Design and Analysis of Fluid Flows through PIV and CFD Modeling

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ABSTRACT
This research project was performed in order to design and analyze fluid flow models "microvalves." Microvalves allow the user to control fluid flow in a microchannel by varying a given macroscopic parameter. The valves can be actuated mechanically, pneumatically, electrokinetically, by phase changes, or by introduction of external force. The Computational Fluid Dynamics (CFD) and the Particle Image Velocimetry (PIV) are integral methods of our investigation. CFD provides a way to simulate fluid phenomena and variables that are not readily attainable for analysis and time consuming and costly for experiments. PIV is an experimental technique which provides a measurement of the various fluid variables including velocity field, vorticity, and visualizations, etc. We are currently more interested in how to use these experimental methods and computational techniques in order to better analyze and design microvalves for flow regulation. We are currently doing several "proof-of-concept" modeling, simulation, and visualization works. Our expected outcome from this project is to further improve the performance of existing micro valves in order to come up with a newer and more efficient model.

INTRODUCTION
Microfluidic chips are now widely employed in a number of areas including chemical biology, biomedical, security, forensics and many other new emerging fields of science, technology and engineering innovations. The development of microchips is largely depending upon the computational, analytical and experimental testing, This design project is comprised with computational skills to model the microfluidic chips and test with state of the art PIV techniques in order to optimize the efficiencies of microchips.

The PIV generates instantaneous velocity maps in a two dimensional cross section of flow domains. The spatial resolution and the accuracy of the measurement, if performed adequately and accurately, are considered to be high. The measured velocity can then be used for a wide range of post processing calculations, including velocity magnitude and direction, velocity gradient, viscous shear, stream function, vorticity, and others [3]. CFD offers the ability to reconstruct the reality of fluid motion and behavior in order to better understand the variables and phenomena of the fluid domain under specified conditions [4]. COMSOL, a commercial Multiphysics software has been employed as our CFD software. Utilizing the simulation results from COMSOL, PIV experimental results will be compared and be used for validation and confirmation of minimum uncertainty. The project was started, first, by studying existing flow models on the ePIV (Educational Particle Image Velocimetry) with its embedded software FLOWEX and later be verified by COMSOL. Varieties of flow models for microvalves will be later tested with ePIV and then will be verified by FLOWEX and COMSOL for fine-tuned final design. The practice of CFD and the PIV lead us to a better understanding of the fluid phenomenon in designing a fluid system. On becoming proficient with these instruments and software, we will be designing (using Solid Works and COMSOL Geometry platform) a fluid flow model of microvalve that can be tested with ePIV. This model was studied and analyzed on the ePIV and CFD.

Purpose

The project's main objective is the design and analysis of microfluidic valves. Our Team will achieve this with extensive research using CFD and PIV techniques. A microvalve is the fundamental component which enables liquids to be controlled on-chip and is the key to realizing microfluidic large scale integration [5]. This would be the first use of this new technology on the campus. The results of the design project will provide opportunities in the future research projects and/or in-class demonstration purposes for other students and/or faculty. Our results will also give insight on the academic field of microfluidic chip technology.

Background

Ever since miniaturization became a scientific accomplishment (Integrated Circuit, 1958), it has been researched extensively [6] in the late 1970's micro electromechanical systems (MEMS) were developed [6]. Over the course of the years more extensive research on MEMS was investigated in the field of biology, chemistry, and biomedical fields [7]. Currently many researchers are working in microfluidics to develop more advancements on all possible fields lab-on-a-chip (LOC) is a much researched technology for hospitals [7]. LOCs are usually in a small credit-card size that requires a small sample volume and are comprised of many laboratory processes in a single unit such as mixing, regulating, separating, detecting and recirculating, etc. As mentioned, these chips have many flow lines and fluid domains that need redesign and reanalysis for optimizations and to enhance their efficiencies. Microvalves are assumed to play significant roles in LOC technology to enhance their effectiveness and therefore this research will be more focused on the optimization of microvalves.

Theory

Microfluidics is a relatively new branch of multi-disciplinary small scaled fluid mechanics that deals with the flow of fluid in fluid systems that are of micrometer size [7]. The following image (Figure 1) shows the ePIV (provider: Interactive Flow Studies), which was used to study the fluid flow's velocity of various fluidic flow models.

