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INVESTIGATION OF FOAM DEVELOPMENT IN POROUS MEDIA USING X-RAY COMPUTED TOMOGRAPHY.

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Summary: In this paper, we investigate foam development in granular porous media, where fluid fractions variations are visualized and quantified using X-ray computed tomography. We provided direct evidence that foam flows in a front like manner leading to a residual liquid fraction of 0.18 ± 0.01, far from the inlet surface of the porous sample. Ideas about the physics of foam flow in porous media are revised in the light of our findings.

When gas is forced through granular porous media containing a surfactant solution, the mobility of the fluids decreases considerably due to foam development [1-3]. This effect can be understood in terms of the increase gas fraction in the porous medium and concurrent decrease in liquid fraction. It is widely accepted that gas resident in the porous medium can be split into a (rather small) mobile fraction and a (rather large) stationary fraction. The apparent viscosity associated with the motion of foam films contributes significantly to the reduction of gas mobility. This experimental work has been undertaken to examine in the dynamic fluid partitioning induced by foam development in porous media which has remained speculative thus far.

X-ray computed tomography (CT) enables the visualization of process within opaque objects by reconstructing the X-ray attenuation coefficients from multidirectional X-ray transmission data. In this study, this technique has been combined with a specially designed experimental set-up for studying porous media flow, enabling thus a real time visualization and quantification of fluid distributions during foam flow through porous media. This approach was used previously (see for instance Kovscek et al. [1] and references therein) but the higher spatial and temporal resolution of more recent CT scanners offers the possibility to probe more accurately the fluid distributions.

Nitrogen gas (N_2) and the surfactant solution were co-injected into the saturated core at fixed rates of 5.0 ± 0.1 standard cm^3/min and 0.5 ± 0.05 cm^3/min, respectively (fraction of gas to total flow rate 91.0 ± 0.5%). After reaching steady state, a mixture of nitrogen (N_2) and Xenon (Xe) and a surfactant solution is co-injected to visualize foam local foam spead. Foam displacement process is visualized by constructing a series of 5 parallel images slicing the core along its axis. The central image is on the plane of the core axis (axis plane) while the other ones are place two by two, symmetrically with respect to the axis plane. The spacing between two adjacent images (i.e., the couch feeding) was 8 mm. Each image series is scanned in sequence from a couch position CP, with CP = 0 for the central image.

The CT images in Fig. 1 reveal that foam displaces the surfactant solution in a characteristic front-like manner (blue is foam and red is the surfactant solution). Three regions can be distinguished along the flow direction. (a) An upstream region, where foam is roughly uniformly distributed and the liquid fraction is low (the relatively high liquid fraction at the inlet is imposed by the injection system and is physically not very significant), (b) A downstream region, where the liquid fraction is unity and finally (c) a frontal region characterized by a mixing of the flowing foam and liquid and by a fine fingering. The scale of the fingering appears to be of the order of the inhomogeneity of the porous medium (in the order of tenths or hundreds of micrometers)

As foam advances in the porous medium the liquid fraction continues to diminish within the foam region. The continuing drop in liquid fraction appears more clearly after the foam front reaches the outlet of the porous medium, however, as indicated by the darkening of the blue region. This secondary liquid desaturation initiates in the central portion of the core and propagates towards the inlet and the outlet and ceases only when a steady state flow regime is reached, which happens at dimensionless times larger than 25.6. Note that the dimensionless time is obtained by diving the current time by characteristic time needed to inject one pore volume of liquid. The relatively high liquid fraction at the inlet mentioned above and the capillary liquid entrapment at the outlet (capillary end effect) are suppressed by the desaturation wave, the former partially and the latter completely within the accuracy of the experiments.

The liquid fractions, averaged over thin slice areas, are shown in Fig. 2 for several dimensionless times. In the early stages of foam injection the liquid fraction profile is an upward-concave function of the position as illustrated by the curve obtained at t = 0.11. The remaining curves before foam breakthrough exhibit roughly the same trend: (a) a low (less than 55%) upstream liquid fraction, (b) a high (100%) downstream liquid fraction, and finally (c) a transition zone where the liquid fraction increases smooth and rapidly towards the downstream. In the upstream region the liquid fraction gradually declines from the inlet towards the frontal region instead of being constant. For example, at t = 0.61 the liquid fraction decreases by almost 10% from the inlet to the position 7.5 cm. This proves that the secondary desaturation starts soon after the beginning of foam flow.

