Effect of evolving biofilm structures on modeling the flow in bio-clogged porous media

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Abstract

The growth of biofilms changes the hydrodynamics of porous media, which will influence the transport of bacteria and contaminants in natural and engineered systems. Traditionally, biofilms have been modeled as an impermeable domain in porous media, such that no water can enter biofilms and contaminants can only enter biofilms via molecular diffusion. Such a modeling approach is based on the assumption that the permeability of biofilms is the same as that of Extracellular Polymeric Substances (EPS), which are considered to have very low permeability. In this study, we investigate the impacts of biofilm properties on water flow using microfluidic device experiments and pore-scale modeling. E. coli biofilm was established inside a microfluidic channel packed with unisized glass beads in a single layer. A 5*5 mm2 area was live-stained and imaged via confocal microscopy at three different growth stages to represent three biofilm levels in the system. After image analysis using FIJI and AutoCAD software, the flow in the bio-clogged porous media was simulated using COMSOL Multiphysics. In these simulations, biofilm was modeled as a separate permeable domain in porous media instead of an impermeable domain. A Forchheimer-corrected version of the Brinkman equations was applied to simulate the flow in the porous biofilm regions. Two properties of biofilms, namely biofilm porosity (BPO) and biofilm permeability (BPE), were altered to examine their effects on the permeability of the system. It was found that different values of BPO and BPE clearly affect the flow paths, velocity patterns, and permeability of the system. Considering biofilms as impermeable results in significant underestimations of the flow properties. In addition, two simplified modeling scenarios, namely uniform coating and symmetric contact filling, were investigated for a possible abridging in the arduous modeling procedure of the real biofilm geometry.

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Motivation

Stormwater accumulates on the impervious surfaces as stormwater runoff, which can result in streambed erosion and flooding events. The runoff can pick up contaminants and pathogens from the surfaces and eventually enter natural aquatic systems

Elevated concentrations of bacterial pathogens, such as E. coli and fecal coliform, have been detected in urban stormwaters, and bacterial pathogens have been reported to be the most common contaminant that impairs stormwater for its non-potable reuse

Engineered infiltration systems (EIS) are structures in urban areas that contain porous filtration media for the infiltration of stormwater to reduce the volume of surface runoff and they recently gained popularity in sustainable stormwater management

EIS are designed to have high hydraulic conductance. Since bacteria are ubiquitous in stormwater, biofilms will undoubtedly grow on the filtration media of EIS that may lead to reduction of conductivity or sectional clogging

Objectives

The visionary goal of this research is to understand how biofilms in EIS influence the flow and contaminant removal in porous media

A microfluidic channel is used to evaluate the effect of biofilms at micro scale

Simplification methods are studied to abridge the arduous modeling procedure of the real biofilm geometry