Figure 1. Educational Particle Image Velocimetry

The measured velocity can then be used for a wide range of post processing calculations, including velocity magnitude and direction, velocity gradient, viscous shear, stream function, vorticity, and others. From the scope of this project, we only focused on the velocity magnitude graph (VMG). The VMG offers a visual representation of how the fluid flow changes velocity at different positions. The post processing calculations from the ePIV are calculated by the FLOWEX software, provided with the ePIV. The quality of the VMG post processing calculations depends on two things: the cleanliness of the ePIV (no air bubbles and/or debris), and the seeding selection. For this experiment the seeding selection depended on how small the seed should be to follow fluid motion and should not alter fluid or flow properties [8]. Interactive Flow Studies provided us with a polyamide seed, which has a diameter of 50μm, a specific gravity of $1.03 g/cm^3$, and a refractive index of 1.5 that is one of the recommended seeds for water flow applications. COMSOL is a general-purpose commercial Multiphysics software platform, based on advanced numerical methods, for modeling and simulating physics-based problems [9].

COMSOL involves pre-processing (geometry, defining boundaries, meshing the domain, setting up parameters and materials, choosing a proper physics or multiphysics, simulations and post processing). In order to have quality simulation, two things are to be considered: governing equations, and meshing (grid generation). The selection of appropriate governing equation depends on the description of the fluid flow passing an object including continuity equation, and momentum equations, energy equations, etc. based on the presence of multiphysics present in the domain. Meshing is a set of nodes/cells in fluid domain at which the COMSOL multiphysics codes solve for governing equations, set-up by the user until the convergence [2]. The two main parameters of a quality mesh depends on the accuracy [2].

The relation between these fluid flow analysis techniques are essential for our design. The CFD allows us to simulate various fluid flow scenarios until appropriate results are obtained and they will be validated with PIV experimental analysis.

Procedure

The design project will be completed in two fold: extensive practice in CFD and PIV; secondly extensive research work on the main topic, design and analysis, and collection of data and modeling.

The design project started by gathering theoretical information on fluid systems, CFD, and PIV. After understanding the basic principles of these concepts, we installed COMSOL Multiphysics software (CFD software), and setup the PIV work area in the WVU Tech Engineering Lab. Once the installation was completed, we began studying the fluidic flow models on the ePIV (6 models), which can be seen on the following image.

Figure 2. Fluidic Flow Models

The ePIV was set to run on 50% of max speed and 100% of max speed. From the various models, we obtained post processing calculations that were later compared to the results obtained from CFD simulation. COMSOL was also used to study the fluid flow's velocity by simulating (numerical analysis) the same conditions and geometry of the fluidic flow models studied on the ePIV. The results of the simulation are compared to the ones collected from ePIV, to validate experimental analysis (ePIV).

RESULTS

Observations

All the post processing calculations from ePIV was recorded and analyzed in FLOWEX software. Some of the preliminary calculations obtained were the velocity vector field (VVF), and the VMG.

The VMG shows the variation (change of color) of velocity magnitude within the flow domain. The velocity is measured at mm/s. The following images are representations of the VMG from each of the fluidic flow model experiments at 50% and 100% max speed.

