SENIOR CAPSTONE DESIGN
MICROFLUIDICS PASSIVE MIXER

DR. PHANEUF
SPRING 2008

MAY 13, 2008

Elyse Canosa
Josh Davis
Colin Heikes
Li Gao
Pavel Kotlyarskiy
Christina Senagore
Maeling Tapp
Alvin Wilson
# Table of Contents

ABSTRACT .................................................................................................................................................................1

MOTIVATION ............................................................................................................................................................1

TECHNICAL BACKGROUND .......................................................................................................................................1

DESIGN GOALS ..........................................................................................................................................................4

TECHNICAL APPROACH ...........................................................................................................................................5

  NUMERICAL CALCULATIONS ...............................................................................................................................5
  PARAMETERS .....................................................................................................................................................6
  BOUNDARY CONDITIONS ..............................................................................................................................7
  CONVERGENCE ..............................................................................................................................................7
  GRID SIZE LIMITATIONS ...............................................................................................................................8
  DIMENSIONALITY ..........................................................................................................................................8
  SHAPE LIMITATIONS ....................................................................................................................................8
  RELIABILITY TESTING OF THE SOFTWARE ......................................................................................................8
  DESIGN OF MIXER ........................................................................................................................................10
    Overall Design .............................................................................................................................................10
    Fabrication of the Mixing Channel ...............................................................................................................10
    Testing the Device .......................................................................................................................................11

ETHICAL AND ENVIRONMENTAL IMPACT ...........................................................................................................12

INTELLECTUAL MERIT ........................................................................................................................................14

BROADER IMPACT ................................................................................................................................................14

RESULTS .............................................................................................................................................................15

  VARIATION OF RADIUS OF CURVATURE .........................................................................................................16
  VARIATION OF X-SPACING ..............................................................................................................................19
  VARIATION OF Y-SPACING ................................................................................................................................22
  NOZZLE ANGLE ...............................................................................................................................................24
  ROWS OF STARS .............................................................................................................................................25
  VARIATION OF SIZE .......................................................................................................................................28

CONCLUSIONS ....................................................................................................................................................30

ACKNOWLEDGEMENTS .......................................................................................................................................31
ABSTRACT

This project thoroughly explored the design components involved with creating a microfluidic mixing channel. Due to the need for such channels in current technology, we analyzed 6 different parameters determined to be most important in affecting the mixing efficiency of the system. We used simulation software including Gambit® to build our channel meshes and Fluent® in order to run the numerical simulations to compute the mixing efficiency channels. We observed the mixing efficiency of each channel while varying one of the 6 parameters at any given time, but also examined the pressure drop in order to ensure proper outflow. It was determined from our simulations that size of star features and the number of stars in the channel greatly influenced the mixing efficiency. Unfortunately, more stars and a higher density of them in the channel lower the pressure considerably. It is from these simulations and extensive background knowledge that we have been able to understand and analyze the results obtained from this project.

MOTIVATION

A number of laboratories and industries have focused their research on microelectromechanical systems (MEMS) because of their applications in many fields including: biotechnology, chemical engineering, pharmacology and energy production. One specific application is the purification of DNA samples for DNA amplification, where blood samples are reduced to only their DNA component of the original sample and then multiplied for use in other procedures. Various MEMS applications utilize a microfluidic element, in order to manage and analyze fluid within the system. The success of many of these microfluidic applications depends on the mixing of two or more reagents within a small, confined space.\(^1\) Therefore, the performance of these devices can be limited by the rate at which mixing occurs. At the micron scale, laminar flow occurs which minimizes the interfacial area between two reagents. This reduction of interfacial area inhibits the uniform mixing of reagents. In order to enhance mixing within these microfluidic channels and overcome the laminar flow, an extensive amount of research is currently being conducted to develop new geometrical configurations of mixing channels to achieve efficient mixing by increasing the interfacial area of contact through which molecules diffuse so that turbulence within the laminar flow would be achieved.

TECHNICAL BACKGROUND\(^{ii,iii,iv}\)

In order to design such a microfluidic mixer, we must understand the physics of the fluid as it travels through our channel so that we can overcome the inherent difficulties in mixing at the micron scale. The first consideration needs to be the calculated Reynolds number of flow through our channel, given by Equation 1, where

\[
\text{Re} \equiv \frac{\rho v L}{\mu} = \frac{v L}{\nu} = \frac{\mu}{\rho}
\]

\(v\) is the velocity of the fluid, \(\rho\) is the density of the fluid, \(\mu\) is the viscosity of the fluid, and \(L\) is the characteristic dimension of the channel. The Reynolds number is a dimensionless parameter describing the flow regime that takes into account the geometry of a channel, the fluid
properties, and the kinetics of the flow. High Reynolds numbers (above ~4000) describe turbulent viscous flow, midrange Reynolds numbers (between ~2000-~4000) describe a mixture of laminar and turbulent flow, and low Reynolds numbers (below ~2000) describe laminar viscous flow. Typical microfluidic channels have Reynold’s numbers on the order of 10E-2 for tubes with dimension of ~10 microns with a flow rate on the order of mm per second. One of our channels has a Reynolds number ~250. Figure 1 shows two different regimes of flow within the same channel.

![Figure 1. Mixed turbulent and Laminar flow and Laminar flow in a channel.](image)

The wider portion of the channel shows a mixture of turbulent and laminar flow, while the narrow region shows laminar flow. Laminar viscous flow describes motion of fluid particles along streamlines that do not intersect. This can be thought of as a series of parallel individual channels of flow that can exchange particles with each other. Turbulent flow describes a flow regime where fluid particles do not obey particular stream lines. The motion of an individual particle can not be predicted except by statistical mean. The flow regime of a microfluidic channel can be described as laminar viscous flow. The equations that describe viscous fluid flow are the *Navier-Stokes* Equation 2 and the conservation of mass equation Equation 3.

\[
\frac{D\vec{V}}{Dt} = -\frac{1}{\rho} \nabla p + g + \nu \nabla^2 \vec{V} \tag{2}
\]

where \( \nabla \cdot \vec{V} = 0 \) then \( \mu = \text{const.} \)

\[
\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{V} = 0 \tag{3}
\]

The *Navier-Stokes* equation is obtained by considering the conservation of mass and the conservation of angular momentum of a unit of volume of a fluid, as well as the contribution of viscous stress. The differential term D/Dt is the material derivative which is a scalar differential operator for the time rate of change of a fluid property. It is given by Equation 4.

\[
\frac{D}{Dt} \equiv \left( \frac{\partial}{\partial t} + \vec{V} \cdot \nabla \right) \tag{4}
\]
The Navier-Stokes equation has three spatial independent variable and a independent time variable, as well as four dependant variables of pressure and the components of the velocity.