Methods and Experimental Setup

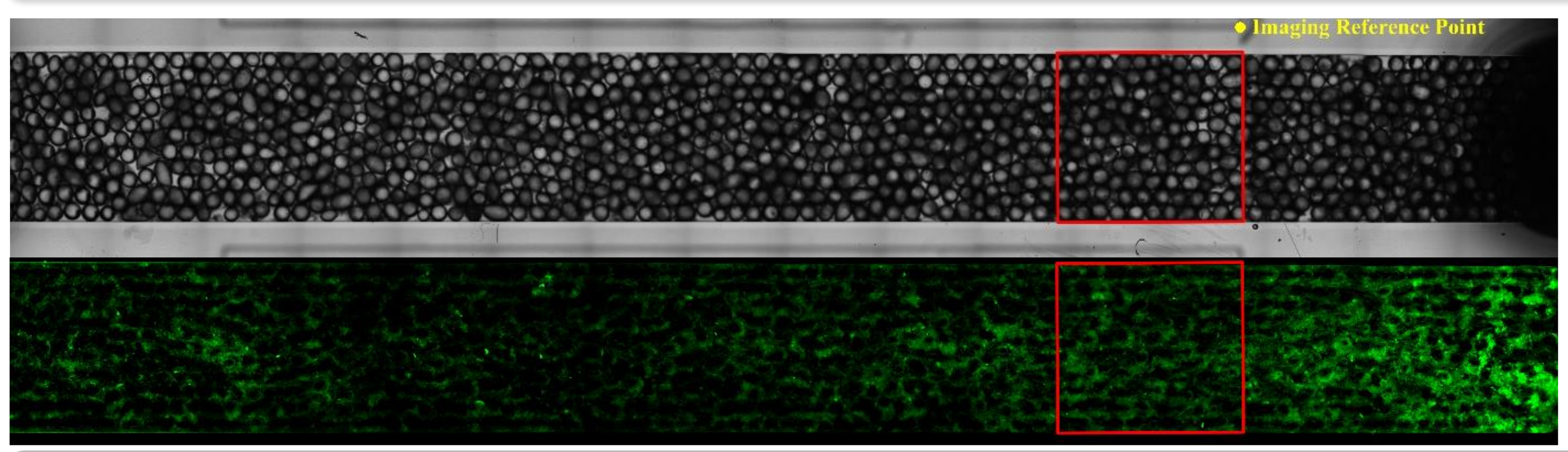
COMSOL Multiphysics

- *Modeling interface*: free and porous media flow (fp)
- *The fluid domain*: Navier-Stokes equations
- *The biofilm domain*: Forchheimer-corrected version of the Brinkman equation
- *Varied biofilm properties*: Biofilm permeability (k_b) and biofilm porosity (ε_b)
- *Main value of interest*: Bulk permeability (k)

ibidi Pump System

Microfluidic channel (50 × 5 × 0.6 mm)
Packed with 0.5 mm glass beads
E. Coli K-12 MG1655 used to form biofilm
LB broth used as the feed

