PIV V2 - Particle Image Velocimetry Integration With the Bioengineering Devices Lab Benchtop Flow Model

Initial Design Report

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DISCLAIMER

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EXECUTIVE SUMMARY

The mission of the 2026 PIV capstone project is to design, manufacture, optimize, and validate a particle image velocimetry (PIV) phantom model. This project is a continuation of the 2025 PIV capstone project which focused on testing the cameras, lasers, particles, and software for the PIV setup. It is the job of the 2026 PIV capstone to seamlessly integrate the previously developed PIV system into the Bioengineering Devices Lab (BDL) benchtop flow model alongside the existing benchtop procedures. The new model must be able to easily convert between standard flow operations and the PIV enabled configurations. The initial task for the team is to develop a repeatable molding process that is designed to meet the required refractive index for a PIV phantom flow model. This process is to be documented in a comprehensive testing and validation plan which will then be executed by BDL lab students when testing medical devices. The phantom model will have a synthetic clot inserted for medical device testing for simulated endovascular applications. As of March 4, 2026, the team has constructed several different CAD models of blood vessels for preliminary testing of the silicone mold manufacturing process. Through extensive calculations, the team has opted to test a modified blood mixture that consists of HPMC and glycerin to match the refractive index of the silicone. This modified mixture allows for the silicone to remain clear and allows the team to use the donated Liquasil clear silicone. The casting process will require the use of the BDL vacuum chamber to degas the silicone and allow for a clear mold. The mold will be made of a PVA 3D printed core which is water soluble and allows for a clear finish. If the preliminary process leads to success, the team will manufacture more advanced models for higher accuracy when testing medical devices.

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1 BACKGROUND

Chapter 1 takes an in-depth look at the PIV project description and the importance of the work that will be conducted. This chapter highlights the goals for the PIV project and what determines the success of the final design.

1.1 Project Description

Stroke is currently the second leading cause of death worldwide [1]. There are two types of strokes: ischemic and hemorrhagic. Ischemic strokes occur when a blood clot blocks blood flow from reaching distal parts of the brain [2]. Hemorrhagic stroke occurs when a section of a vessel in the brain has weakened, also known as an aneurysm, and ruptures, causing a brain bleed [3]. The Bioengineering devices lab (BDL) has a current simulated surgical suite with a benchtop flow model that tests novel medical devices that have the aim of treating both ischemic and hemorrhagic strokes. This current benchtop flow model only collects pressure and overall flowrate data but does not have the ability to see real time hemodynamic velocity in flows, or the stresses on medical devices and the vessel. This is where a particle image velocimetry (PIV) system can be incorporated to bridge the gap in this data collection.

PIV is used to evaluate fluid flow with outputs of velocity that can be derived to find stress and strains. This can be done by casting a phantom model, in this case the aim is to use silicone, and a flow loop going through it with an outside laser illuminating microscopic fluorescent particles within the fluid flow. By using high speed cameras these particles can be traced by recording their position between frame rates and analyzed using a data analysis system called PIVlab. PIVlab can display a map with vector arrows showing direction and magnitude of a flow as seen in figure 1.

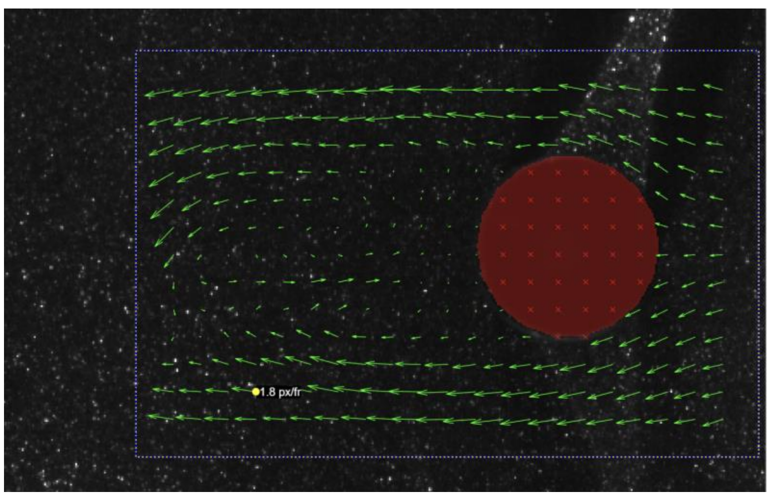


Figure 1: Flow analysis using PIVlab showing vectors

This capstone is a continuum of the previous Spring 2025 – Fall 2025 capstone group. Last year's team constructed a PIV setup that has a laser powerful enough to illuminate particles through thick silicone walls and project a laser sheet wide enough to capture the flow region to be studied. The next steps are to incorporate interchangeable phantom models that are physiologically relevant to the neurovascular anatomy and install it side by side with the BDL benchtop flow model.

1.2 Deliverables

Majority of the deliverables that will be produced throughout the PIV project are the course deliverables for ME-476C. Alongside the coursework for the class, the client only requests that we have this setup functioning by the end of fall 2026. Throughout this semester we are responsible for three presentations, two reports, two prototype demonstrations, a website, a CAD model, and a bill of materials for our final design. As of March 8^{th}, 2026, the first report, two presentations, a rough CAD model, and a bill of materials have been delivered and submitted.

