A STUDY OF THE EFFECTS OF VARIOUS FLOW OBSTRUCTIONS ON HETEROGENEOUS CATALYSIS AND MICROMIXING IN BIOCATALYTIC MICROCHANNELS

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Abstract

A computer simulation study was conducted to understand how changes in packing arrangement and number of packing particles affect micromixing and conversion efficiency in microbioreactor channels. The experimental reactors were simulated using CFD-ACE+ multiphysics software. The focus of this study is to optimize the placement and number of packing to more efficiently meet conversion goals, taking into account micro fabrication and operational constraints. The micro scale dimensions of the channel cross section (125 by 500 micrometers) cause all flows to be laminar. Behavior in the range $0.1 < Re < 100$ is examined.

Introduction

The fields of chemical engineering and nanotechnology have in recent times overlapped, creating the rapidly growing field of chemical process miniaturization. The microreactor is the progeny of this merger and promises improvements in chemical process control, product quality, and safety. Typically, a microreactor consists of any number of micro-sized pipes or channels through which fluid passes and undergoes a chemical reaction. On the order of tens to hundreds of micrometers in size, the very small cross-dimensions of these channels offer large surface area to volume ratios allowing for rapid heat and mass transfer. This small scale also creates a more efficient use of reactive sites, improving yield and selectivity. The addition of packing particles to these channels further improves their efficiency. Applicable to biological processes as well, the microreactor is renamed "biomicroreactor" when all inside surfaces of the channels, including packing, are coated with an enzyme to mimic a biological system and its corresponding reactions. In the biomicroreactor system, heterogeneous catalysis occurs when fluid reacts with the solid enzyme active surfaces.

Fabrication and physical experimentation is a long and expensive process [1]. Enzymes alone can cost well over $2,000 per oz (cost of catalase). Additionally, thousands of experiments could be run to optimize channel design. Since physical experiments are expensive and time consuming, computer simulation is preferred. The present study uses Computational Fluid Dynamics (CFD) software to model a catalase biomicroreactor in lieu of physical experiments. CFD simulation uses grids that model the three-dimensional shapes of actual microchannels. Validation of this technique comes from past successful CFD modeling of physical experimentation with a urease biomicroreactor. This previous research considered only one intuitive but arbitrarily chosen packing configuration [2, 3]. Figure 1 shows a Scanning Electron Micrograph of the physical 500μm x 125μm x 500mm urease biomicroreactor channel.

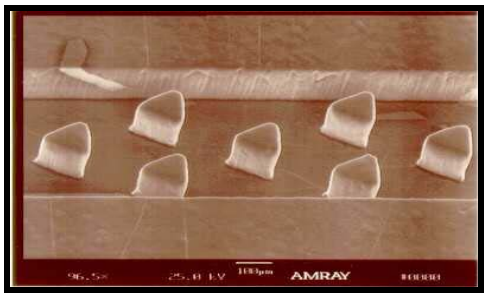

Figure 1. SEM of PDMS Microchannel Used in Physical Experimentation [2]

The objective of the present study is to use CFD software to gain fundamental understanding of the interactions between fluid flow patterns and chemical reaction behavior in biomicroreactor channels. Modeling logical variations of packing configurations for a catalase biomicroreactor will achieve this goal. The reaction taking place involves hydrogen peroxide reacting with catalase to produce water and oxygen (dissolved). This is shown in Equation 1.

$$H_2O_2 \xrightarrow{catalase} H_2O + \frac{1}{2}O_2 \qquad \mathbf{1}$$

A series of six packing configurations that vary placement and number of triangular packing particles in a 500μm x 125μm x 10mm microchannel are simulated and compared to the base case of an empty microchannel. In each case, all packing and inside surfaces of the channels are programmed to be catalytically active. The surface area and dimensions of each individual packing element are held constant. Resulting flow fields are analyzed based on their ability to redistribute fluid and increase conversion by the end of the 10mm length. Consideration is given to pressure drop, residence time, and shear stress produced.