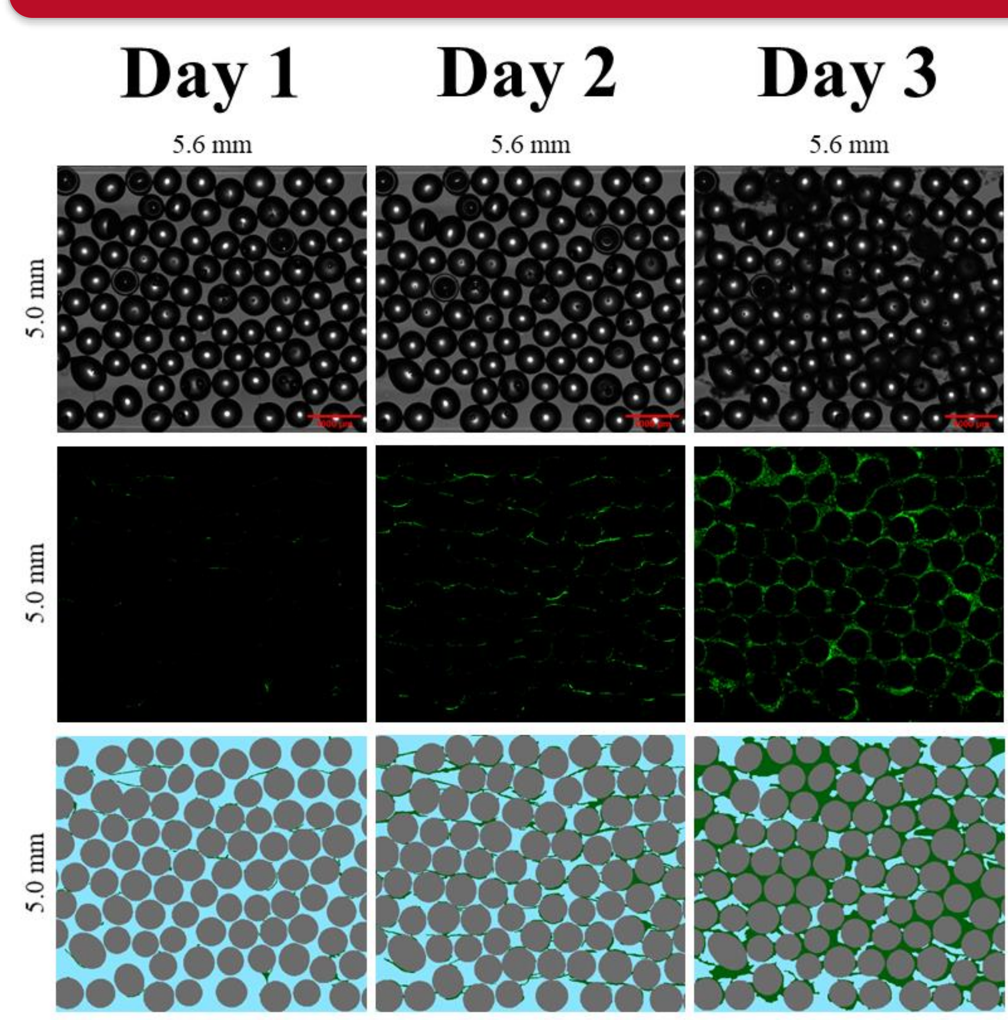
Confocal Imaging and Analysis

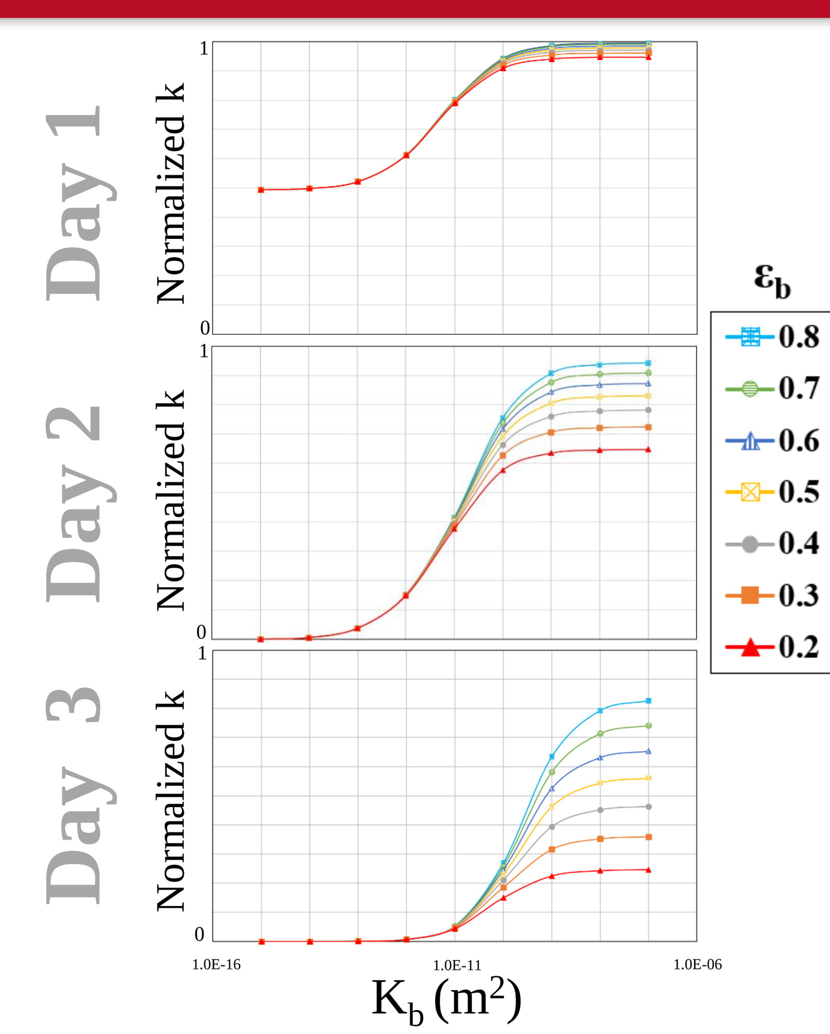


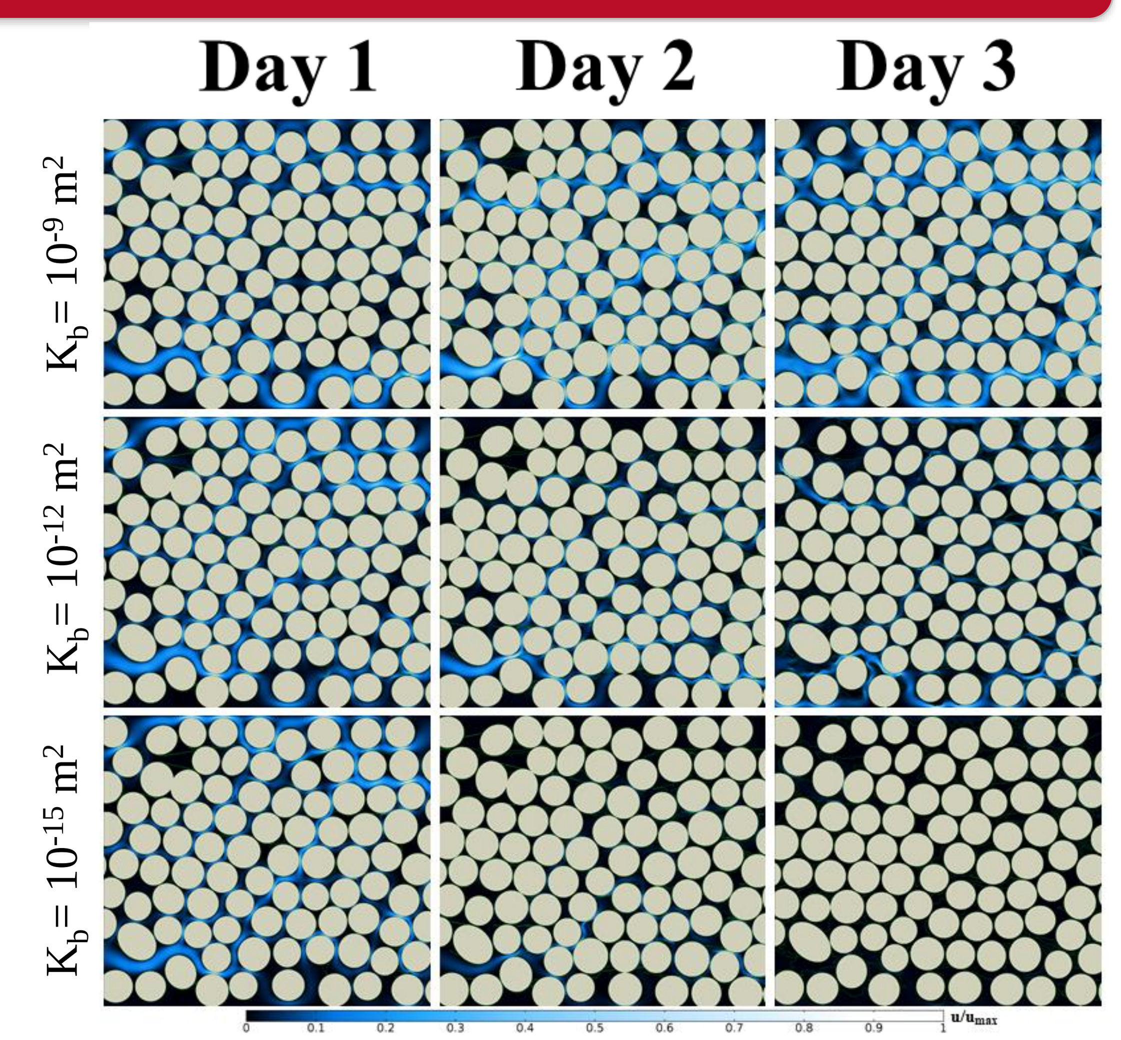
Time	Porosity (%)	Biofilm Ratio* (%)
Day 1	30.8	2.7
Day 2	26.6	17.6
Day 3	32.1	55.2

$$^{*}Biofilm\ Ratio = \frac{Area\ covered\ by\ biofilm}{Pore\ area} \times 100$$