In order to start solving this equation and the conservation of mass equation, we must input initial and boundary conditions. The boundary condition that we select is the no-slip condition which states that the fluid particles which are adsorbed to the walls of the channel have the same velocity as the wall of the channel itself. Because in the reference frame of the channel, the walls of the channel are not moving, we can say that the particles of fluid at the walls have a velocity of zero. For a non-circular tube-like channel the Navier-Stokes equation can be simplified to equation 5 by applying the geometric boundary equations of the tube cross section where v and w are the z and y components of the fluid velocity respectively. In this equation $p^*$ is given by equation 6 in terms of pressure and the gravitational constant.

$$0 = \left(-\frac{dp^*}{dx}\right) + \mu \left(\frac{\partial^2 v}{\partial z^2} + \frac{\partial^2 w}{\partial y^2}\right)$$

$$p^* = p - \rho g \cdot \vec{R}$$

For a rectangular tube this can be solved analytically to obtain the Darcy-Weisbach equation given in Equation 7, where $f$ is the Darcy friction factor given by Equation 8, L is now the channel length, and $D_h$ is the hydraulic diameter given in Equation 9.

$$\Delta p^* = \left(-\frac{dp^*}{dx}\right)L = f \left(\frac{1}{2} \rho V^2\right) \frac{L}{D_h}$$

$$f \equiv \frac{\left(-\frac{dp^*}{dx}\right)}{\frac{1}{2} \rho V^2}$$

$$D_h \equiv \frac{4 \times \text{Area}}{\text{Perimeter}}$$

If we put all of these together with the Reynolds number, which can now be described as a function of the hydraulic diameter by replacing $L$ with $D_h$, we can write an equation for the pressure drop in a channel that depends on the volumetric flow, the Reynolds number, the channel dimensions, the materials properties of the fluid, and the Darcy friction factor. This is given in Equation 10.

$$\Delta p^* = \frac{(Re_h)f}{(D_h/b)^2} \left(\frac{\mu VL}{2b^2}\right)$$

Our channel will not be a simple rectangular tube so we must consider the effect of our planned obstructions for mixing on the fluid dynamics. We can do this by considering our channel to be porous. If we have a porous channel, we can define a constant called the permeability that will allow us to describe the effect of the internal structure of the channel on the pressure drop across the channel. This definition comes from Darcy’s Law given in equation 10. In this equation $k$ is
the permeability, \( p^* \) is the pressure combined with the effect of gravity, \( \mu \) is the viscosity, and \( V_d \) is the flow rate per unit area of solid in the channel.

\[
V_d = \frac{\kappa \nabla p^*}{\mu} \tag{11}
\]

Now that we have the understanding of how the fluid is moving through a channel, we must understand how two fluids flowing through a channel will mix. The chemical mixing between two miscible fluids will be dominated by the inter-diffusion of the molecules of the fluids. This inter-diffusion cannot be described only by Fick’s 2nd Law. We must take into account that we have a moving reference frame with Fick’s 2nd Law. We must instead use a theory developed in the 1950’s by Taylor to experimentally determine binary diffusion coefficients. Taylor’s theory describes diffusion in a circular pipe instead of a rectangular channel like the ones that we are considering, but the principle holds. The equation for Taylor diffusion is given in equation 12. \( D \) is the standard Fick diffusivity given by equation 13 where \( E_A \) is the activation energy and \( D_0 \) is the maximum diffusion constant at infinite temperature.

\[
\frac{\partial c}{\partial t} + \vec{u} \cdot \nabla c = D \nabla^2 c \tag{13}
\]

\[
D = D_0 e^{\frac{E_A}{RT}} \tag{14}
\]

The diffusion happens at the interface between the two mixing fluids so in order to speed up the inter-mixing, we can increase the number of places at which diffusion can occur. This is equivalent to increasing the interfacial area between the fluids. In flow of miscible fluids, we must increase the interfacial area by stretching the volume units of the fluid. In the case of laminar flow, the streamlines of the volume units are not being stretched by themselves so the interfacial area is not maximized. In our case we plan to use the principle of splitting the flow and recombining the flow to stretch the volume units, thereby increasing the interfacial area between the two fluids. We will define our mixing efficiency as the spatial uniformity of the concentration of the fluid through the channel. This can be measured using any two fluids that will show a linear change in observable property with change in concentration. One example is the use of a fluorescent dye being mixed with a solvent in which it is miscible, but which is not also fluorescent.

**DESIGN GOALS**

When first approaching the project, we established a set of goals for the project to accomplish by the end of the project. We wished to design a microfluidic mixing channel in order to understand mixing efficiency, create an adequate pressure drop and optimize the mixing efficiency. In this design, we hoped to specifically target six parameters that we believed to be vital to the efficiency of the system including the number of rows of features, the spacing of the first, the radius of curvature, the nozzle angle and the size and density of the features. Although there may be many components and features to the channel that affect mixing that we have not examined, these were believed to be the most important. We decided the channel must have a pressure drop that gives a minimum outflow rate, therefore, this pressure was determined to be \( \mu \)L/s. Through these adjustments in the channel, we hoped to calculate and optimize the mixing
efficiency of the channel by defining the efficiency with the average reading in the channel and relating it with the standard deviation.

By accomplishing these goals and analyzing the parameters of the mixing channel, we hoped to have a broad goal of possessing a theoretical knowledge of the determined relationships based on the basic science of the channel and applying it to our findings. Through the course of our investigations, it is our belief that we have successfully achieved these goals by the end of our project.

**TECHNICAL APPROACH**

**NUMERICAL CALCULATIONS**

Fluid flow within complex structures cannot be simply calculated by applying the Navier-Stokes Equation 2 and the conservation of mass Equation 3 CFD programs such as Fluent® use complex differential equations that are derived from the conservation of mass Equation 2 and conservation of momentum Equation 15.

\[
\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mathbf{T}) + \rho \mathbf{f} + \mathbf{F} \tag{15}
\]

Where \( \rho \) is the static pressure, \( \tau \) is the stress tensor, \( \rho g \) is the gravitational force, and \( \mathbf{F} \) takes into account any other external forces that may be acting on the fluid. The stress tensor are the forces acting upon the coordinate surfaces that is represented by equation 13.

\[
\mathbf{T} = \mu \left[ (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \nabla \cdot \mathbf{u} I \right] \tag{16}
\]

Where \( \mu \) is the molecular velocity, \( I \) is the unit tensor, and the second term on the right is the volume dilation.