Supporting Theory

The simulation technique used to model microreactor behavior in the present study is characterized by governing equations that are differential in nature. The computational solver software, CFD-ACE+, finds solutions to these equations for each computational grid volume (computational cell) in the model. Boundary conditions are imposed on the microreactor surfaces, inlets, and outlets to model enzyme coverage of internal surfaces and flow rates. The various inlet flow rates simulated are compared using the dimensionless parameter Reynolds number, since flow conditions and micromixing are studied.

Governing Equations

The flow, mixing, and heterogeneous liquid-solid reaction in the catalytically active microchannels are described by a complex set of coupled nonlinear partial differential equations. For this study, several assumptions are introduced that significantly simplify these equations:

- The density and viscosity of the reacting fluid are determined by its primary constituent, water. The very small concentration of the substrate (hydrogen peroxide) has no appreciable effect on these parameters. This small substrate concentration also negates the minimal amounts of heat produced in the reaction, so the system is considered to be isothermal.
- The fluid flow is steady state, incompressible, and characteristically laminar due to low fluid velocity and small dimensions of the channel.
- Chemical reactions are heterogeneous, taking place only at solid-liquid interfaces where enzyme is present.

With these assumptions the flow field (velocity and pressure gradients) within a reactor microchannel is determined by solving the following forms of the conservation of mass (continuity) and Navier-Stokes (momentum) equations:

$$\nabla \cdot \mathbf{V} = 0 \qquad \mathbf{2}$$

$$\rho \mathbf{V} \cdot \nabla \mathbf{V} = -\nabla p + \mu(\nabla^2 \mathbf{V}) + \rho \mathbf{g} \qquad \mathbf{3}$$

where $\mathbf{V}$ = Cartesian velocity vector (m/s)

ρ = bulk mixture density (kg/m^3)

p = pressure (Pa)

μ = bulk mixture absolute viscosity (N·s/m^2)

$\mathbf{g}$ = gravitational acceleration vector (m/s^2)

The steady-state concentration field is described by

$$\mathbf{V} \cdot \nabla C_i - D_i \cdot \nabla^2 C_i = 0 \qquad \textbf{4}$$

where i = species indicator (one equation for each species)

C_i = concentration of species i (M)

D_i = diffusivity of species i in solvent (m^2/s)

The kinetics of the heterogeneous chemical reaction that takes place at the solid-liquid interfaces is described using the Michaelis-Menten model:

$$v = \frac{V_{\max}[S]}{k_m + [S]} \qquad \textbf{5}$$

where v = reaction rate (mole/($s \cdot m^2$)

$[S]$ = substrate concentration at the solid surface (M)

$V_{\max}$ = the maximum reaction rate (mole/($s \cdot m^2$); $V_{\max} = k_{cat}[E]$

k_m = Michaelis constant (concentration that gives $v = V_{\max}/2$) (M)

k_{cat} = turnover number (s^{-1})

$[E]$ = enzyme concentration at the solid surface (mole/m^2)

Boundary Conditions

The boundary conditions associated with flow and reaction in microchannels are as follows. At the channel inlet, a uniform velocity distribution and substrate concentration were specified, while at the channel exit, a fixed pressure boundary condition was assigned. A no-slip boundary condition ($\mathbf{V} = 0$) was applied at all solid surfaces. If no enzyme is present on a solid surface, the concentration boundary condition is given by

$$D_s \frac{d[S]}{dn} = 0 \qquad \textbf{6}$$

where D_s = diffusivity of substrate in solvent (m^2/s)

n = distance in direction normal to the solid surface (m)

If enzyme is present at the surface, the following boundary condition, which includes Michaelis-Menten kinetics, was applied to implement the steady, heterogeneous catalysis reaction:

$$-D_s \frac{d[S]}{dn} = \frac{V_{\max}[S]}{k_m + [S]} \quad (7)$$

Dimensionless Parameter

One dimensionless parameter of particular interest in this study is the Reynolds number (*Re*) given by

$$Re = \frac{\rho U d}{\mu} \quad (8)$$

where U = velocity magnitude (m/s)

d = smallest channel cross-dimension (m)

The Reynolds number represents the ratio of inertial forces to viscous forces within the moving fluid, and it is a determining factor in transition from laminar to turbulent flow. All flows in this study are laminar.