1.3 Success Metrics

The overall goal for this capstone project is to integrate a PIV set up into the BDL lab's surgical suite. This could be having a switch in the already manufactured flow loop of the benchtop model that can switch between a 3D printed circle of Willis and a phantom silicone mold manufactured by this capstone.

This project is seen as successful if the lab can retrieve hemodynamics (the study of the physical principles governing blood flow, pressure, and resistance within the cardiovascular system [4]) from a particle image velocimetry system by collecting data of the velocities of particles in a fluid flow. This data can be taken and derived to calculate the stresses on the medical products being tested, the synthetic blood clots, and the vessel walls.

2 REQUIREMENTS

Chapter 2 is a discussion of the requirements for the final product. The PIV project was given specific requirements to meet by the client as seen in 2.1. The team then formulated various engineering requirements to quantify the requirements of the customers as seen in 2.2. Finally, the requirements are combined into a House of Quality 2.3 to compare the customer requirements and engineering requirements.

2.1 Customer Requirements (CRs)

This list of customer requirements were brainstormed at a client meeting when discussing the project. Each of these requirements contain an aspect of the project and a PIV set up and when combined can lead to a successful outcome of our capstone.

- **Conversion Time**
- In order to incorporate the PIV set up with the BDL benchtop model we will have two flow loops used by the same pump. This conversion time will allow for easy set up of the PIV system and the change between the two loops. How long does it take to switch from PIV flow loop to standard benchtop model loop?
- **Particle Selection**
- Two particles will be needed when collecting data, one saturating the fluid flow and another mixed in with the synthetic blood clot solution before they are cured. Each particle must be distinguished from the other in order to collect two data sets. Which particle is best for visibility? Which particle will be in the flow loop, and which particles will be used in clots?
- **Laser Wavelength (Color)**
- The laser that will be illuminating the fluorescent particles can be different colors selected by the team, each color illuminates the particles differently. Which laser color will best illuminate the particles?
- **Clarity of Silicone**
- The clarity of silicone is important for data collection. This phantom silicone mold must be clear in order to collect the most accurate data. Important for visibility when using cameras to capture the particles within the phantom.
- **Refractive Index Match**
- When there is a differing refractive index between materials, in this case the HPMC blood analog fluid and the silicone and offset can be cause creating a skew in the data collected. Matching the two refractive indexes will eliminate the offset and optimize data collection.
- **Validation**
- This phantom model and PIV set up will be used by the BDL lab in order to test medical devices. Validating the Phantoms by molding a more intricate and physiological accurate model will allow for testing of these novel medical devices. Validation will include performing medical procedures by aspirating synthetic blood clots with catheters in the phantom model.

2.2 Engineering Requirements (ERs)

- **Decrease time to convert between flows**
- Being able to switch back and forth between two flow loops in under 2 minutes will increase the amount of time to focus on the experiments and now have to wait for the set up to be complete. **Increase particle density in fluid**
- Calculate the number of particles best fit for a certain volume of fluid so the visibility is 0.1 particles per pixel of an image. This will determine the seeding of the particles in the fluid.
- **Change laser color**
- Find the best fit wavelength for laser color, should be around 532 nm for a green color. Test different wavelengths of the laser with different colored particles and analyze capture images in PIVlab to see best visibility.
- **Visibility of particles**
- Selecting the best particle size and color to get the best visibility for analyzing images and calculate the particle density for seeding of the particles.
- **Visibility of silicone**
- Prototype different methos for casting silicone including removal of male inner mold, eliminating bubbles, and preventing discoloration. This requirement can be calculated using the refractive index.
- **Match refractive index of all materials, silicone and synthetic blood mixture**
- Change the properties of either the silicone or blood mixture to match each other. This will eliminate offsets in the images collected and have a clear view of the hollowed phantom model.
- **Success rate when testing on phantom**
- An 80% success rate is ideal for a phantom under an aspiration test. Will we be able to track the flow around the catheter and clot? Will visibility be high? Will the software for PIV work accordingly? Will this process and set up be repeatable?

2.3 House of Quality (HoQ)

System QFD

Project: PIV
Date: 2/2/2026

Technical Requirement	Decrease time to convert between flows	Increase particle density in fluid	Change laser color	Visibility of particles	Visibility of silicone	Match silicone to HPMC refractive index
Decrease time to convert between flows						
Increase particle density in fluid						
Change laser color						
Visibility of particles			9			
Visibility of silicone						
Match silicone to HPMC refractive index					9	
Success rate when testing on phantom	9			3		9

Legend
S Stomach
K Kidney
B Brain

Customer Needs	Customer Weights (Scale 1-5)	Decrease time to convert between flows	Increase particle density in fluid	Change laser color	Visibility of particles	Visibility of silicone	Match silicone to HPMC refractive index	Success rate when testing on phantom	*1 Poor*	*2*	*3 Acceptable*	*4*	*5 Excellent*
Conversion time	4	10										B	
Particle selection	1		8	8									
Laser Wavelength (Color)	2			10									
Clarity of silicone	3				10					S		K	
Refractive index match	5				7	8	10			K			S
Validation	4	8			7	7	8	10	S				B
Technical Requirement Units		s	particles/ pixel	nm	color	%	Unitless	%					
Technical Requirement Targets		120	0.1	532		90	1.35	80					
Absolute Technical Importance		72	8	28	93	68	82	40					

Figure 2: House of Quality

3 Research Within Your Design Space

Chapter 3 is an in-depth review of similar designs that are currently available on the market as well as state-of-the-art methods used for manufacturing the intricate phantom models 3.1. This chapter also includes a review of the sources used during the research for this project 3.2. The final section of chapter 3 is a complete review of the mathematical modeling calculations that have gone into the project thus far and how they have informed our design.