Equations 15 and 16 can only be used in 1-dimensional fluid flow; therefore they are modified for a 2-dimensional flow. Equation 17 is the conservation of mass equation in 2-D, while Equation 18 is the axial momentum conservation equation, and Equation 19 is the radial momentum conservation equation.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u_x) + \frac{\partial}{\partial r} (\rho u_r) + \frac{\rho u_r}{r} = 0 \tag{17}
\]

where \( x \) is the axial coordinate, \( r \) is the radial coordinate, \( V_x \) is the axial velocity, and \( V_r \) is the radial velocity.
These equations are solved for each point of a grid that was set up for a mesh, assuming each side of a particular rectangular cell sums up to zero in mass flow. This whole process is called the Finite-Volume Method. For a complex mesh these calculations are nearly impossible for any person to perform, that is why CFD programs such as FLUENT are necessary to compute these calculations for us.

PARAMETERS

When designing our micromixer, we varied 5 different parameters to see their effect on mixing efficiency and pressure drop across the channel. These parameters are the spacing of the star obstructions, the size of the obstructions, the radius of curvature of the obstructions, the number of rows of stars and the nozzle angle of the device.

We divided the spacing into x spacing and y spacing, where one dimension would be held constant while the other was varied by a fraction of the diameter of one of the stars. We varied the spacing from .25d to 1.25d in .25d increments. The reason that the spacing is in terms of the diameter and not a specific distance is due to the program we used to construct the meshes of the micromixer. In Gambit, the dimensions are unitless, so they provide a ratio which is then given dimensions in the Fluent program. Thus, depending on the scaling factor in Fluent, the spacing would change. The y spacing varied, while the x spacing was held constant as desired, however, this would not the case with the x spacing. To increase the x spacing, the channel of the micromixer had to get wider. Because the channel became more wide, the nozzle angle needed to be modified in one of two ways. Either the aperture size would be increased to accommodate the widened channel, or the nozzle would be lengthened to maintain the aperture size. We initially changed the aperture size, but found that this had a more profound effect than the spacing did, so in order to see the effect of spacing, we chose to lengthen the nozzle. This caused a slight variation in the y dimension when we were varying the x dimension.

To vary the size of the obstructions, we fixed the width of the channel and inserted more stars into each row. Each size is described not by the size of a star, since it is unitless in Gambit®, but rather by the number of star shapes in each row. The number of rows was also a straightforward
variation. We maintained the width and length of our channel and inserted extra rows, into otherwise empty space.

The way that we varied the radius of curvature of the stars was by changing the radius of the circle used to make the star. In the Gambit program, the star was made by making a square and then removing part of it. A circle, whose arc intersected the square in the middle of two of its edges, overlapped part of the square. These overlapping areas were removed, leaving behind a star. To vary the radius of curvature, the radius of the circle was changed from 7 to 35 units in increments of 7.

The nozzle angle variation was less uniform than the other parameters due to special circumstances surrounding it. Ideally, we would have tried it at 0, 30, 45, 60, and 90 degrees, however, this would have caused a change in the aperture size between the different nozzles and we wanted to see the effect of angle, not aperture. There was no way to make the 0 degree nozzle have the same aperture as the other nozzles without changing a different parameter, so it was replaced with a 15 degree nozzle. In order to maintain a constant aperture among the different nozzle angles, the lengths of the nozzles were slightly different. However, this difference in distance did not seem to affect the general nozzle angle trend.

**BOUNDARY CONDITIONS**

The two inlets are velocity inlets where the fluid is given a specific velocity, and scalar properties of the fluid are defined. We chose not to use a mass flow inlet because we are modeling an incompressible flow, so the velocity input will fix the mass flow. To ensure that the inflow stagnation properties were fairly uniform, the first solid obstructions were set relatively far away. All of the walls of the micromixer have a zero velocity boundary condition. These walls include both the walls of the device as well as the geometrical obstructions placed in the path of the fluid. The outlet of the device is a free boundary condition where no pressure or velocity is imposed on the fluid.

**CONVERGENCE**

For Fluent to consider a solution as converged either the scaled residual must decrease to $10^{-3}$ for all equations except the energy and P-1 equations, which must decrease to $10^{-6}$, or the program must run a user defined number of iterations if such residuals are never achieved. We chose 200 as the number of iterations and all of our simulations converged according to the reduced residuals. The reason that the scaled residue converges at a number higher than zero is due to the rounding error of the computer. A computer with infinite precision would have all of the residuals go to zero as the solution converged. The equation for the scaled residual is:

$$R^p = \frac{\sum_{\text{cells } P} | \sum_{\text{nb}} a_{nb} \phi_{nb} + b - a_p \phi_p |}{\sum_{\text{cells } P} |a_P \phi_P|}$$

Here $a_p$ is the center coefficient, $a_{nb}$ are the influence coefficients for the neighboring cells, and $b$ is the contribution of the constant part of the source term $S_c$ in $S = S_c + S_p \phi$ and of the boundary conditions.
GRID SIZE LIMITATIONS
Because we are solving equations numerically, there is some error in our solution as compared to the actual solution from the equations. The larger the number of grid points, the more closely the numerical solution follows the actual solution. Ideally, the grid would be infinitely fine; however, due to limitations of both the storage space and speed of the computers we used, we limited the number of grid points to a number that made meshing and solving the equations doable in a reasonable amount of time without sacrificing the integrity of our results. Without an easy way to compute the actual solution, we must compare simulations that are identical in every way, except for the number of grid points. If the difference between our two numerical solutions is small enough, we can assume that our grid is sufficiently fine and the results of the numerical solution are reflective of what is being modeled.

