POLYSACCHARIDES AND BACTERIAL PLUGGING

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Objective

The objectives of this research are to elucidate and model bacterial transport in porous media, to determine the importance of polysaccharides bridging as a retentive mechanism, and to identify key parameters that influence porous media plugging.

This project has been subdivided into three tasks: Task 1 is the determination of the growth kinetics of the Leuconostoc bacteria and how they are affected by 1) the nutrient feed, and 2) surface effects; Task 2 will quantify the importance of polysaccharide production as a cell retention mechanism; and Task 3 is the elucidation of the rate of polysaccharide production and the combined effect that polysaccharide production and cell growth has upon plugging.

Summary of Technical Progress - Terri L. Stewart

Micromodel experiments were conducted to determine the effect of polysaccharide production on cell capture, retention, and release in porous media. The micromodels are glass plates which are etched with patterns representing flow channels within porous media. These micromodels are placed under a microscope and monitored via video camera and recorder which allows direct observation of physical processes occurring within the network of flow channels. Based on the results of these experiments, four regimes are identified that describe the transport of the polysaccharide-producing cells.

Experimental Procedures

The micromodels used in these experiments had a network consisting of pore bodies and pore throats arranged in cubic patterns; the coordination number was six. The width of the pore throats varied, creating a heterogeneous system. In one set of experiments, the glass surfaces of the network were untreated and hence, considered water-wet. In the second set of experiments, the surfaces were treated with trichloromethylsilane to render them oil-wet. A syringe pump was used to deliver solutions of bacterial and nutrient feed solutions to the micromodel at a constant flowrate of 0.008 mL/min. A constant back pressure of 50 psig was maintained throughout the experiments to keep the CO2 evolved during cell growth in solution, thus avoiding introduction of a second phase in the flow system. Inlet and back pressures were monitored with time to determine the pressure drop across the micromodel as cells grew and produced polysaccharides.

Leuconostoc mesenteroides was the bacteria studied. For each experiment, the bacterial cells were grown in a solution of glucose and fructose to avoid production of polysaccharides. After the cells reached the stationary phase of growth, the cell suspension was centrifuged and the cells were separated from the supernatant. They were then resuspended in a solution of 10 g/L yeast extract and 30 g/L sucrose for inoculation of the micromodel. With sucrose as the carbon source, the cells both grow and produce polysaccharides. To inoculate the micromodel, the suspended cells were injected into the network overnight. Subsequently, a feed solution of 10 g/L yeast extract and 30 g/L sucrose was injected. The video camera was used to record biofilm development over the next 25 to 35 hours.
Experimental Results

The cell capture, retention, and release mechanisms for the water-wet and oil-wet networks were similar. Four transport regimes corresponding to both characteristic pressure changes, structure of cell units, and location of cell units in the network were identified.

In the first regime, there was no measurable change in the pressure drop across the micromodel network as shown in Figures 1 and 2. This behavior was observed for a period of 4 to 5 hours after initiation of nutrient injection which corresponds to the lag time for polymer production as reported previously. During this period, individual cells were observed flowing in the flowing nutrient solution and a few cell units began to form in pore throats. These units arise from either incomplete separation of cells after division or from aggregation due to electrostatic, hydrodynamic, or polymer bridging forces or a combination of both these mechanisms. These units appear to be a loose collection of cells located predominantly in the pore throats. Some local shearing was observed causing some of these units to dislodge from pore throats and move into pore bodies. At the end of this period, the areal coverage of the micromodel by the biomass (i.e., cells and polysaccharides) was less than 10%.

The second regime corresponds to a low rate of pressure increase. (See Figures 1 and 2.) In this regime, the number and areal extent of the cell units increase due to three possible mechanisms: growth of cells within the unit, filtration by the cell units of individual cells flowing freely in the nutrient solution, and "sticky" collisions between immobile cell units and free cell units that had been dislodged by shearing. Areal coverage of the micromodel by biomass increases from about 10% to 20% in this regime. The cell units are still located predominantly in the pore throats and are becoming denser with some surfaces becoming shiny as the polysaccharide concentration increases. The size of an individual cell unit is on the order of the dimensions of the pore throats.

In the third regime, the pressure increase is very sharp as can be seen in Figures 1 and 2. Areal coverage of the network by biomass increases to more than 70% in the inlet region, extending to the middle region of the network. As the pressure increases, cell units are dislodged from pore throats into pore bodies where the units increase in size by the same mechanisms observed in the second regime. The size of the cell units is on the same order of magnitude as the dimension of the pore bodies in which they are trapped. The surfaces of the units become more textured and have a gelatinous appearance. Local pressure changes cause deformation of these units, sometimes forcing them from one pore body to an adjacent pore body through a pore throat. As this displacement occurs, units are often torn due to shearing.

The fourth regime is characterized by oscillations in pressure as shown in Figures 1 and 2. As pressure reaches a critical value, biomass is suddenly moved and redistributed rapidly in some of the flow channels through the micromodel. These channels consist of several consecutive pore throats and bodies. As this movement occurs, the pressure drops rapidly. In this process, the large cell units characteristic of the third regime are sheared and smaller units of translucent, gelatinous globules are observed. The size of the globules is on the same order of magnitude as the pore throat or smaller. It can be surmised that the size of these globules are a function of pore geometry. The globules can slide past each other and pack densely into pore bodies. Log jams of the globules can form at pore throats, causing a subsequent increase in pressure drop across the micromodel. Once again, as a critical pressure is reached, the log jam breaks and the globules flow rapidly through the channels of least resistance until they are either swept from the system or they create a new log jam dowgradient. In this regime, areal coverage of the micromodel by
biomass is nearly 100% in the inlet region and extends beyond the middle region of the network. The coverage occurs due to this cycle of fill and release of the globular cell units along flow channels.

In summary, there are four regimes that describe cell capture, retention, and release of bacteria producing polysaccharides. Each regime corresponds to characteristic pressure changes as well as structure and position of cell units within the porous media. Understanding these regimes will aid in the development of an injection strategy for control of bacterial plugging.
Figure 1. Characteristic pressure changes in each transport regime for bacteria in a water-wet micromodel network.

Figure 2. Characteristic pressure changes in each transport regime for bacteria in an oil-wet micromodel network.