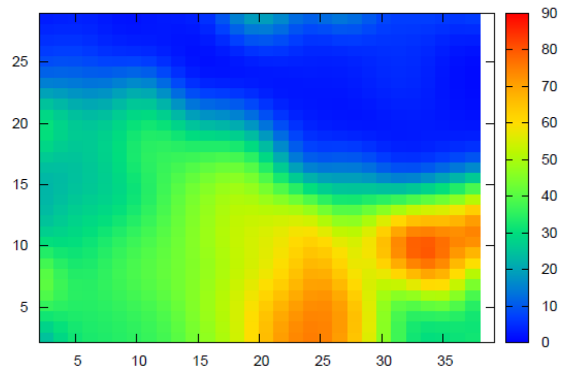

Figure 3. Velocity Magnitude Graph for model 1 at 50% of max speed

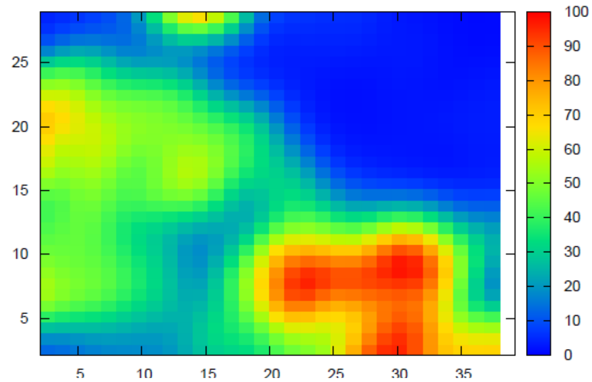

Figure 4. Velocity Magnitude Graph for model 1 at 100% of max speed

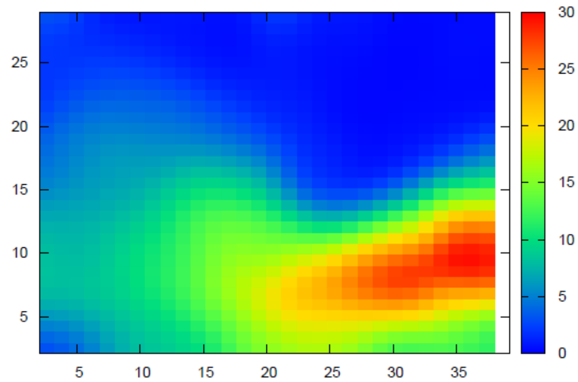

Figure 5. Velocity Magnitude Graph for model 2 at 50% of max speed

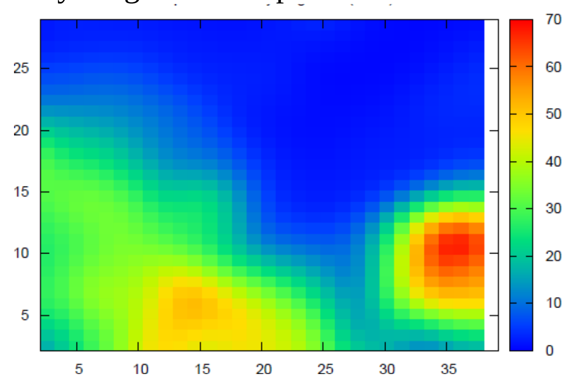

Figure 6. Velocity Magnitude Graph for model 2 at 100% of max speed

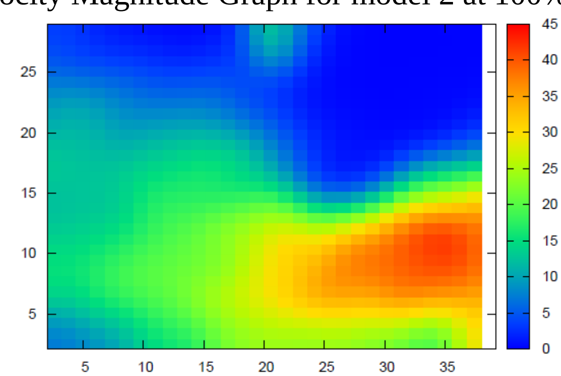

Figure 7. Velocity Magnitude Graph for model 3 at 50% of max speed

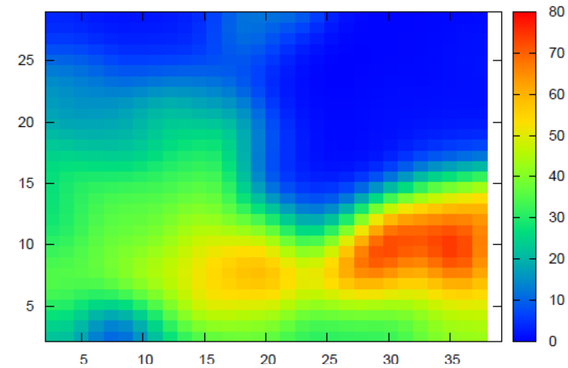

Figure 8. Velocity Magnitude Graph for model 3 at 100% of max speed

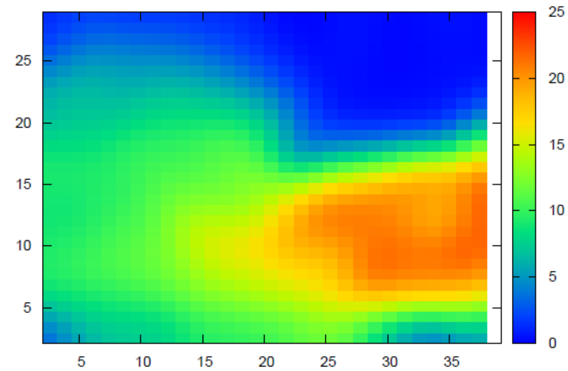

Figure 9. Velocity Magnitude Graph for model 4 at 50% of max speed

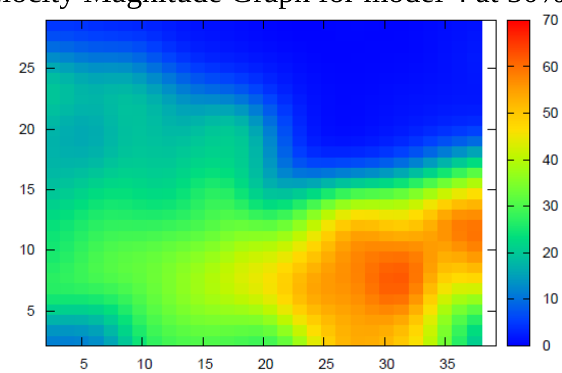