DIMENSIONALITY
There are two considerations for the dimensionality of this program, time and space. To simply our results we built two dimensional meshes and performed simulations in the steady state. We believe that 2D modeling is sufficient for this application because the flows on this size scale are laminar. Laminar flows smoothly vary their velocity fields in space and time in which individual sheets of fluid move past each other without generating cross currents. By minimizing the effect of time in our analysis, we can focus on the role that obstruction geometry plays in mixing. You will recall that the Fluent code is using a finite-volume method which attempts to replace the continuous problem domain with a discrete domain using a grid. In 2D, a grid of quadrilateral cells is meshed over the flow area. The integral form of each of the conservation equations is applied to the control volume defined by a cell to get the discrete equations for the cell. In the discrete domain each flow variable is defined at the grid points. Values at other locations are determined by interpolation.

SHAPE LIMITATIONS
The Fluent and Gambit software package offer the flexibility to represent complex geometries and model flow around arrays of obstructions. Fluent offers various grid resolutions within the same model allowing small areas within a mixing profile to be fully resolved, in addition to expanding the grid cell size with distance from the built up area. The pre-processing software, Gambit, allows for the creation of solid-model based geometries and intelligent meshing.

RELIABILITY TESTING OF THE SOFTWARE
In order to prove that our chosen simulation software was in fact reliable for the production of meaningful results, it was necessary to compare simulation results to theoretical data. To accomplish this, a simple rectangular mesh was constructed in Gambit® without obstructions. Simulations were run through Fluent® using a mesh width value of 0.6 mm and channel length value of 4 mm in order to calculate the value for the pressure drop. The theoretical value for the pressure drop may be found through use of Equation 8. The reference by Fay provides a table with \((RcDh)f\) and \(Dh/b\) values for a simple rectangular tube with various aspect ratios. The variable of \(b\) is given as the height, and \(a\) is given as the width. Values from the reference are provided in Table I.
Table I. Given values for variables used in Equation X according to tube aspect ratio.

<table>
<thead>
<tr>
<th>Aspect ratio (b/a)</th>
<th>B value (m)</th>
<th>((Re_{DB})f)</th>
<th>(D_b/b)</th>
<th>Pressure Drop (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00E-03</td>
<td>56.91</td>
<td>1</td>
<td>1.79E+02</td>
</tr>
<tr>
<td>0.5</td>
<td>5.00E-04</td>
<td>62.19</td>
<td>1.333</td>
<td>4.41E+02</td>
</tr>
<tr>
<td>0.2</td>
<td>2.00E-04</td>
<td>76.28</td>
<td>1.667</td>
<td>2.16E+03</td>
</tr>
<tr>
<td>0.1</td>
<td>1.00E-04</td>
<td>84.68</td>
<td>1.818</td>
<td>8.07E+03</td>
</tr>
</tbody>
</table>

Since only constructed two-dimensional meshes were created, the height was set equal to zero and the width equal to 1 mm, 0.5 mm, 0.2 mm, and 0.1 mm respectively for each given aspect ratio. The theoretical pressure drop was then calculated, which is also given in Table I. In order to compare the simulated pressure drop to the calculated value, a curve was first constructed of the given aspect ratio vs. the calculated pressure drop, shown in Figure 2.

Figure 2. Calculated pressure drop vs. given aspect ratio for two dimensional rectangular mesh.

The simulated data gave an average inlet pressure of 101329.3 Pa and an average outlet pressure of 101321.0 Pa, thus yielding a pressure drop of 8.275 Pa. For comparison, the height value of the calculated aspect ratio was set to zero, thus setting the aspect ratio itself to zero. If we extrapolate the above curve down to zero on the y-axis, then the fact that the simulated pressure drop is very small compared to the calculated pressure drop appears to fit the given curve. Thus we can conclude that the simulated data fits the calculated data.
DESIGN OF MIXER

Overall Design
We initially intended to fabricate a microfluidics prototype channel, however, due to shifting importance in the design aspect of the project, we omitted the prototype from our project. Nevertheless, we still researched the scale-up and how we would approach building such a device given more time.

The channel itself would be modeled after one or a combination of the simulations ran in Fluent® from the simulation portion of the project. There would be two inlet channels converging at 45° angles into the main channel with a single outlet channel narrowing slightly near the end. The channel would be two dimensional with a top and bottom preventing fluid from escaping the channel. Figure X shows an example of a top-view of the mixing channel from the Fluent® simulations.

![Figure 3. An example of the microfluidics channel used to create the prototype.](image)

It is important to keep in mind that the size and arrangement of the features inside the mixing channel depended solely on the results of our simulations. Therefore, Figure 1 is only a possible layout of the mixing channel.

The mixing channel itself would be made from a polydimethylsiloxane (PDMS). PDMS is a transparent polymer generally used in current microfluidics research. It is easy to use and relatively inexpensive. A more in-depth explanation of the fabrication of the channel follows. A thin glass slide will be fused to the top of the PDMS chamber in order to prevent leakage out of the channel during testing.

Fabrication of the Mixing Channel
In order to build the microfluidics channel, photolithography must be used to create a mold of the channel before PDMS can be poured into the mold. To do this, we planned to use a photoresist called SU-8 manufactured by MicroChem. We also planned to use Figure 1 to create a CAD drawing of the desired channel and send it to a company like CAD/Art Services in California in order to obtain a photoresist mask for photolithography.

After obtaining our mask and the photoresist, we can create the mold. We would first spin the photoresist onto a silicon wafer. To create a 250 µm thick SU-8 100 photoresist layer, we would spin at 500 rpm for 5 to 10 seconds for the spread cycle and then at 1000 rpm for 30 seconds for the spin cycle. After obtaining our mask and the photoresist, we can create the mold. We would first spin the photoresist onto a silicon wafer. To create a 250 µm thick SU-8 100 photoresist layer, we would spin at 500 rpm for 5 to 10 seconds for the spread cycle and then at 1000 rpm for 30 seconds for the spin cycle. We could increase the thickness by repeating this process after a soft bake, however, we were not confident that this would work reliably. The mask would then be used in photolithography for the specified exposure time followed by development of the photoresist.
with SU-8 Developer supplied by MicroChem. This process yields an SU-8 mold that we can then use to mold our microfluidics mixing channel with PDMS. Before the PDMS can be poured onto the SU-8 mold, it must be properly mixed. We planned to obtain a PDMS Kit called 184 Sylgard Elastomer Silicone Kit. The pre-polymer must be combined with the curing agent and then placed in a dessicator for about 45 minutes. The SU-8 mold should be placed into a shallow dish and then the PDMS can be poured onto it. The dish with the PDMS is then placed on a hot plate where it cures and then peeled away from the dish. To seal the channel irreversibly, follow with a plasma treatment to permanently bond a glass side to the open side of the PDMS channel.

