Modeling wormhole formation in digital rock samples: the role of segmentation and permeability-porosity relationships

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Introduction

- Dissolution of pore matrix by reactive fluids creates these beautiful patterns aka wormholes.

- The dissolution process is complex because of interaction of reactive fluid and medium.

- These dissolution channels can be numerically studied either with Darcy-models or with pore-scale models.
Sample used in Numerical simulation

- Wierzbica limestone sample with porosity in range 15-20% and permeability around 2mD is used in numerical simulation.
- XCMT images of 60micron resolution are obtained.
- These images are further processed to remove noise.

Fig-1: Slice of Wierzbica limestone sample
Fig-2: Wierzbica limestone sample with dimensions
Segmentation

- Segmentation is done by distinguishing the pores and solid matrix phase.
- Using the threshold value of pores and grains, porosity of sub-resolved phase is calculated [1]

Modeling

- Darcy-Brinkman Equation
  \[-\frac{\mu}{\phi} \nabla^2 V + \frac{\mu}{K(\phi)} V = -\nabla p\]

- Convection-Diffusion-Reaction
  \[-V \nabla c + \nabla \cdot (D \phi \nabla c) - R(c) = 0\]

- Kinetic rate law
  \[R(c) = k_s(\phi)c\]

- Porosity evolution
  \[\frac{d \phi}{dt} = R(c) v\]

We are using an OpenFOAM based solver, PorousFOAM developed by Tony Ladd
(https://github.com/tonyladd/porousFoam)
Porosity ($\phi$)-Permeability ($K$) relation:

$$K = K_0 \frac{\phi^n}{(1 - \phi)^2}$$

Model of reactive surface area:

- **Sugar-Lump model**
  
  $$s(\phi) = a \phi (1 - \phi)$$

- **Constant area model**
  
  $$s(\phi) = \text{const}$$
Now by following the Darcy-scale models, can we correctly predict the wormhole formation?
Wormholes as porosity contours

Fig-3: Comparison of porosity contours of (a) lab-dissolved core with (b) simulated wormhole using Carman-Kozeny (n=3) porosity-permeability relation and sugar-lump reactive surface area model has been used.

- Darcy-Brinkman solver with Carman-Kozeny porosity-permeability relation and sugar-lump reactive surface area model has been used.
- The simulated wormhole grows at the same place but is quite thicker.
- The thickness of dominant wormhole at the inlet, where the competition between wormholes occur, is more which shows the limitation of model.

(a) (b)
Other numerical experiments
Wormholes as porosity contours

Fig-4: Wormhole with n = 6 using sugar lump model

Fig-5: Wormhole with n = 10 using sugar lump model
Wormholes as porosity contours

Fig-6: Comparison of porosity contours lab-dissolved core (a) with simulated wormhole (b, c) for n = 6 using constant reactive surface area model
Conclusion

- The simulated wormholes are thicker than experimental wormholes.
- Higher thickness of simulated wormhole shows limitation of Darcy scale models.
- Numerical study of dissolution of pore matrix is very sensitive to reactive surface area models and porosity-permeability exponent.

Questions and Suggestions are welcomed