Figure 10. Velocity Magnitude Graph for model 4 at 100% of max speed

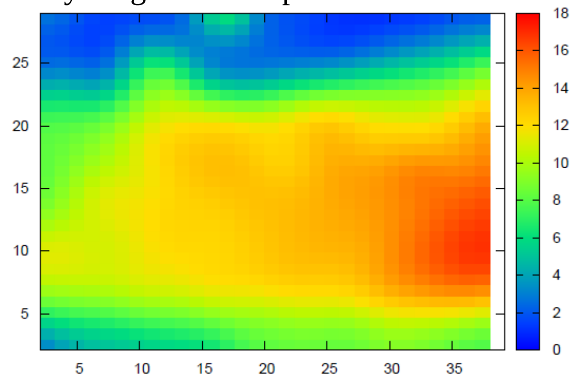

Figure 11. Velocity Magnitude Graph for model 5 at 50% of max speed

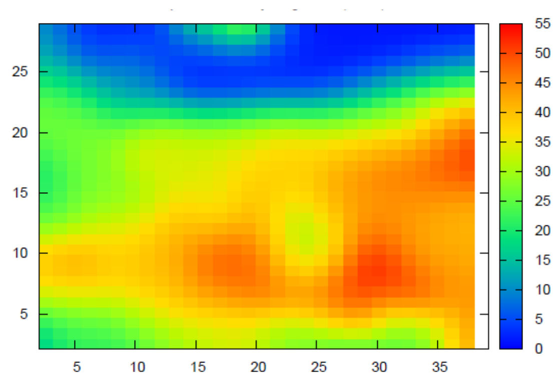

Figure 12. Velocity Magnitude Graph for model 5 at 100% of max speed

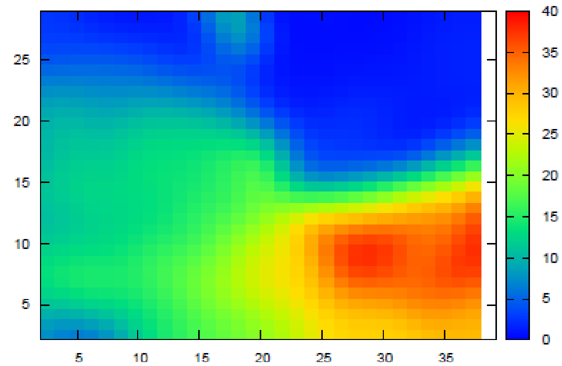

Figure 13. Velocity Magnitude Graph for model 6 at 50% of max speed

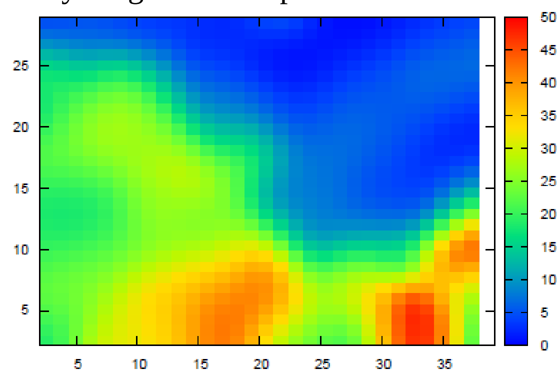

Figure 14. Velocity Magnitude Graph for model 6 at 100% of max speed

The VVF shows arrow representations of the fluid particles magnitude and direction. The size of the arrows indicates the magnitude. The following images are a representation of the VVF from each of the fluidic flow model experiments at 50% and 100% max speed.