**Testing the Device**

In order to test our microfluidics channel, we devised a basic set-up based on a gravity pump. The mixing material will be an aqueous solution of dye that will produce fluorescence. We planned to image the mixing efficiency on the stage of a laser-scanning microscope (LSM) at the Laboratory of Physical Sciences (LPS). This would allow us to image the fluorescence of the solution as it traveled through the channel. The basic set-up is shown in Figure 2 below.

![Figure 2](image-url)

**Figure 2.** A macro-scale diagram of the microfluidics prototype experiment.

The LSM has been generalized by the large blue block, but there is 17 inches between the top of a 3 foot by 5 foot table and the stage where the microfluidics channel will be placed. The tall silver pole represents the chemical stand set-up that will hold the gravity pump. The upper limit was arbitrarily set at 3 meters, because it would be extremely difficult and impractical to set it higher. The lower limit has been set at 12.5 cm in order to create enough pressure to keep fluid flowing through the device with a gravity set-up. Tubing will travel from the fluid holder down to the microfluidics channel on top of the LSM stage. We will need to attach metal couples to the inlet channels and secure them with epoxy to prevent leakage at the entry points. The metal couples will be attached by using corers approximately the size of metal...
couples and then fitting the metal couples into these holes. The microfluidics channels will sit on top of the LSM stage and we will generate real-time images as the fluid travels though the channels in order to ascertain the degree of mixing.

**ETHICAL AND ENVIRONMENTAL IMPACT**

With the development of any new product or process, the effects of implementation whether beneficial or adverse must be evaluated in order to argue for its need for implementation. It has been mentioned earlier that the development of smaller and efficient passive micromixers will enhance the success of many MEMS that incorporate these components. Specific applications that will benefit from the development of the proposed passive micromixer design are derived from the “lab-on-a-chip” idea, a proposed goal for microfluidic systems. The “lab-on-a-chip” systems are designed to integrate various aspects of modern biology and chemistry labs on a single microchip.

Examples of certain biological/chemical procedures that will benefit from miniaturizing their process through incorporation of MEMS with passive micromixing elements include DNA analysis and enzyme assays. These areas will be of benefit due to the fact that the miniaturization of their processes leads to reduction of sample size, decrease of assay time, and minimization of reagent volume needed. The performance of these procedures can be enhanced with more effective passive micromixers since these processes rely on how quickly and how well fluids can be mixed. Details of DNA analysis were discussed earlier. Enzyme assays are conducted to determine an enzyme’s reaction kinetics, and include steps such as cell lysis, protein extraction by diffusion and detection by fluorescence. The incorporation of a passive microfluidic mixer in this process is essential for the cell lysing procedure.

The fabrication of the proposed passive microfluidic mixer involves the basic steps of creating a mask for photoresist deposition, creating the photoresist master, and then creating the PDMS micromixer from the photoresist master. The materials of importance, as it relates to environmental effects, used in each step will be discussed based on OSHA’s Hazard Communication Standard. It is this standard that requires that any known hazards of materials that employees may be exposed to in the workplace be disclosed. Any potential hazards are made known by the use of material safety data sheets (MSDS). The MSDS sheets for the materials used in the fabrication of the proposed passive micromixer are found in the appendix.

In creating the transparency mask, a mylar film is used in conjunction with a laser photoplotter. The mylar film is considered to be an article, and is therefore not considered hazardous. An article is defined by OSHA to be the following:

“Article" means a manufactured item: (i) which is formed to a specific shape or design during manufacture; (ii) which has end use function(s) dependent in whole or in part upon its shape or design during end use; and (iii) which does not release, or otherwise result in exposure to, a hazardous chemical under normal conditions of use.

The main materials and chemicals used in creating the photoresist master are the SU-8 photoresist and the SU-8 developer. SU-8 photoresist is an organic resin solution that contains Gamma Butyrolactone (CAS: 96-48-0); 22-60%
Mixed Triarylsulfonium/ Hexafluoroantimonate Salt; (CAS: 89452-37-9)/(CAS: 71449-78-0); 2.2%/<1%, Propylene Carbonate (CAS: 108-32-7); 1-5% and Epoxy Resin (CAS: 28906-96-9); 35-75%. It is not considered to be a major health hazard, but can cause severe irritation to the eyes or moderate irritation to the skin upon contact. There are also no occupational exposure limits set for this material. Use of this material should occur under a chemical hood. The amount of SU-8 resist needed to create the mixer is around 2-4 mL. The guideline for disposal of this material is to burn in an EPA licensed chemical incinerator that is equipped with an afterburner and scrubber at an approved waste disposal facility. The SU-8 developer is an organic solvent solution that consists of 1-Methoxy-2-propyl acetate (CAS: 108-65-6), 98-100%. Moderate irritation if exposed to the eyes or skin may occur. Due to the potential irritation caused by its fumes, this chemical should also be used under a chemical hood. The amount of SU-8 developer needed is around 400 mL. Unused developer must also be burned in a chemical incinerator.

The last step involves the creation of the PDMS mixing chamber using the photoresist master. The main materials used in this step are the Sylgard 184 silicone elastomer base and the Sylgard 184 silicon elastomer curing agent. The Sylgard 184 silicone elastomer base consists of silicone in its liquid form. It is not considered to be a hazardous material. There are no significant effects if in contact with the skin or by inhalation from a single short-term exposure. There are also no known effects for prolonged exposure. The amount of Sylgard 184 silicone elastomer base needed for the mixer is around four grams. Because the base is not considered to be a hazardous material as it pertains to disposal, there are no requirements for disposal. The Sylgard 184 silicone elastomer curing agent is a silicone resin solution. There are no significant adverse effects if the curing agent is inhaled or comes into contact with the skin for single short-term exposure. A ventilated area is recommended when using this material due to minute quantities of hydrogen gas that can evolve from this product. The amount of Sylgard 184 silicone elastomer curing agent needed for fabrication is around 0.4 grams, as a 10:1 ratio is required for mixing of the base and curing agent. For both the base and the curing agent, it is important to keep them away from oxidizing materials, which can liberate flammable hydrogen gas. The curing agent is classified as a RCRA Hazard Class D003, which corresponds to a reactive characteristic waste. Any unused curing agent must be burned in a chemical incinerator.

