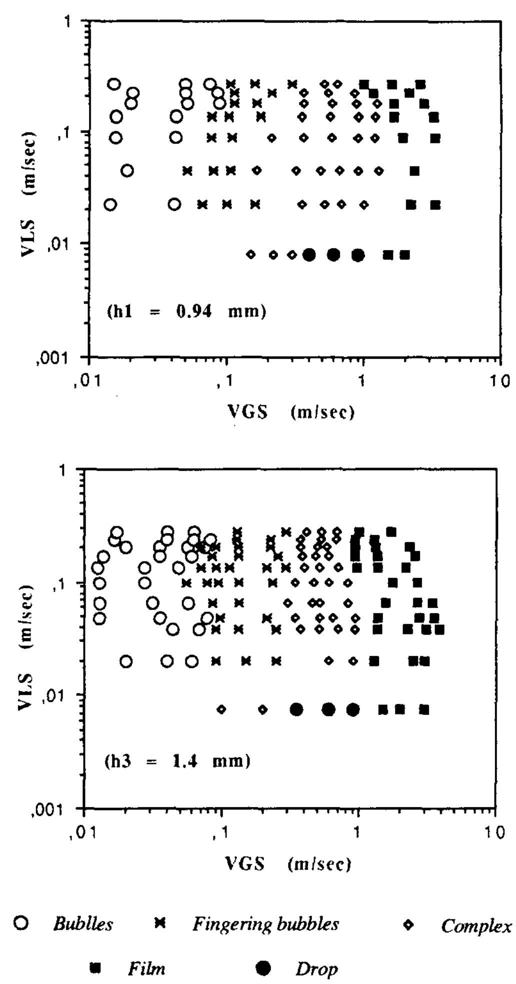

Fig. 3. Flow structure map

Model of Darcy

We suppose that the two-phase flow in fractures is governed by the generalized Darcy's law (1) and (2). In these equations, the relative permeability expresses the degree to which each phase impedes the flow of the other. In our experiments, the capillary pressure is uniform, then $\nabla P_G = \nabla P_L = \nabla P$, where ∇P is the observed pressure gradient under two-phase flow conditions. Then:

$$K_{rL} = -\frac{12\mu_L V_{LS}}{h^2 \nabla P} \quad (4)$$

$$K_{rG} = -\frac{12\mu_G V_{GS}}{h^2 \nabla P} \quad (5)$$

The calculated K_{rL} and K_{rG} are plotted against the measured saturation in Fig. 4. The curves are qualitatively similar to classical K_r curves obtained in porous media.

However, a family of curves are found (instead of one single curve as in porous media) depending on V_{LS} and V_{GS}. Relative permeabilities are therefore not unique functions of saturation under these conditions. In Fig. 5, the data are replotted as K_{rL} vs K_{rG}. These figures show that there is no unique relationship between K_{rL} and K_{rG} and the sum of K_{rL} and K_{rG} is less than one at all saturations.

The generalized Darcy's law cannot be used to correlate our relative permeabilities and saturations data because it does not take into account inertial forces or phase interference (coupling). Actually, the data in Fig. 2. show that in rough fractures even in single-phase liquid flow, the effect of inertial forces is not negligible.

CONCLUSIONS

Two-phase (air-water) flow experiments have been conducted in artificially roughened fractures of hydraulic aperture approximately 1 mm. The fracture consisted of