3.1 Benchmarking

Benchmark #1:

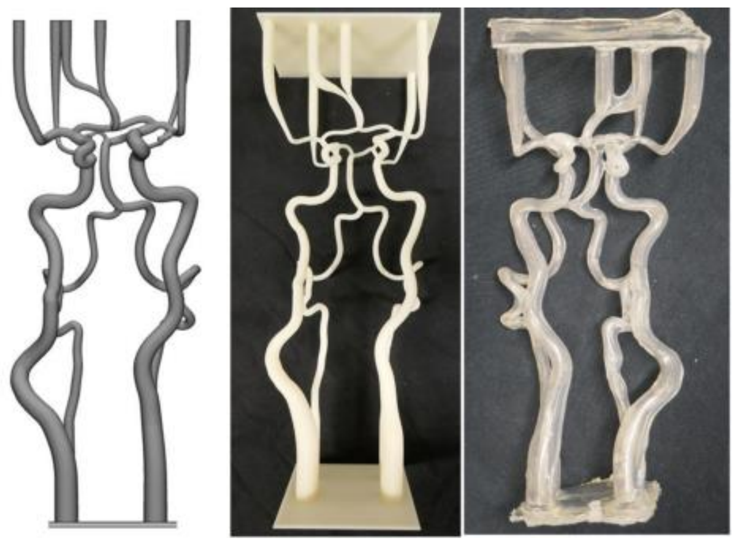


Figure 3: Cerebral arteries phantom [5]

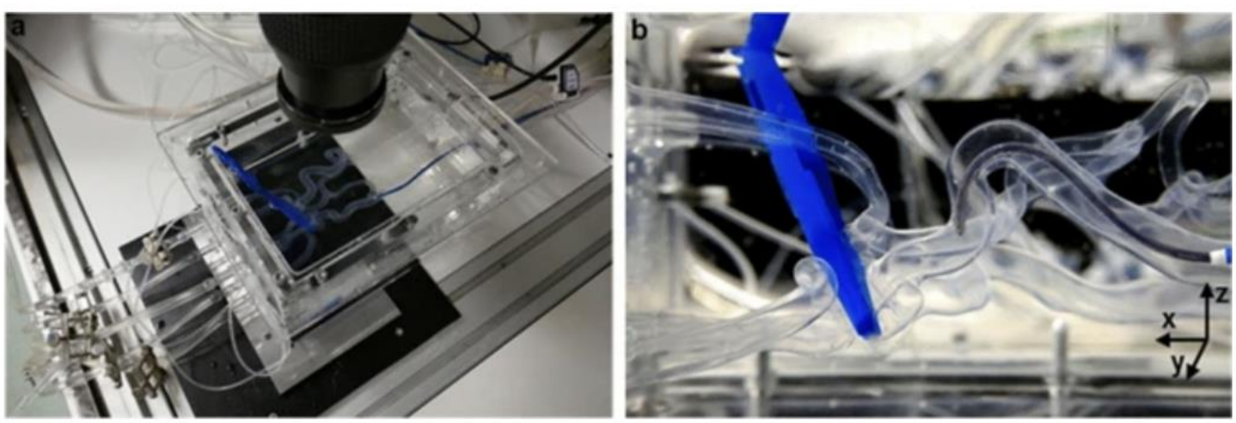


Figure 4: Flow set up with phantom model [5]

This model is an intricate system of the cerebral arteries in the brain including the circle of Willis. The current testing system in the BDL lab has 3 inlet vessels and 8 outlet vessels. This model is a goal for our team in the future and something we can model our phantom after. The tests conducted on this model include performing aspiration thrombectomy which is the removal of a blood clot via a suction pump or syringe pump to restore flow. This same test is what will be conducted in the BDL lab. The data that was produced from this journal article will likely be what we compare our data to. This benchmark will allow us to see the setup of the phantom, with the laser and camera as well as the whole flow loop with the pump and reservoir.