Currently, there have been no studies that have focused on the determination of the lifetime of a PDMS microfluidics channel. One of the reasons for this is because the process of creating a PDMS channel is relatively simple and cost effective as the photoresist master from which the PDMS channel is created, can be used up to around 50 molding cycles. However, one method that could be used to determine the lifetime of the mixer would be to run a mixing test multiple times and measure the resultant mixing efficiency. If a limit for the mixing efficiency is set with an acceptable error (i.e. 98% ± 0.05%), then when the resultant mixing efficiency has reached this limit, the number of tests that were conducted will determine the lifetime of the device. This procedure could be carried out several times in order to compute an average lifetime, which would improve the accuracy of the calculated lifetime of the device.

As it relates to the disposal of the PDMS microfluidic mixer, the PDMS mixture is considered to be non-hazardous, therefore there are no specific requirements for disposal. Studies have been conducted on the degradation effects of PDMS in the natural environment to confirm its non-hazardous nature. Studies of PDMS presence in soil have proven that neither PDMS or its
main degradation product, dimethylsilanediol, have an adverse effect on the soil environment.\textsuperscript{xvii,xviii}

After evaluating the materials used in this fabrication process and their potential hazard, it is concluded that the fabrication process does not impose any significant harmful effects on those that will be carrying out this procedure. Therefore, it will be of great benefit to implement the new design of this PDMS microfluidic mixer because of the benefit it will bring to society in providing potential “lab-on-a-chip” applications that were described earlier.

**INTELLECTUAL MERIT**

This project involves furthering the understanding of mixing at the micron scale in passive micromixers. At this scale, Reynolds numbers are small, therefore, the flow regimes is laminar instead of turbulent. This project will systematically investigate the effect of mixing channel geometry on the mixing efficiency of a microfluidic device. We intend to simulate the effects of five different geometric factors on the mixing efficiency and the conduction of the device using a unique star-like obstruction. The five factors are feature size, feature spacing, channel length, nozzle angle and radius of curvature. The resultant relationships we determine will allow for the creation of reliable and efficient pass mixing channels.

With the mentoring of faculty at the University of Maryland and the knowledge gained from Physics, Chemistry and materials engineering courses, our project team is well equipped to successfully complete a microfluidics research project. Numerous facilities and software packages offered through the University will provide the necessary tools and resources to conduct our research.

**BROADER IMPACT**

As previously stated, passive micromixers do not involve the use of moving parts and rely on the geometry of the device to enhance mixing through chaotic advection and fluid lamination. It has been proven that these mixers are reliable, easy to manufacture, and often offer high performance.\textsuperscript{xix} Passive micromixers can be integrated for use in medical testing, pollution detection and chemical and biological weapon detection. The efficiency of passive micromixers is attributable to the reduction in the volume of reagents used for testing and in the overall size of the device including the micromixing component. We chose to design a passive microfluidics mixer for these reasons and to understand the relationship between mixing efficiency and channel components.

A possible application for our proposed micromixer design is DNA purification. DNA purification is a necessary step involved in conducting effective DNA analysis. DNA purification involves disrupting the cellular structure to create lysate. This lysate forms by mixing a DNA solution and a buffer, which degrades the cell membranes. The process releases the DNA from its host cells. The soluble DNA is separated from cellular debris and other insoluble material. Lastly, purifying the DNA from other soluble proteins and nucleic acids.\textsuperscript{xx}

Previous research conducted focused on the development of a microfluidics chip for DNA purification. A generic microfluidics chip consists of a microfilter, micromixer and DNA purification chip.\textsuperscript{xxi} One particular design incorporated the use of a passive micromixer that
achieved mixing by repeated fluid twisting and flattening (Figure 1). The overall size of the microfluidics device was 30 mm x 15 mm and the lengths of the main channel and flattened channels were 6.0 and 1.7 mm respectively.

![Figure 5. Schematic of passive micromixer geometry from Lee, N., Yamada, M. and Seki, M.]

The mixing efficiency of this particular design was evaluated by calculating the coefficient of variation (CV) of signal intensities of the cross-section of the microfluidic channel using a confocal laser-scanning microscope. CV was defined as the standard deviation of the signal intensities divided by the average signal intensity. Therefore, a low CV value would indicate a high mixing efficiency. For their design, they were able to yield CV values around 0.015, which they defined as a homogenous mixture.

With our passive micromixer design, we hope to achieve mixing efficiencies between 90 and 98%, using a shorter length scale for our mixing channel, which would be ideal for the application of DNA purification. Through the variation of other parameters in our design, we will be able to optimize our design for the maximum mixing efficiency.

**RESULTS**

We have chosen to express our data in terms of a raw value read directly from the simulation, and also as a normalized value where we scale the raw data by the total length of the channel. We made this decision based on results that showed that both the pressure drop and the mixing efficiency scale linearly with the length of the channel. These results are shown in Figures 6 and 7 respectively. The linear dependence of pressure on channel length is expected from the previously given Darcy-Weisbach equation.
**Variation of Radius of Curvature**

The effect of the radius of curvature in the mixing channel was analyzed by varying the radius of curvature with 5 different values. In order to create the radius of curvature, boxes were created for each star and a circle of varying radius was used to cut out the corners to create curved values. We also compared a traditional diamond shape to the performance of the star shapes and this value is represented by the value of 10. The baseline size was set as $m$, the radius of the circle. In Figures 1 through 4, the x-axis values correspond to the following: $0 = m$, $2 = m + 2$, $4 = m + 4$, $6 = m + 6$, $8 = m + 8$ and $10 = \text{flat sides or diamond shape}$.
There is no apparent effect of the radius of curvature on the mixing efficiency shown in Figure 8 and the normalized mixing efficiency shown in Figure 9. The normalized mixing efficiencies range from 10-11.5%/mm. We expected increases in the radius of curvature of the stars towards a simple diamond to decrease the mixing efficiency. As the surface area of the stars decreased the fluid had to travel a shorter path to go around the stars. We thought that the decrease in the path would bend the streamlines less, inducing less mixing. This is not the case. If we examine the local pressure drop given in figure 5 for a mesh with stars compared to a mesh with diamonds, we see that the pockets formed on the backside of the stars create a larger local drop in pressure.
Figure 10. Local pressure drop in the meshes with different start radii.

The graphs of the pressure drop and normalized pressure drop are shown in Figures 11 and 12, respectively. The data displays a decreasing trend in the pressure drop and normalized pressure drop. The pressure drop ranges from around 80 Pa to 55 Pa, whereas the normalized pressure drop ranges from 20 – 14 Pa/mm. The dead space on the back sides of the stars may explain the trend we see in the meshes with increasing pressure drop with decreasing radii of curvature. The bigger the pocket, the more local drop we have.