Nevertheless, the desaturation effect manifests itself more clearly after foam breakthrough. First of all, as discussed above just after breakthrough liquid fraction is still significant near the in- and outlet of the core. Then considering a fixed position, for example at 12.0 cm, the liquid fraction decreases over time, from about 38% to less than 18%. Even at the position 2.0 cm, where the steady state profile indicates that much liquid still remains in the core, the liquid fraction decreases from 55% to 48%. It is not completely clear why so much liquid is retained near the core inlet. Perhaps the injected liquid somehow undergoes a filtration in that region.

The secondary liquid desaturation appears to be driven by gas expansion and to be controlled by the competition between viscous and capillary forces. When foam flows for the first time in the porous medium it penetrates primarily the largest pores as dictated by dominant capillary forces. Gas expansion sets in immediately as the foam travels down the pressure gradients but foam does not easily penetrate the smallest pores because of these have a large entry capillary pressure. As foam development proceeds, its apparent viscosity increases and thus the gas can progressively invade smaller pores containing liquid. The expanding gas and partial remobilization of trapped bubbles is likely to trigger further lamella generation mostly by snap-off and leave behind mechanisms [1,2], leading to a the refinement of the foam texture. It is not easy to quantify separately the contribution of snap -off and lamella division as the pressure gradient for lamella mobilization is exceeded. The process of foam generation associated with liquid desaturation is self-amplifying as the former requires the local pressure gradient to be sufficiently high while, on the other hand, further foam generation leads to high pressure gradient. Bubble generation is expected to cease, however, when foam approaches the limiting capillary pressure.

In conclusion, the idea of foam partitioning in mobile and immobile fractions the situation is not supported by our experiments. In the light of the visual data obtained in this study, it appears that the role of trapped gas during transient foam flow is not as important as it might have been believed previously. Apparently the transient foam displacement appears to be under the influence of a much subtler interplay between capillary and viscous forces. A further elaboration will be discussed in the future.

References

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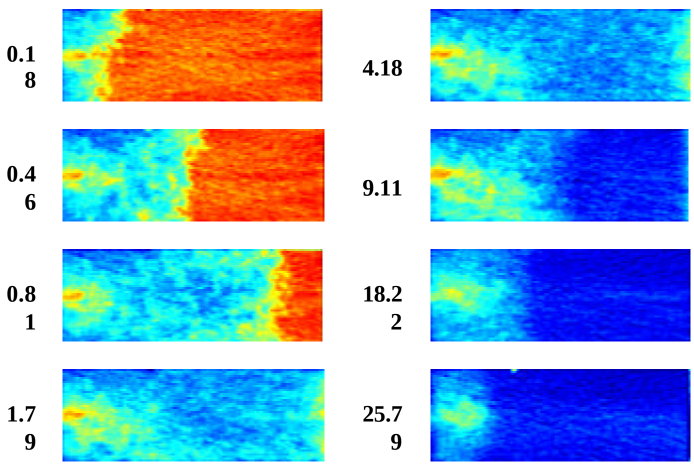

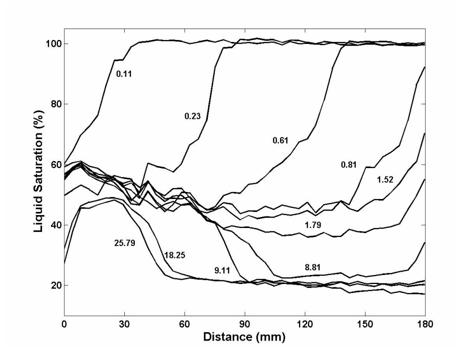

FIG. 1: CT images (CP = 0) of foam displacement (green/blue) in a porous medium initially saturated with surfactant solution (red/yellow). Nitrogen and surfactant solution are co-injected at 5 (standard) cm^3/min and 0.5 cm^3/min, respectively. The sharp foam front traverses the core and breaks through after at t = 1.79. A secondary liquid deliquid fraction arises in the foam bank and spreads towards the in- and outlet of the porous medium. Steady state is reached at t = 25.

FIG. 2 Liquid liquid fraction profiles (liquid fractions versus distance from the inlet) corresponding to foam motion in a porous medium initially saturated with surfactant solution (see images in Fig. 1). The liquid fraction profiles exhibit a characteristic diffuse front-like pattern from t = 0.11 up to the breakthrough at t = 1.79. The secondary liquid deliquid fraction is visible from t = 061. This secondary liquid deliquid fraction becomes dominant from t = 1.79 up to t = 25.79.