Numerical Solutions Method

The differential governing equations associated with momentum, mass, and chemical species conservation were solved numerically using the CFD-ACE+ computational package developed by ESI CFD Inc., located in Huntsville, Alabama [4]. CFD-ACE+ is a finite-volume-based code that employs a variation of the SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations Consistent) algorithm [5]. As with all finite-volume methods, the physical domain is broken down into a series of small control volumes (computational cells) and the governing differential equations are replaced by a set of approximating algebraic finite-difference equations (which are solved in each control volume).

Design Simulation Details

Data from physical testing of a catalase biomicroreactor that converts hydrogen peroxide to water and oxygen in the presence of the enzyme catalase was successfully modeled by CFD software in previous research [3]. The associated reaction is shown in Equation 1 in the Introduction section. The purpose of the present study is to begin optimization of a catalase biomicroreactor using computer simulation techniques. Optimization includes increasing the level of conversion reached at the exit of the reactor, finding the most efficient length of reactor needed, and finding the most efficient operating speed for the reactor. In the search for optimum operating conditions, a study of static micromixing (laminar fluid redistribution) and its effects on conversion within

microreactor channels is the first step. Results of this type of study apply to other heterogeneous biomicroreactor systems and lend new fundamental information to the understanding of physical laws governing micromixing.

To study micromixing and its effects on conversion in microchannels, packing particles were added and compared to an empty catalase biomicroreactor channel computer model. The location and number of triangular particles were varied. A triangular shape was chosen for the packing because this shape divides flow and directs it towards enzyme active walls. Seven packing configurations were chosen with the expectation that they would contribute to a fundamental understanding of the nature of micromixing and aid in the optimization of microreactors. Figure 2 shows a top view of these patterns. When extruded into three dimensions, these 500μm x 500μm x 125μm configurations form what are called unit cells. Each unit cell is repeated 20 times to form a channel. The first set of channels and their respective configurations are referred to as Empty, One Triangle, Two Triangle Asymmetric, Two Triangle Inline, and Three Triangle. The second set represents a study of the effect of two triangle placement. These are named Two Triangles Inline, Two Triangles 2/5, Two Triangles 1/3, and Two Triangles 1/4 according to the location of their packing.