Figure 11. The plot of pressure drop versus radius of curvature.
**Figure 12.** Graph of the normalized pressure drop versus radius of curvature.

**VARIATION OF X-SPACING**

We analyzed the effect of x-spacing of the stars by varying the spacing between stars in each row in increments of 7 units as defined by the meshes created in Gambit®. Therefore, we looked at the x-spacing values of 7, 14, 21, 28 and 35. If we estimate that 28 units are ~80 microns, we can say that every 7 units are ~20 microns.

**Figure 13.** Mixing efficiency with varying x spacing.
Figures 13 and 14 above shows the results obtained from the Fluent® simulations where the X Spacing was varied between the stars in the channel. The X Spacing is considered the distance between stars in the same row, where a star is 28 units wide which corresponds to approximately 80microns. We see from the data that there is little variance between channels when varying the X Spacing, while the overall mixing efficiencies of each channel were around 97-98%.

When we do our normalization, we find that the normalized mixing efficiency is always around 17.25 %/mm regardless of the X Spacing. We expected to see an increase in the mixing efficiency with decreased channel spacing in the x direction. As the flow is more constrained, it should bend more thus inducing more stretching of the streamlines. From our data we can conclude that for spacings as large as our smallest spacing tested, decreased spacing doesn’t increase the confinement of the fluid.
We obtained the data shown in Figure 15 by examining the calculated absolute pressure from the Fluent® simulations and subtracting the pressure at the beginning of the mixing channel with the pressure at the end of the mixing channel. We see that as the spacing between stars in the x-direction increases, the pressure drop decreases. The maximum pressure drop recorded was 70 Pa at an x-spacing of 7 units, while the pressure drop at an x-spacing value of 35 units was only...
about 3 Pa. If we remember the *Darcy-Weisbach* equation given again in equation 1, this pressure drop relationship can be explained by an analogy with Ohm’s law.

\[
\Delta p^* = \frac{(\text{Re}_h) f}{(D/h/b)^2} \left( \frac{\mu \bar{V}L}{2b^2} \right)
\]  

(I)

The Darcy friction factor correlates to resistance in electronic conduction. As we reduce the characteristic dimensions of the channel, we reduce the mean free path of a unit of volume before it hits an obstacle which in turn increases the friction factor, \(f\), given in equation 1. This increases the pressure drop.

**VARIATION OF Y-SPACING**

The effect of the y-spacing of the stars was studied by selecting five different y-spacing values for the stars. These values are .25d, .5d, .75d, 1d, and 1.25d, where \(d\) corresponds to the diameter of the star. Once again, the estimate diameter of the star is ~80 microns. The results were plotted in terms of calculated mixing efficiencies, normalized mixing efficiencies, pressure drop, and normalized pressure drop all as a function of the discrete values of y-spacing that were chosen. The mixing efficiency varied between 97.498 – 97.530% which is not a significant variation Figure 17. The same lack of variation is seen as well in the normalized mixing efficiency plot Figure 18. The normalized mixing efficiencies range from 21.571 to 21.578 %/mm. Once again, we expected to see an increase in the mixing efficiency with decreased channel spacing in the y direction. As the flow is more constrained, it should bend more thus inducing more stretching of the streamlines. From our data we can conclude that for spacings as large as our smallest spacing tested, decreased spacing doesn’t increase the confinement of the fluid.

**Figure 17.** Mixing efficiency versus y spacing.
The plots of the pressure drop and normalized pressure drop indicate that there is a slight decrease in pressure drop due to the variation from 0.25d to 1.25d (Figures 19, 20). The pressure drop ranges from 30.850 to 31.985 Pa, while the normalized pressure drop ranges from 6.826 to 7.077 Pa/mm. This trend can be explained once again by analogy with Ohm’s law. As we reduce the characteristic dimensions of the channel, we reduce the mean free path of a unit of volume before it hits an obstacle which in turn increases the friction factor given in equation 1 and increases the pressure drop. We see that y spacing has less of an effect than the x-spacing does on this friction factor. This makes sense in the regime of laminar viscous flow because the velocity of the fluid at a wall is zero so if the walls are closer together radially we increase the amount of wall. Changing the y spacing does not increase the wall area.
Figure 20. Normalized pressure drop versus y spacing.

NOZZLE ANGLE

Nozzle angles are changed at the channel outlets, varied from 15 degree, 30 degree, 45 degree, 60 degree and 90 degree. Channel dimensions for this parameter are scaled to be 1 mm for width and 4.65-5.02 mm for length. Figure 16 shows the results for both pressure drop and mixing efficiency for nozzle angle. The results showed that there is no significant effect arising from this parameter. The mixing efficiency ranges from 94.7% to 97.5%, they are slightly higher for 30, 45 and 60 degrees than for 15 and 90 degrees. Normalized mixing efficiency by dividing channel length showed a slight decreasing trend with increasing nozzle angles. This decreasing trend is within the error of the calculations. This trend may be due to the differences in aperture before and after the nozzle. The channel becomes more constrained after the aperture so the flow should be more laminar. The more severe the angle, the longer the narrower portion of the channel is in relation to the total length. The zero degree angle nozzle has no aperture reduction and has the highest efficiency which supports this idea. The pressure drop in the mixing channel has similar trend as mixing efficiency. The pressure drop ranges from 27.2 Pascal to 27.5 Pascal in total, normalized pressure drop ranges from 5.4 Pascal to 5.9 Pascal per millimeter. This pressure drop is too insignificant to define a trend even though the plot appears to have a reduction of pressure drop with increased nozzle angle. We not expect to see a trend in pressure drop across the channel, assuming that the aperture in each case is the same. Our aperture for the zero angle is not the same diameter so there should have been some difference, but from our measurements this difference is less than a Pascal.
Figure 21. Top left: Mixing efficiency as a function of nozzle angle. Top Right: Mixing efficiency normalized to channel length. Bottom Left: Pressure drop as a function of nozzle angle. Bottom Right: Pressure drop normalized to channel length.