Benchmark #2

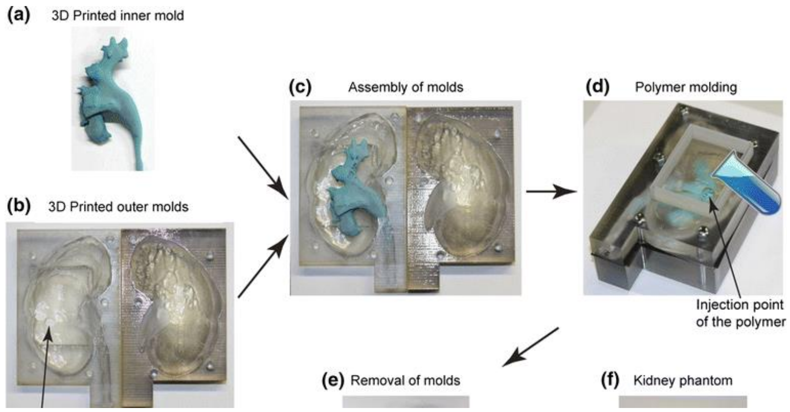


Figure 5: Kidney Phantom [6]

This benchmark is a phantom model (subsystem of PIV) of a kidney and although we are not modeling a kidney the process is a good benchmark. The inner mold was 3D printed in wax and the outer mold is 3D printed in photopolymer, once the liquid polymer is poured into the mold it is then degassed. Once solidified the outer mold is removed and the inner mold is dissolved in ethanol. This step by step is not a solid block of silicone like our plan but it is very similar. We will compare our materials to theirs and the process of molding.

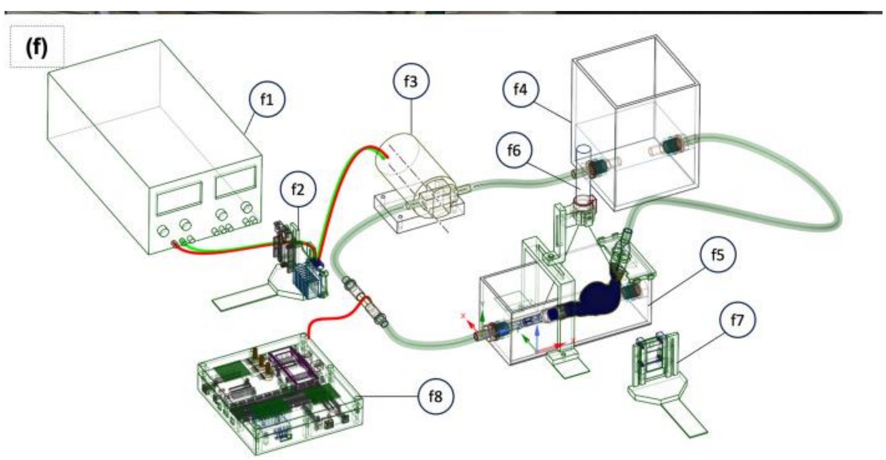


Figure 6: Abdominal aortic aneurysm phantom and PIV set up [7]

This last benchmark is for another PIV set up; this one is for an abdominal aortic aneurysm. This system has a silicone phantom that has a 2mm thick wall submerged in a tank of blood mimicking liquid, not a solid block of silicone. This PIV system has good imagery for the flow loop set up as seen in figure 5 This shows us the pump, reservoir, phantom pool, laser, and image sensor. It also shows the injection molding process to create a hollow tube that is then submerged in liquid.

3.2 Literature Review

3.2.1 Carley Barton

- **Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of light [8] (Book Ch 2.3)**

  In chapter 2.3 of this book titled Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of light the author explained how to solve for the refractive index of a mixture using the Lorentz-Lorenz equation. This source was used to inform our mathematical modeling section multiple times. For example, it was first used to calculate the refractive index of the HPMC blood analog mixture that is currently used in the BDL lab and has similar properties to blood. Once that refractive index was found we needed a way to change the refractive index of silicone to match that of the HPMC. Lastly, after finding out that the silicone refractive index could not be changed, we had to pivot and will have to change the blood analog mixture to have a higher refractive index matching to the silicone. This Lorentz-Lorenz equation from this book informed us through our mathematical modeling and validated our solutions.

- **Refractive index of Pharmacoat 606(Hydroxypropyl methylcellulose, HPMC) [9] (Website)**

  In order to solve for the refractive index of the HPMC blood analog mixture HPMC which is abbreviated for Hydroxypropyl methylcellulose is a polymer mixed with 90% water and about 10% ethanol in order to create a mixture with similar properties to blood. In order to solve for the total refractive index of this mixture the refractive index of the HPMC powder was needed along with water and ethanol. This website has a graph with equations and validations for many materials such as inorganic, organic, glasses, or miscellaneous materials.

- **Particle Image Velocimetry [10] (Book Ch. 10)**

  Chapter 10 of the book Particle Image Velocimetry is titled Practical Guidelines. This chapter goes over many questions about PIV and an experiment set up. When talking about the set up of PIV it brought light to variables that we were unaware of. For example, selecting the image density, surface flare, and test section cleanliness. Bringing light to these variables will help inform decisions later on in the manufacturing process.

- **Fabrication of deformable patient-specific AAA models by material casting techniques [11] (Journal)**

  This journal article highlights casting techniques for patient-specific AAA(Abdominal aortic aneurysm) models. Although our set up is not for AAA molds we can use the same techniques which are highlighted specifically in section 2.3. This section goes through the steps of lost core casting which is most likely what our manufacturing process of a phantom will look like. Their research also used PVA 3D printing filament for their core which is water soluble. In table 1 it also consists of multiple parameters when 3D printing such as layer height, nozzle diameter and temperature, support density, etc.