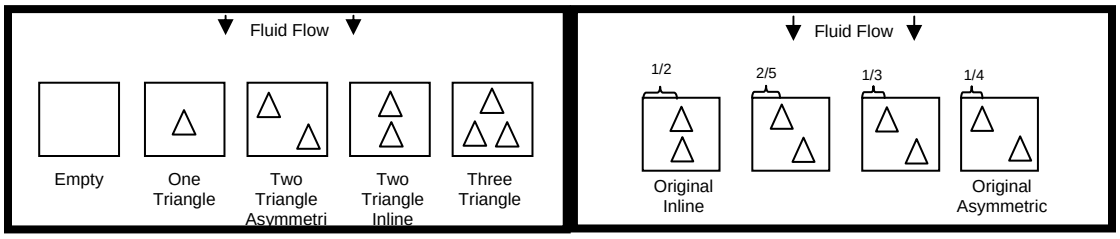

Figure 2. Microchannel Obstruction Configurations

The biomicroreactor channels modeled are 10mm in length so that a dense computational grid could be used (~1million computational cells). This allows for small computational grid volumes lending more accuracy to the numerical solutions of the governing equations. Each computational cell is solved multiple times (iterated) until a stable solution is reached. A Dell Precision 670 server with an Intel Xenon 3.6GHz processor and 3GB Ram is used as the computing machine. A total of 56 computer simulations were performed with the unit cell designs shown in Figure 2. In the study presented, each channel configuration is simulated for fluid flow and chemistry solutions sequentially (due to the constraints of the computing power available). The inlet concentration of H_2O_2 is held constant at 0.0147M H_2O_2 in water. Additionally, each configuration is simulated at four Reynolds numbers, 0.1, 1, 10, and 100, which correspond to fluid inlet velocities of 0.001048, 0.01048, 0.1048 & 1.048 m/s. Parameters used in the CFD model are: bulk mixture density (ρ) = 998 kg/m^3, bulk mixture kinematic viscosity (v) = 1.31x10^{-6} m^2/s,

Diffusivity of H_2O_2 in water (D_i) = $1.0x10^{-9}$ m^2/s, Michaelis constant for breakdown of H_2O_2 by catalase (k_m) = 0.025 M, and turnover number for breakdown of H_2O_2 by catalase (K_{cat}) = 1.0x107 s^{-1}. These simulations produced flow velocity fields and conversion information that are presented and discussed in the following section.

Results and Discussion

The reaction environment of the simulated microchannels is characterized by heterogeneous catalysis of the flowing fluid. The conversion of the fluid from H_2O_2 to H_2O and O_2 depends on its contact with the enzyme-active walls as well as residence time and the reaction rate of the enzyme catalase. Improving this heterogeneous reaction environment requires fluid redistribution to the large surface area of the walls. The performance of the various packing configurations shown in Figure 2 is investigated for mixing and reaction conversion (shear stress at walls and pressure drop results not presented).

Effect of Design on Fluid Redistribution

The simulation of an empty channel biomicroreactor with no packing serves as a basis of comparison for the various design configurations tested and reported in this study. Empty channel simulations produce levels of conversion that decrease as Reynolds number increases. Figure 3 shows a cross-sectional view of the H_2O_2 concentration fields at the exit of the empty channels at the four Reynolds numbers simulated. The percent conversion achieved by each is shown in overlay.

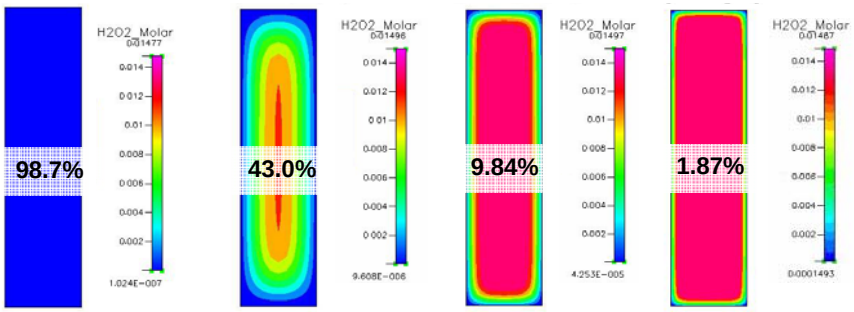

Figure 3. Outlet Conversion Fields of the Empty Channel at Various Reynolds Numbers

The blue regions shown in this figure represent fully reacted fluid that has contacted an enzyme active wall. For the slowest flow (Re = 0.1), there is complete conversion. As Re is increased, the central unreacted regime grows outward. Diffusion alone is responsible for these patterns. Since diffusion is time dependent, increases in fluid

velocities result in decreases in residence time and effective diffusion. At a Re of 0.1, high conversion is expected since this corresponds to a fluid inlet velocity of 0.001048 m/s. Under such conditions, a high residence time of 9.54 seconds allows diffusion of reactants to the walls for catalysis by enzymes. An order of magnitude increase to a Re of 1 produces less than half the conversion attained in the creeping flow conditions due to the reduction in residence time and therefore reduction in the effectiveness of diffusion.