**ROWS OF STARS**

Channel dimensions are 1mm for width and 3.1 mm for length. By using the same mixing channel length and adding different number of rows of star, mixing efficiency varied from 84% to 87%. In this case, the absolute mixing efficiency and pressure drop show the same trends as normalized values due to the same channel length. Pressure drop increases with number of rows linearly up to 11 rows. For 14 rows of stars, the pressure drop jumps non-linearly. If each row acts as an individual contribution to the friction factor, we can consider each row as a resistor in series. The resistance should increase linearly, which is what we see for 2 rows to 11 rows. It is unclear why the slope of the pressure drop jumps for the addition of 3 more stars. Mixing efficiencies decrease with increasing number of rows almost linearly in the small range.
Figure 22. Top Left: Raw mixing efficiency as a function of number of rows of stars. Top Right: Normalized mixing efficiency as a function of number of rows of stars. Bottom Left: Raw pressure drop as a function of number of rows of stars. Bottom Right: Normalized pressure drop as a function of number of rows of stars.

Less rows of star give a slight better mixing than more rows due to larger diffusion length and space in the channel. This trend is the opposite of what we expected to see. If our geometry was inducing mixing, we should see more mixing with increased numbers of rows. After obtaining this result we realized that throughout the simulation we had been assuming water diffusing into water with an inter-diffusivity of 2.88E-5 m^2/s. We should have been considering the diffusion of fluorescein into water. Browne and Zimmer have calculated this diffusivity to be 4.4E-10 m^2/s. When we look at the mixing for 11 rows at 2.88E-5 m^2/s in Figure 23 we see that the streamlines are bending around our features, but the features are acting to constrain the flow and thus impede the spread of the water into the other water. The features are reducing the mean free path of the water molecules within the other water molecules. When we remove all the stars there is no impediment so the system is more efficiently mixed. If we reduce the diffusivity to the actual value of fluorescein in water, we see that there is only a mixing of 9.23% for no stars while there is an efficiency of 31.89% for the 11 rows of stars. This is shown in Figure 24 and 25, respectively. These simulations confirm that our stars do in fact introduce mixing, but only if they are spaced further apart than the mean free path of a molecule diffusing through a media.
Figure 23. Bending the streamlines and confinement of flow through 11 row mesh with water-water diffusivity.

Figure 24. Mixing for no stars with correct diffusivity.
VARIATION OF SIZE

The effect of the size of the stars was studied by selecting 6 different star sizes. The star sizes were varied from a baseline size of m, which has been defined previously as the radius of the circle used to create the corners on the stars. In the plots below, the size axis values correspond to the following: 0=(m-1), 1=(m), 2=(m+1), 3=(m+2), 4=(m+3), 5=(m+4). Decreasing the star size also increases the number of stars in a given row and therefore the star density. The plots show that the size of the stars has a small effect on mixing properties. The plot shows that the mixing efficiency slightly decreases with an increase in star size. The mixing efficiency ranges from 61.278 – 67.146%, while the normalized mixing efficiencies range from 22.487 to 24.461 %/mm (Figures 26, 27). We expect for the reduced star densities that there will be less manipulation of the flow and therefore less mixing. We see in figure 22 that there is a reduction of mixing efficiency with reduced star density.
The plots for the pressure drop and normalized pressure drop show a slight decreasing trend with respect to increasing star size (Figures 28, 29). The pressure drop ranges from 69.385 to 110.010 Pa, while the normalized pressure drop ranges from 25.462 to 40.371 Pa/mm. The observed trend in pressure drop can be explained by the changes in density of the mesh. The larger features have fewer obstructions and thus less contribution to the friction factor. Each star has the local pressure drop discussed in the section on radius of curvature, so the more of these local pressure drops, the greater the overall pressure drop. There are also fewer rows of larger stars. The total length of the channel that contains obstructions is held constant, which means that the number of rows changes which explains the reduction in pressure drop for larger stars.
CONCLUSIONS

From our simulation data, we can conclude that the most important of these variables for mixing efficiency are number of rows of stars and the size of the stars or the star density. Both of these factors say that having more stars in a given row and more rows of stars will increase the mixing through the channel. Unfortunately these two factors also have the greatest impact on pressure drop. We must consider that we need to have flow through the channel when we implement this style of mixing channel we must carefully consider the flow rate needed and from that the total pressure drop allowed. For our system we stated that we needed a flow of 1 microliter per second which corresponds to a gauge pressure of $1.4E-7$ Pa at the output. We have stated that our maximum gravity pump height was 2m which would give us a total possible pressure drop across the channel of 19400 Pa. We cannot speak to the reality of using such a pressure drop without considering the strength of our proposed PDMS channel, which has not been considered for our case. A pressure drop of 19400 Pa would correspond to a force of ~1.5 (mN/number of pillars) per pillar if we take the size of the channel to be 1mm$^2$ and the size of the star to be 80 microns in diameter.

We made the mistake during our simulations of using the interdiffusivity of water in water for our simulations instead of the interdiffusivity of a dye, such a fluorescein, in water. Based on our results in Figures 24 and 25, if mixing efficiency scales linearly with number of rows then we would need 44 rows to achieve 99.87% mixing efficiency in such a channel. This would correspond to a pressure drop of 800 Pa if our 14 row point is actually an error, or a pressure drop of greater than 1571 Pa if the slope does shift for numbers of rows above 11. These pressure drops are within our range of pressure drop given by the possible height of the gravity pump. From this we can conclude that our system will work as a mixer for needed applications.

**Figure 29.** Normalized pressure drop versus size.
Our mistake relating to the choice of interdiffusivity has illustrated an important point relating to mixing at this scale. We have two different effective mean free paths that we must discuss, one referring to the mean free path of a unit volume in the channel, and the other referring to the mean free path of a dye particle diffusing though the solvent media. Our features spacings should be smaller than the mean free path of the fluid unit volume in order to increase the area of the unit volume, but our feature spacing must be larger than the mean free path of the diffusion of the dye molecules within the water. When the dimensions are smaller than the mean free path of the water molecules the features impede the diffusion that is necessary for mixing.

ACKNOWLEDGEMENTS

Special thanks to Dr. Phaneuf, Dr. English, Tom Loughran, Dean Berlin, Dr. Rubloff, Dr. Julia Heetderks, and Dr. Shy-Hau Guo.
References


vi Arranz de Blas, Carlos. CFD Analysis of Air Flow within a Front Wheel Cavity. Cranfield University, School of Engineering, MSc Automotive Product Engineering.

vii FLUENT Inc. FLUENT 6.2 Documentation. 5 May 2007 <http://193.204.76.120/fluent6.2/help/index.htm>