- **Evaluation of a desktop 3D printing rigid refractive-indexed-matched Flow Phantom for PIV measurements on cerebral aneurysms [12] (Journal)**

  This journal article explains the parameters for a refractive index matched flow through a phantom for PIV. They explain two set ups, a phantom consisting of a idealized model and a physiologically realistic model. The methods section explains the fabrication of the flow phantom. This phantom model was printed using a Formlabs Form 2 Desktop SLA printer using a clear photopolymer resin. The downside of using this resin is that the refractive index is closer to about 1.51instead of a silicone refractive index of 1.41. This higher refractive index is harder to match, and the printing process is a lot more expensive, informing us that this manufacturing process would not be the best for our set up.

- **Fabrication of low-cost patient-specific vascular models for particle image velocimetry [13] (Journal)**

  This article is another source that highlights the lost core casting method of casting around a PVA 3D printed mold and removed after silicone is solidified around it. Their images are also good research to see how the fluid inside should look if the refractive index is matched correctly.

- **What is Hemodynamics? [4] (Website)**

  This website informs us on what hemodynamics is and how blood flows through your arteries and veins. It talks about the effects of change in blood flow and what the causes are, for example a blood clot blocking flow.

3.2.2 Blake Pottinger

- **Optics and Lasers in Engineering, chapter 4.1. Spatial Resolution [14]**

  This resource was important for calculating the spatial resolution needed for the camera to have a clear view of the particles. If done correctly the PIV program will display vectors on each of the particles allowing the team to calculate the velocity and direction of the individual particle. Chapter 4.1 was particularly useful as it was used during section 3.3.3 for the first mathematical model.

- **Spatial Resolution and Dissipation Rate Estimation in Taylor—Couette flow for tomographic PIV, chapter 5.2.2. Effect of the size of the interrogation window [15]**

  Chapter 5.2.2 uses a 3D model to show how the interrogation window affects the accuracy of the estimations for the PIV vectors. This resource was also used for the mathematical model 3.3.3 in estimating the window size needed to clearly show the PIV particles.

- **Micro-PIV for the Analysis of Flow Fields near a Propagating Air-Liquid Interface [16]**

  This state-of-the-art PIV system is a similar medical set up to our product that measures the flow in the respiratory system. This source was important to our group as it gave an idea of what is available in the current medical field giving us a goal to reach .

- **Ghost Cells as a Two-Phase Blood Analog Fluid [17]**

  This reference informed the group of a PIV system that uses artificial blood out of dead cells that created similar velocity fields to that of real blood. As calculated in mathematical model 3.3.2, the team needs to create a new analog blood mixture with a refractive index to match the silicone, and this type of fluid is a possible option.

- **Viscosity of Whole Blood [18]**

  This data chart shows the measurement data of blood viscosity based on temperature. This source gives us a target for how to create the most accurate model using the most accurate blood analog.

- **Modeling pipes / blood vessels in SOLIDWORKS [19]**

  This video series was used during the individual learning assignment to learn advanced skills in SolidWorks. The skills were specific to the PIV project since they taught how to make realistic blood vessels as well as how to run a flow simulation on any object.

- **Modeling blood vessel blockage in SOLIDWORKS [20]**

  This video was another advanced tutorial that showed a way to add a simulated aneurism blockage and run a flow simulation around it. This video was important as it gave the group a way to test velocity and stress on a model before manufacturing it.

3.2.3 Clinton Nelson

- **Cardiovascular Hemodynamics, Flow in Arteries, (Book Chp.5) [21] –**In the Chapter, Flow in Arties, it talked about how particles reacted to different walls while in flow but more importantly how much the density matters to the adhesion of particles to the walls.
- **Cross-Correlation Digital Particle Image Velocimetry (Paper) [22] –** In this paper we gathered that particles have an interesting way of moving while in flow, most of the particles would be flowing in the same directions from heart to other regions in a, somewhat, constant velocity but a very few particles would be in the opposite direction in a lower velocity.
- **Density Marker Beads - 1.010g/Cc - Precision Microspheres, Beads, Microparticles for Creating Percoll Density Gradients (Website) [23] -** We used this website to get basic information of the particle we would be using while in test runs and to get a basic idea of the particle density we would be seeing in our calculations.
- **Investigation of Cerebral Hemodynamics during Endovascular Aspiration: Development of an Experimental and Numerical Setup (Website) [24] –** This Website gave us a theorical understand of the number of particles we would be seeing in our set up and how we should go about using the particle density equation we used in our mathematical model.
- **Structural Reconfiguration of Interacting Multi-Particle Systems through Parametric Pumping (Paper) [25] –** Helped in understanding particle behavior.
- **Particle Imaging in Electrohydrodynamic Pumps Operating at Several KV (Website) [26] –** In this reference it gave us a different perspective based on our results and the answer we would get. There is more to particle density than getting a numerical answer and that that numerical answer could be far off when looked at in different ways or without other known values or assumptions.
- **Cardiovascular Hemodynamics(Draft) (Book pg.1-25) [27] –** This draft book gave me the basic understanding of particle physics in a simulated or real scenario giving me basic equations, equations we've seen in fluid dynamics, as well as new equations and theories related to basic fluid dynamics. It also had different ideas of particle behaviors in different vascular regions of the body, how they flow, in the shape or direction they assume they flow.