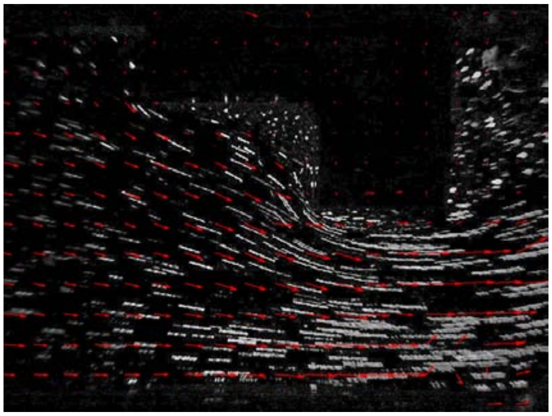

Figure 15. Velocity Vector Field for model 1 at 50% of max speed

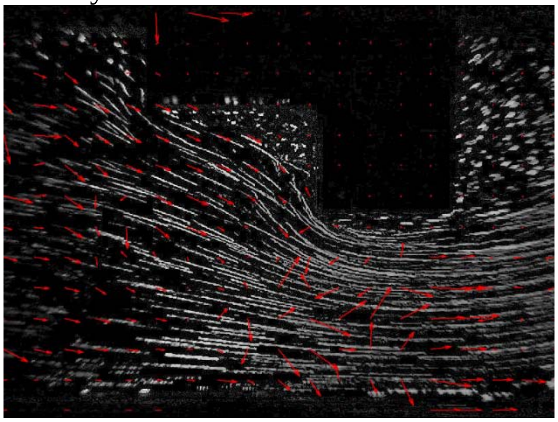

Figure 16. Velocity Vector Field for model 1 at 100% of max speed

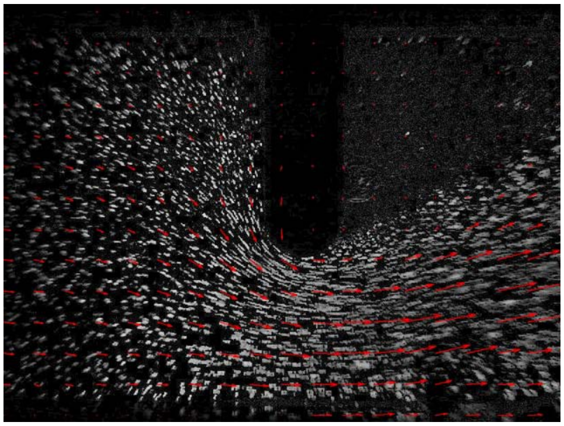

Figure 17. Velocity Vector Field for model 2 at 50% of max speed

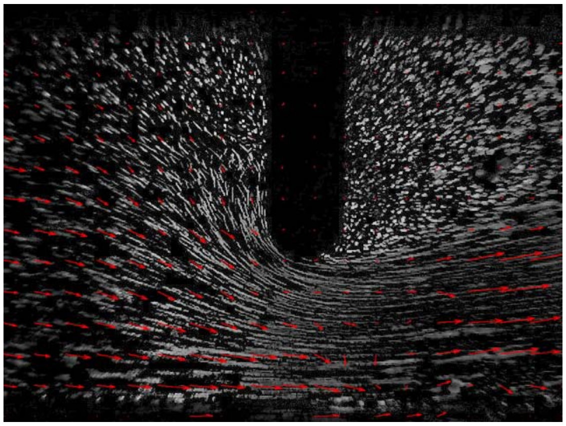

Figure 18. Velocity Vector Field for model 2 at 100% of max speed

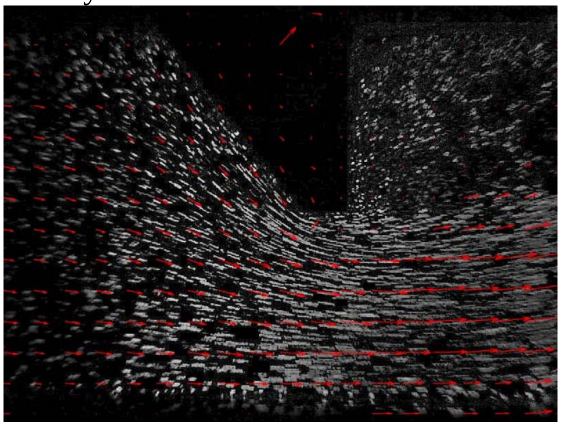

Figure 19. Velocity Vector Field for model 3 at 50% of max speed

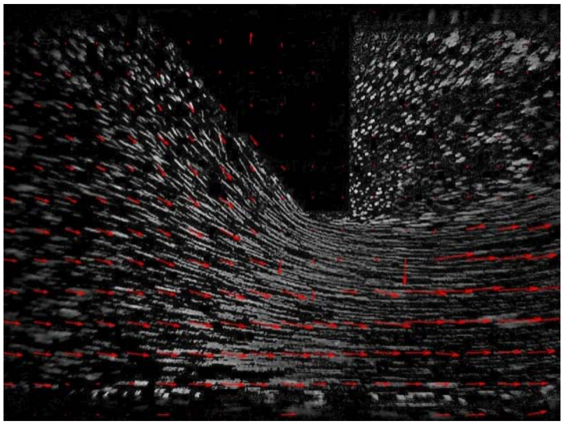

Figure 20. Velocity Vector Field for model 3 at 100% of max speed

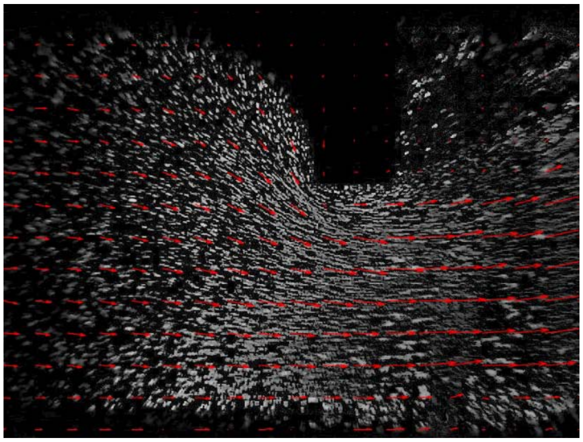

Figure 21. Velocity Vector Field for model 4 at 50% of max speed