Complete conversion could have been reached for each Reynolds number by lengthening the channels thereby increasing residence time and diffusion. However, in this study flow obstructions are added to aid in the redistribution of the reacting fluid to the large surface area of the enzyme-active walls. This is intended to increase conversion while keeping reactors small. Smaller reactors that can accomplish the same level of conversion are cheaper to fabricate and use less enzyme, making them superior.

The addition of triangular packing particles results in improved fluid redistribution which increases conversion levels. Figure 4 shows each channel's resulting flow velocity field at Re = 10.

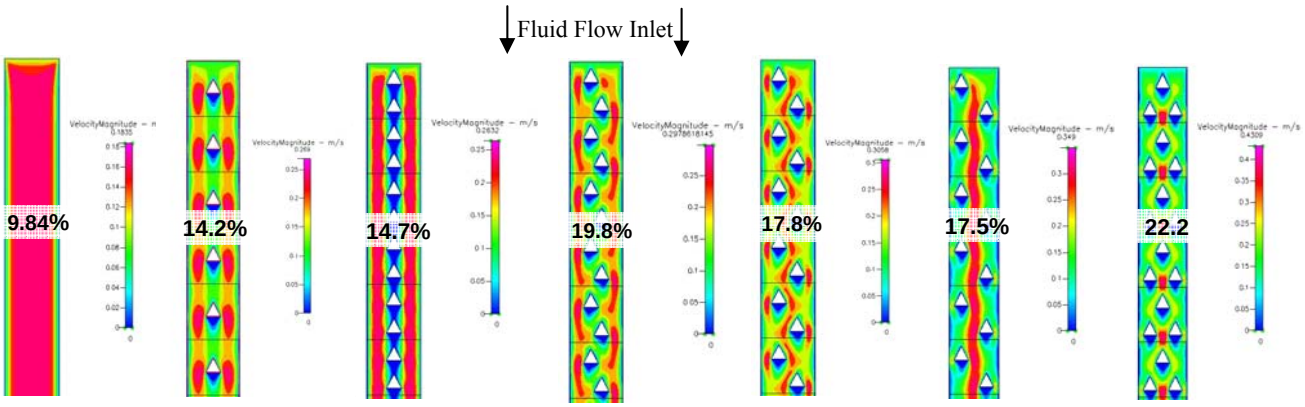

Figure 4. Top View of the Various Packed Channels Showing Velocity Fields at Re = 10

The packed channels' advantages over the empty channel are visible in that faster fluid (red) is directed to the reactive outside walls in most cases, carrying reactants that might not otherwise have diffused there. The resulting conversion levels show the effect of improved mixing, where the highest level of mixing occurs in the Three Triangle channel. Since the surfaces of the triangles are enzyme-active, presenting more reactive surface area to the flow, it is important to note that each adds only 5.6% extra surface area to each unit cell.

The reduction in flow cross-sectional area due to each triangle causes an increase in velocity within the channel and likewise a higher Reynolds number in certain regions. This increases pressure drop through the

channels and shear stress imposed by the fluid at the walls (results not shown). It is also important to note that the wake regions (blue) and flow patterns produced by each packing configuration at Re = 100 (flows not shown) are distinctly different from those at the lower Re of 0.1, 1, and 10, which are very similar to each other. Somewhere between Re 10 and Re 100, the fluid flow in the channels breaks into a new regime. The high velocity regions (red) seen in the flow fields of the lower Reynolds number simulations merge at Re 100 to form high velocity streams. This new regime has various consequences for conversion levels.

Effect of Design on Conversion

All variations in packing configurations are found to significantly affect conversion. For each case where fluid was redistributed in a cross-channel direction toward catalytically active side walls, higher conversion was reached compared to the empty channel case. Figure 5 is a log-log plot of the conversion of H_2O_2 versus Reynolds number for each of the configurations.