3.2.4 Ryan Abelman

- **Fox and McDonald's Introduction to Fluid Mechanics [28] (Book)**

  In this book, the basic properties of fluids that affect their movement and flow are introduced. With our project centered around blood, a fluid with its own distinct properties, it is vital to know how to calculate and understand the meaning behind these values. Knowledge of concepts such as, velocity fields, streamlines, pressure, etc., will prove useful to apply these numbers to real life and further our project.

- **Mathematical Background of Statistical PIV Evaluation [29] (Book Ch. 3)**

In this book reference, it reveals more ways to understand what is coming from the Particle Image Velocimetry. This is done through potential equations and ideas that we can extract from the images take with our Phantom set up. It also explains the main focus of process of PIV and how the tracking of particles and comparisons of images can give us information about the velocity of a fluid. Furthermore, it provides equations for the averaging of these displacements, along with considering uncertainty errors with the tools used.

- **Mechanical and adhesive properties of RTV silicone rubber blended with silicone polyurethane modified epoxy resin [30] (Journal)**

  The material used for our Phantom unit is very important as we need something to provide visibility to get the data we need from the blood vessel created. In this journal, the properties of a potential silicone are identified to see how it will interact with water, curing procedures, and durability. Using these properties, we can create the best blend of silicone for desired outcomes.

- **Soft 3D-Printed Phantom of the Human Kidney with Collecting System [31] (Journal)**

  Although it will not mainly be used in our realm of this project, this journal was used to understand more about Phantom units in general and their application. It also provided insight on how to print 3D objects that resemble actual tissue in the body. Employing strategies from the development of this effective "human kidney", can help us in our creation of something similar to a Circle of Willis further along into our testing.

- **Global Burden of Stroke [32] (Journal)**

  The ultimate goal of this project is to gather more information on the causes of strokes and solutions to them once they occur. The goal of this specific journal is for the group to remember the importance of why we are doing it and find more background facts to inform our project/decisions.

- **Silicone Website Cost [33] (Website)**

  This website provided the foundation for the Phantom cost analysis. Using the website, I was able to find values for a 5.5 kg amount of silicone which helped me find how much each pour would cost per volume. Other information about various properties for a specific type of silicone to see if this is what we would want.

- **Art of the Part, " SolidWorks: Core & Cavity Assemblies for Casting & Mold Making," [34] (Video)**

  Mainly utilized in the self-learning assignment, this video elaborates on the creation of molds in SolidWorks. This step by step video highlights various tools in SolidWorks needed to create an interactive version of a mold. One of these tools, "Cavity", gives our group representation of potential blood vessel shapes a mold could make without having to use materials. It could also give us the ability to potentially 3D print the mold.

3.3 Mathematical Modeling

3.3.1 HPMC Refractive Index – Carley Barton

When running flows through a silicone phantom each material has a different refractive index. If these indexes don't match there will be an offset in the data collected. Just like how a straw looks cut when you put it in water.

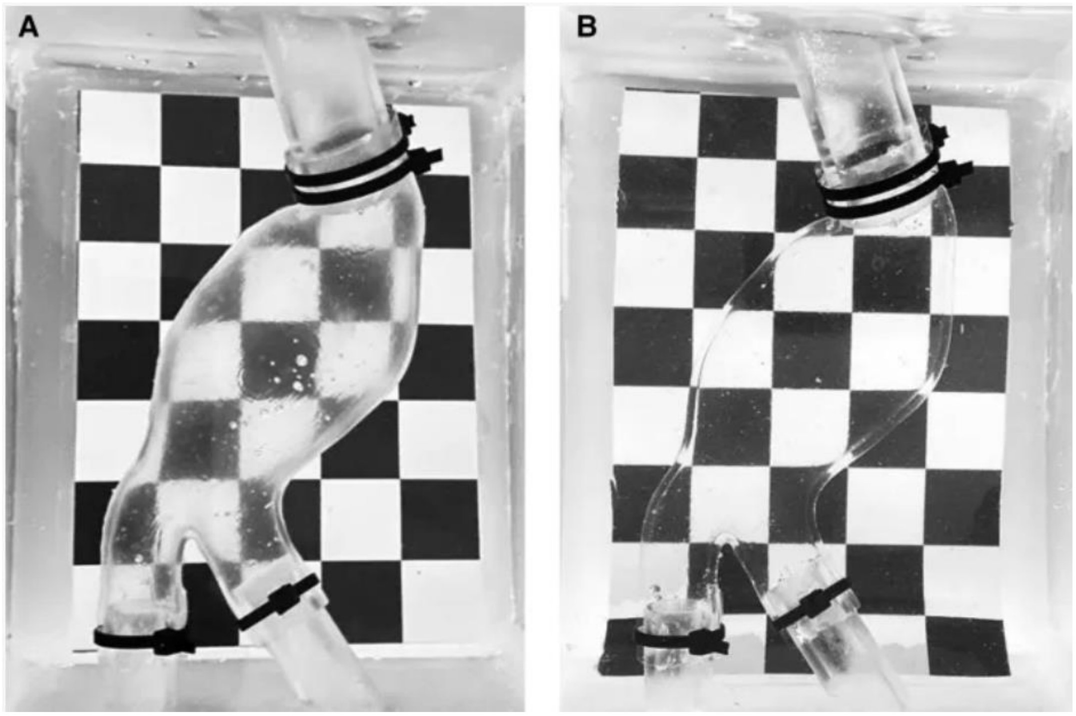


Figure 7: Left side (A) water flowing through model, right side (B) refractive index matched fluid [12]