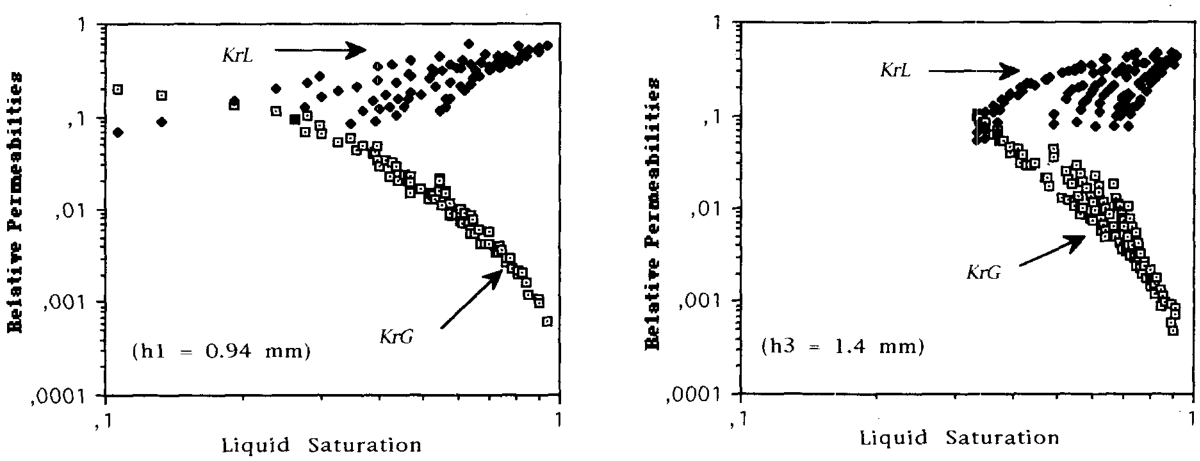

Fig. 4 Model of Darcy

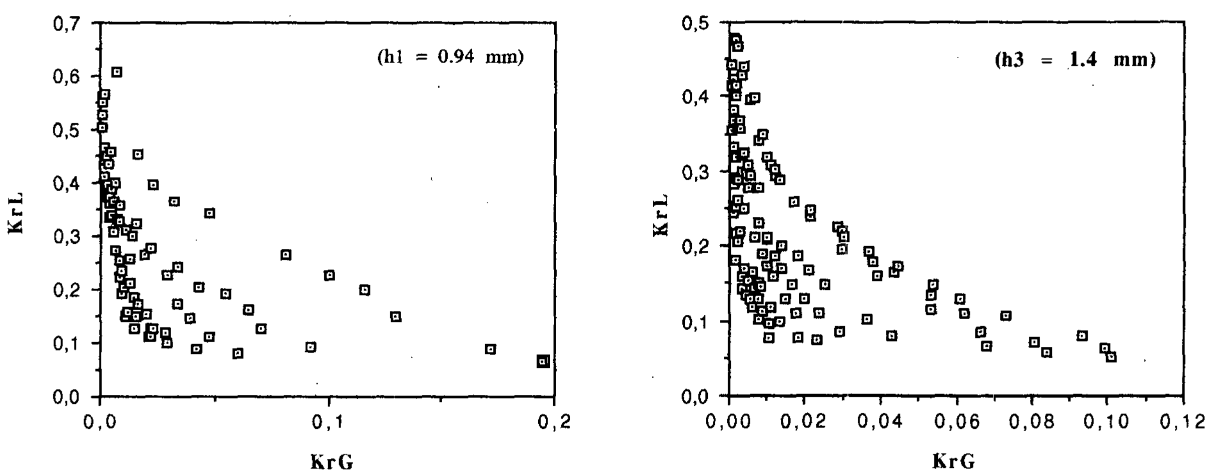

Fig. 5. Relative permeability factors

two horizontal glass plates, Im long and 0.5 m wide. The plates were artificially roughened by gluing a single layer of 1 mm glass beads to each plate.

Hydraulic aperture was calculated from the single-phase liquid flow taking into account the inertial forces due to roughness of the fracture walls.

By varying liquid and gas flow rates, we have identified several flow structures: bubbles, fingering bubbles, complex, films, and drops. These structures are similar to those observed in two-phase flow in pipes.

To interpret our data of flow rates, pressure drops, and saturations, we have used the generalized Darcy's law. The data showed that, contrary to what is commonly assumed, the relative permeability factors are not linearly dependent on saturations. Thus, K_{rL} is not a unique function of K_{rG}, and the sum of K_{rL} and K_{rG} is less than one at all saturations.

Because the flow structures observed present similarity to the structures observed in pipe flow, models for two-phase flow in pipes were examined (Fourar et al. 1992) in order to fit the data.

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