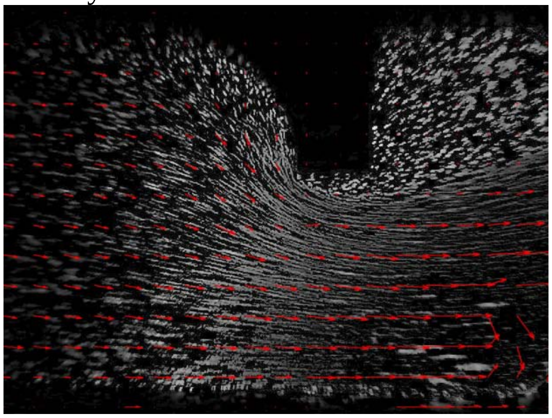

Figure 22. Velocity Vector Field for model 4 at 100% of max speed

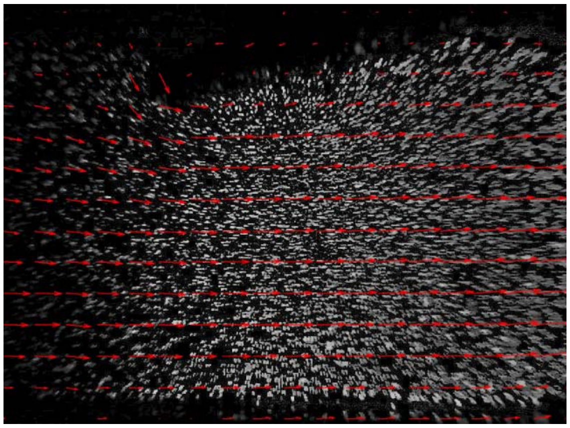

Figure 23. Velocity Vector Field for model 5 at 50% of max speed

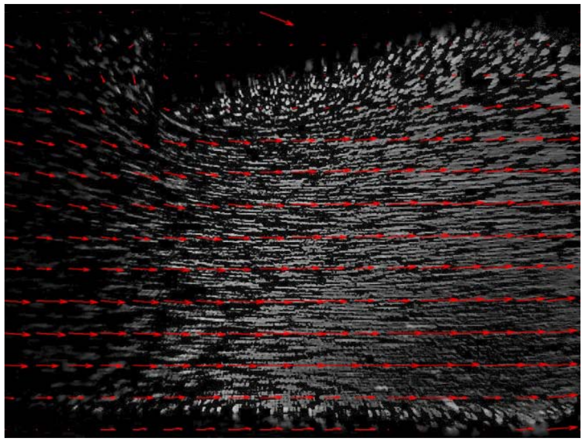

Figure 24. Velocity Vector Field for model 5 at 100% of max speed

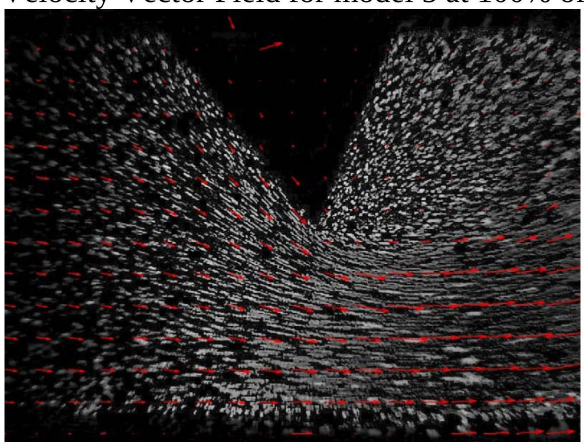

Figure 25. Velocity Vector Field for model 6 at 50% of max speed

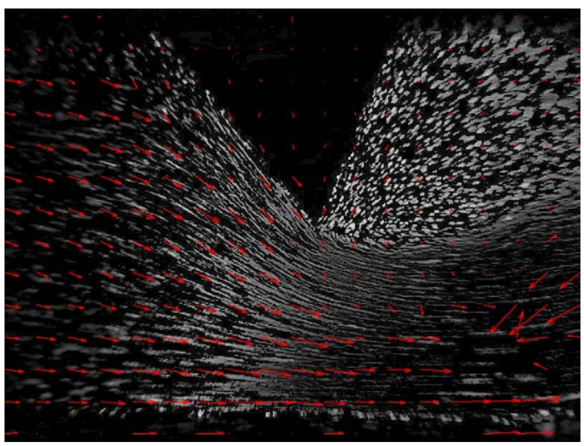

Figure 26. Velocity Vector Field for model 6 at 100% of max speed

All six studies of the fluidic flow models have been completed. This gives leeway to completely focus the project on working with COMSOL to study fluid flow simulations and develop our design of the microfluidic valve.

Discussion

After running tests on ePIV and learning how fluid behaves under certain conditions. The main focus of our microvalve design is to design the microvalve system of a micromixer. The micromixer will have a laminar static mixer with two parallel sets of split-reshape-combine mixing elements. The design of the micromixer will be done on Solid Works CAD software. From the acquired knowledge on the ePIV testing, the design will include appropriate design parameters (pressure distribution and velocity manipulation). This design will later be imported to the COMSOL software and numerical analysis will be performed.

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