As you can see in figure 1, the flow with water through it isn't as clear and the checkered board shown behind it has an offset. The section on the right has an index matched fluid that is also blood mimicking. This matched fluid has a much clearer visual and will have better success when collecting data.

Our client originally didn't want to change the components of blood mimicking fluid that will be going through the phantom, this fluid is known as HPMC which is comprised of a small amount of HPMC powder (Hydroxypropyl methylcellulose) mixed with ethanol and water. By taking these components and the known weight fractions and refractive index, we can solve for the overall refractive index of the fluid.

Lorentz-Lorenz equation [8]

$$\frac{n^2{}_{mix} - 1}{n^2{}_{mix} + 2} = \sum \emptyset_i \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

$$N_i = \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

Variable definition:

N_i= Lorentz-Lorenz parameter of component

$\emptyset_i$= Volume fraction

n_i= refractive index of component

Refractive index HPMC = 1.48 [9]

Volume fraction HPMC = 0.007

RI Water = 1.333

Volume fraction Water = 0.093

RI Ethanol = 1.361 [15]

Volume fraction Ethanol = 0.090

1st step is solving for the Lorentz-Lorenz parameter of each component, ethanol, water, and HPMC powder.

$$N_{water} = \frac{1.33^2 - 1}{1.33^2 + 2} = 0.204$$

$$N_{ethanol} = \frac{1.361^2 - 1}{1.361^2 + 2} = 0.221$$

$$N_{HPMC} = \frac{1.48^2 - 1}{1.48^2 + 2} = 0.284$$

2nd step: By multiplying the Lorentz-Lorenz parameter by each component's weight fraction we get the parameter for the mixture.

$$N_{mix} = (0.903 \cdot 0.204) + (0.090 \cdot 0.221) + (0.007 \cdot 0.284) = 0.206$$

3rd step: Plug in the N_{mix} to the equation below and you will get the refractive index.

$$n_{mix} = \sqrt{\frac{1 + 2N_{mix}}{1 - N_{mix}}} = 1.3335$$

HPMC blood analog mixture has a refractive index of 1.3335. We will now take this value and match the silicone refractive index to it.

Validation: These values were validated by using a Brix% refractometer on the HPMC fluid. This test includes placing a small drop of fluid on the refractometer and holding it up to

3.3.2 Silicone RI Match – Carley Barton

In order to lower the refractive index of a substance you can mix another material with it that has a lower refractive index. After some research, the best option that is low cost and has a low refractive index would be water. After solving for the refractive index of HPMC in section 3.3.1 the value was found to be 1.334. This is the index we will bring the silicones refractive index of 1.41 down to.

Using the same Lorentz-Lorenz equation we will re-arrange to solve for the weight fraction of water to be added.

Lorentz-Lorenz equation [8]

$$N_i = \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

$N_{mix} = \emptyset_s\, N_s + \emptyset_w N_w$

N_i= Lorentz-Lorenz parameter of component

$\emptyset_i$= Volume fraction

n_i= refractive index of component

Known:

RI Water = 1.333

RI Silicone = 1.41

RI of HPMC from section 3.3.1 = 1.334

1st step: find the Lorentz-Lorenz parameter for each component, silicone, water, and the final silicone mixture.

For silicone

$$n_s = 1.41 \implies {n_s}^2 = 1.988$$

$$N_s = \frac{1.988-1}{1.988+2} = 0.248$$

For water

$$n_w = 1.333 \implies {n_w}^2 = 1.777$$

$$N_s = \frac{1.777-1}{1.777+2} = 0.206$$

Target silicone mixture (after adding water)

$$n = 1.334 \implies n^2 = 1.7796$$

$$N = \frac{1.7796-1}{1.7796+2} = 0.2063$$

2nd step: Then by multiplying the weight percentage by parameter we can rearrange to solve for the weight fraction of water.

$N_{mix} = \emptyset_s\, N_s + \emptyset_w N_w$ Since $\emptyset_s + \emptyset_w = 1$; rearrange this and plug in

$\emptyset_w = 1 - \emptyset_s$ along with the corresponding values for each variable

$$0.2063 = \emptyset_s\,(0.248) + (1- \emptyset_s)(0.206)$$

Solve for $\emptyset_s$ and $\emptyset_s = 0.00714$

Therefore, the volume fractions would be 0.71% silicone and 99.29% water which is not possible.

Since this is not possible to have a silicone mixture of 0.71% silicone and have it cure, as a group we will have to pivot and come up with a solution with the client. Most likely having to change the fluid going through the model.