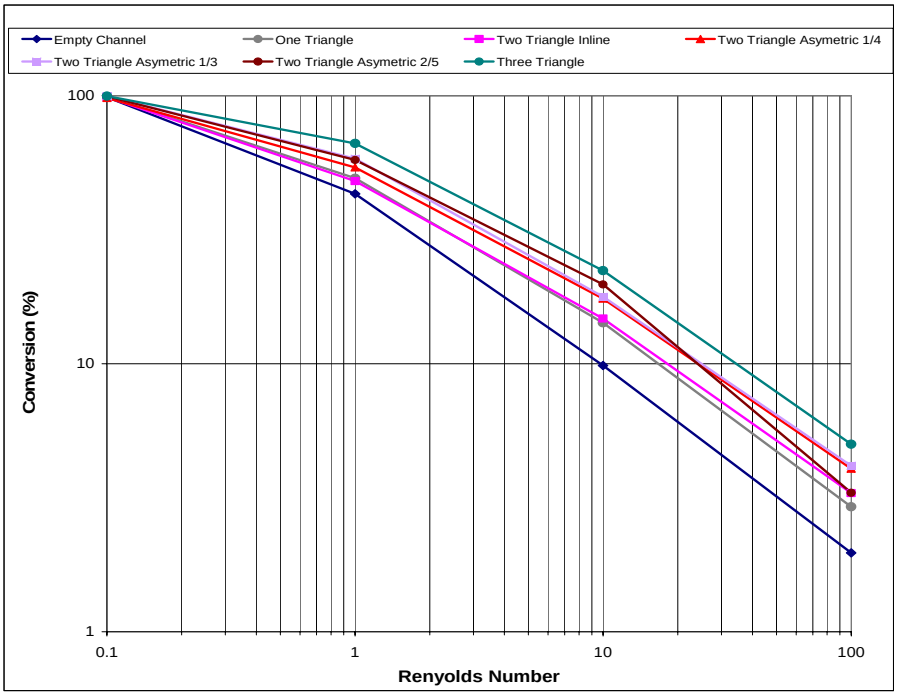

Figure 5. Log-Log Plot of Conversion versus Reynolds Number for Each Configuration

At a Reynolds number of 0.1, all of the configurations performed equally well due to creeping flow and long residence times. At Re = 10 and 100, the effects of diffusion contribute minimally to the conversion achieved, and yet substantial increases are accomplished compared to the empty channel. Within the set of two triangle channels (Two Triangles Inline, Two Triangles 1/4, Two Triangles 1/3, Two Triangles 2/5), an increase of 35% was achieved

at Re = 10 by simply altering the placement of the triangles. In this case the increase was attained without increasing enzyme active surface area. For the Three Triangle channel, an increase of 150% was achieved compared to the empty channel at Re = 100.

Conclusions

In all cases, the addition of triangular packing particles increases conversion compared to empty channels. These increases are always greater than the increase in reactive surface area. In fact, conversion has been increased by as much as 150%. Increased conversion is directly attributable to redirecting flow toward reactive surfaces.

Changing packing position changes flow patterns and the amount of mixing. Conversion has been improved by as much as 35% due to varying the packing positions in a two triangle per unit cell system.

Pressure drop increases with packing population and fluid velocity (results not shown). Pressure drops may become problematic at Reynolds numbers above 10 for more heavily packed channels. Higher pressures may threaten the structural integrity of actual microdevices.

The shear stresses at surfaces due to Reynolds numbers of 10 or greater may threaten the functions of the enzymes or cells attached to the walls of actual microdevices (results not shown) [6]. Future studies may explore these effects in physical experimentation.

These findings are directly applicable to current microreactor research in the areas of biodiesel, bioartificial organs, and pharmaceuticals. Since packed microchannels have been minimally investigated up to this point, the results of this study may improve the efficiency of existing microreactors. This may also make microprocessing an option for previously overlooked processes that require ample mixing of the entering fluid or fluids.

Future computational research for the optimization of microreactors is recommended. This should include the use of various packing shapes and further investigation of packing placement. A study of micromixing in terms of mixing length would also be revealing. Also, physical experimentation to understand the accuracy of the model predictions is recommended.

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