Modeling the Experimental Data Using COMSOL Multiphysics

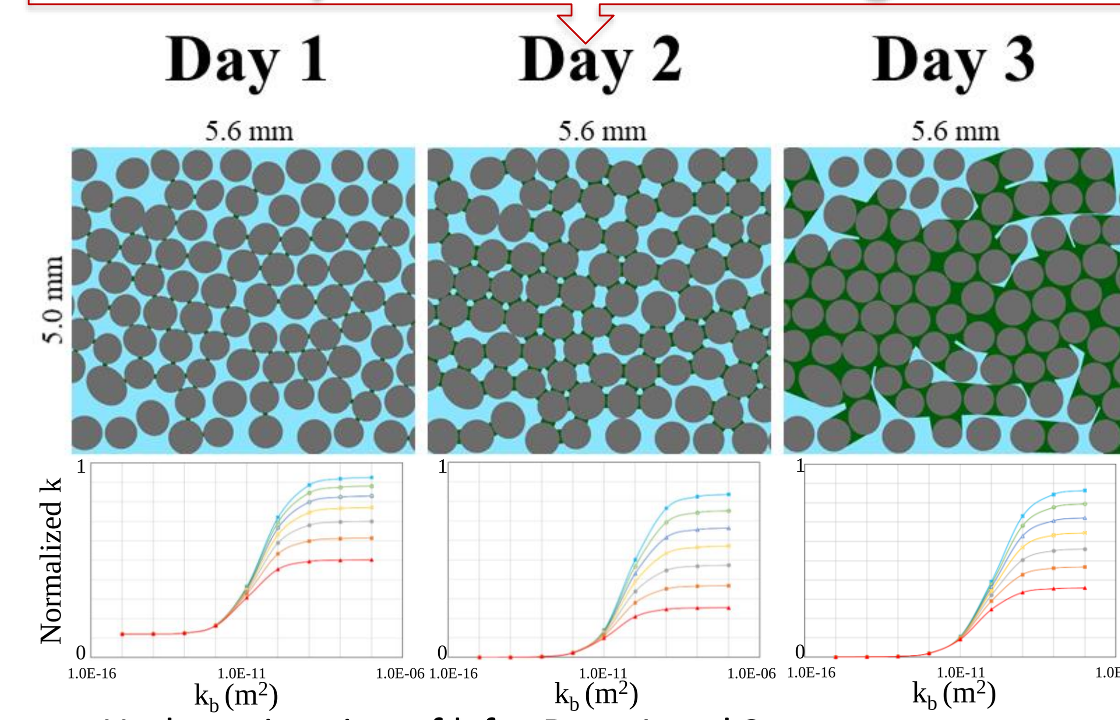






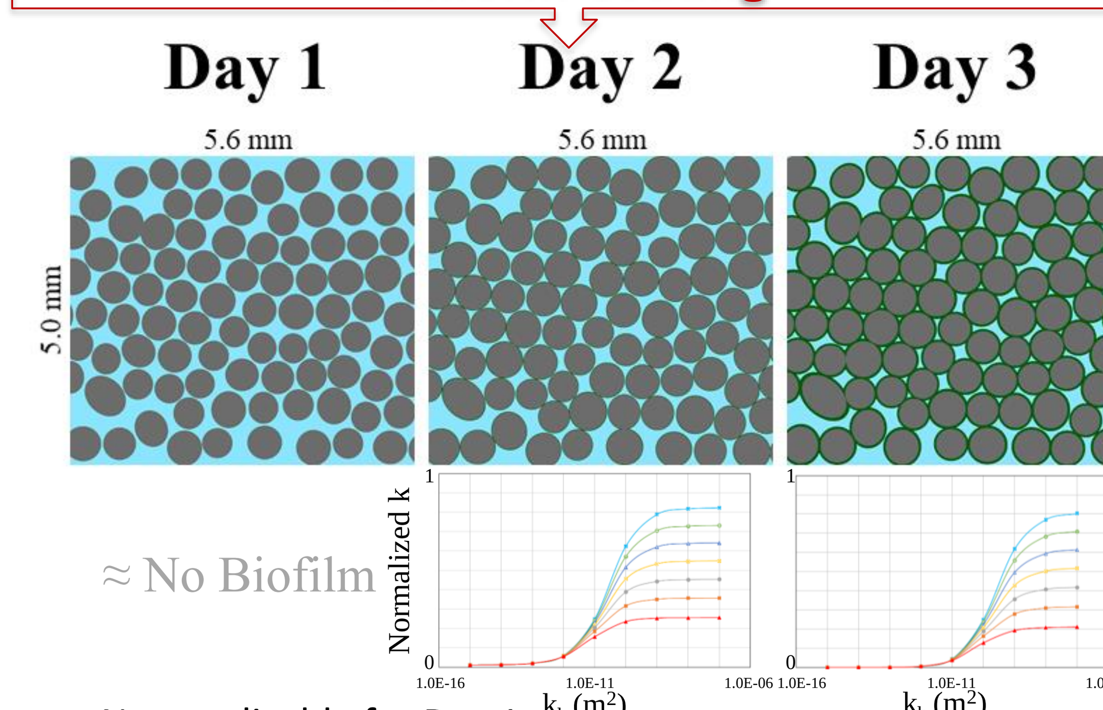
Simplified Modeling Approaches

Symmetric Contact Filling



- Underestimation of k for Days 1 and 2
- Very accurate k values for Day 3

Uniform Coating



- Not applicable for Day 1
- Underestimation of k for Day 2
- Very accurate k values for Day 3

Major Findings

- Considering biofilms as impermeable leads to significant inaccuracies
- Biofilm permeability and biofilm porosity directly affect the flow and bulk permeability
- Both simplification scenarios can be used only at the biofilm ratios above 50%
- For initial stages of biofilm formation, the experimental data should be used for modeling

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