論文 / 著書情報
Article / Book Information

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Title(English)	Study on drying and drainage processes in porous media
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博士課程)
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論 文 要 旨

THESIS SUMMARY

系 ・ コース： Department of, Graduate major in	機械 エネルギー	系 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of	(Engineering)
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Thesis Summary (approx.800 English Words)

Chapter 1 introduces drying and drainage as multi-phase transport processes in porous media. Drying of 3D porous media involves pore-scale liquid transport processes that influence drying characteristics. However, there is limited information on how pore-scale mechanisms, such as capillary rearrangements, interplay of viscous, capillary, and gravity forces within different drying regions, and parameters like gas-liquid interfaces and porous medium wettability affect the drying process. In the drainage process of porous media, pore-scale relative permeability is essential for assessing CO_2 injectivity and storage, but traditional methods oversimplify fluid displacement. Therefore, in this study, we examined pore-scale drying and drainage processes in porous media using distinct approaches. We used X-ray micro-tomography to understand the 3D pore-scale drying process, characterize drying regions, in particular the liquid film region and the invasion front, and investigate wettability effects on the drying process. For drainage process, we performed simulations using a weakly compressible scheme to analyze pore-scale saturation and relative permeability of CO_2 under various injection velocities and wettability conditions.

Chapter 2 provides a comprehensive understanding of the pore-scale drying process, characterizing the liquid film region and the invasion front. Key findings include the visualization of the gas invasion process, which describe the capillary rearrangement. We also found that total gas-liquid-specific interfacial area as more gas invades the porous media, this does not affect the drying rate, indicating that evaporation is significant only at the upper tip of the liquid film region. Drying regions were also characterized based on liquid phase distribution and saturation. A sharp decrease in liquid saturation occurs at the invasion front, where saturation ranges from 1 to about 0.15 ($0.15 < S < 1$). The invasion width σ_p, which characterizes the roughness and disorder of the invasion front, follows the scaling law of the percolation model, indicating significant limitation by capillary and gravity interactions. However, in the liquid film region ($0 < S < 0.15$), cluster size distribution deviates from the universal power-law behavior. This suggests the presence of a liquid film in the cluster region, where the viscous force is comparable to the capillary force.

In Chapter 3, we further analyzed the critical parameter that influences the capillary arrangement during drying process, which is the wettability of the porous medium. Results show higher wettability increases capillary pressure, which enhances the rearrangement of liquid from large pores to small pores. We also found that liquid clusters are unlikely to disappear for a long time confirming that higher wettability supports the flow through liquid film. This study also provides new insight that capillary flow by liquid film is associated with branch clusters. These clusters maintain the gas–liquid interfacial area that acts as the evaporation surface. As a result, drying is intensive in a water-wet porous medium with a longer constant rate period in which drying is controlled by external diffusion. In a neutral-wet porous medium, an early drop-in drying rate occurs. Thus, drying is mainly a falling rate period limited by vapor diffusion through the newly emerging dried region within the medium.

In Chapter 4, we discussed the drainage process. We found that saturation is highest for viscous fingering, lowest for crossover ($-5.82 < \log Ca < -4.86; \theta < 60°$), and remains high in the capillary fingering regime even though the relative permeability of CO_2 is minimum due to Haines jumps. At low injection velocity and contact angle, frequent permeability fluctuations result in high saturation despite the low relative permeability. At intermediate injection velocity and low contact angle, both the relative permeability and its fluctuations are moderate, leading to lower CO_2 saturation. The present work bridges understanding of displacement-front advancement at the pore-network scale with relative permeability, which links the pore-scale meniscus dynamics with the large-scale Darcy-flow parameters. In large-scale GCS applications, as the CO_2 flows away from the injection site, the displacement pattern exhibits crossover regime, resulting in minimum displacement efficiency. In a strongly wetting porous medium, this condition is severe because crossover regime spans a wide range of capillary number.

Chapter 5 summarizes the key conclusions from each chapter and offers suggestions for future research directions. Study on drying process reveals that capillary rearrangement supports the drying mechanism. We also characterized the drying regions, in which invasion front limited by capillary-gravity interactions and a liquid film region where viscous forces are comparable to capillary forces. Water-wet porous media was found to enhance this capillary rearrangement, exhibiting a longer constant rate drying period. Branch clusters in the liquid film region provide high interfacial area for evaporation. In the study on drainage process, we found that saturation is highest for viscous fingering, lowest for crossover ($-5.82 < \log Ca < -4.86; \theta < 60°$), and remains high in the capillary fingering regime even though the relative permeability of CO_2 is minimum due to Haines jumps. At intermediate injection velocity and low contact angle, both the relative permeability and its fluctuations are moderate, leading to lower CO_2 saturation.