Validation: This was validated by the source the Lorentz-Lorenz equation came from [8], there were many examples of this equation being used and since there were a lot of known variables there isn't that much variation within the answer.

3.3.3 PIV Spatial Resolution – Blake Pottinger

When filming the microscopic PIV particles, it is important to get a clear picture to collect the data efficiently. To do so the correct camera equipment is needed as well as the proper software. The previous capstone had bought the correct camera equipment, but it was up to us to determine the ideal factors such as the interrogation window size and particle diameter. When plugged into a computer program, the particles' information is tracked using vector arrows (figure 8). These arrows return crucial information such as particle velocity, direction, and stress on the walls and around aneurisms.

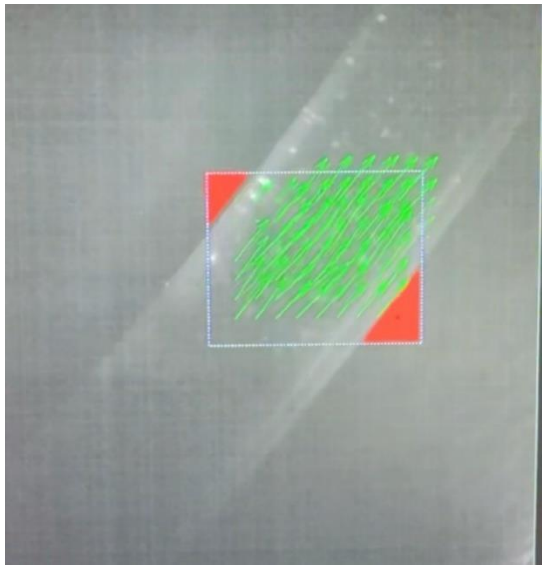


Figure 8: PIV particle vectors

The information below will be validated once testing has commenced. The team will begin with a resolution of about 4.33 mm, and we will adjust the resolution of the specific camera as needed. But this calculation gives our team an amazing starting estimation and future resolutions will be listed below.

PIV Spatial Resolution Equation [14]

$$\text{RES} = (\text{D}_1 + \text{D}) \cdot \frac{\text{S}}{\text{M}}$$

Variable Definition

RES: The resolution in physical space represented by a velocity vector.

$\mathbf{D_1}$: Interrogation window size

D: Particle Image Diameter

S: Camera sensor pixel spacing

M: Optical Magnification

Solution

$$\text{RES} = (32\ [\text{pixels}] + 8\ [\text{pixels}]) \cdot \frac{6.5 \times 10^{-6}\ [\text{m}]}{0.06}$$

$$\text{RES} = 40\ \cdot 1.083 \times 10^{-4}$$

$$\text{RES} = 0.00433\ [\text{m}]$$

$$\text{RES} = 4.33\ [\text{mm}]$$

3.3.4 Change RI of HPMC – Blake Pottinger

Following the calculations done in mathematical modelling section 3.3.2, the team needed to calculate a new blood analog to fit the refractive index of the silicone. To do so, the current HPMC mixture could be mixed with glycerin to match the target refractive index of the silicone which was 1.41. The calculations below show the new mixture needs to be comprised of 56% glycerin and 44% of HPMC.

To validate the new mixture composition, the team needs to compare the properties of the mixture to that of 100% HPMC as well as to the properties of blood. If the client deems the analog blood to be suitable for the current benchtop model, we will then need to test the refractive index of the mixture to that of the silicone. Once both of these crucial criteria are met, we can move forward with the rest of the product testing.

Lorentz-Lorenz equation [8]

$$N_i = \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

$N_{mix} = \emptyset_G\, N_G + \emptyset_H N_H$

N_i= Lorentz-Lorenz parameter of

component

$\emptyset_i$= Volume fraction

n_i= refractive index of component

Known:

RI HPMC = 1.334

RI Silicone= 1.41

RI Glycerin = 1.473 [6]

- **For glycerin**

$$n_G = 1.473 \Rightarrow n_G{}^2 = 2.17$$

$N_G = \frac{1.988-1}{1.988+2}$ = 0.281

- **For HPMC**

$$n_w = 1.334 \Rightarrow n_w{}^2 = 1.78$$

$N_w = \frac{1.78-1}{1.78+2}$ = 0.206

- **Target silicone mixture**

$n = 1.41 \Rightarrow n^2 = 1.988$

$N = \frac{1.988-1}{1.988+2}$ = *0.248*

$N_{mix} = \emptyset_G\ N_G + \emptyset_H N_H$ Since $\emptyset_G + \emptyset_H = 1$ we can plug in

$\emptyset_H = 1 - \emptyset_G$ and solve

$0.248 = \emptyset_G$ (0.281)+(1- $\emptyset_G$)(0.206)

Solve and $\emptyset_G = 0.56$

In order for out fluid mixture to have a refractive index of 1.41 it needs to be comprised of 56% glycerin and 44% HPMC

3.3.5 Particle Density – Clinton Nelson

Particle Density

Particle density is an important aspect of PIV because it will determine the seeding concentration of particles for good velocity measurements. These equations of an output of the percentage of the image is occupied by particles.

$$A_{Particle} = \pi\left(\frac{d}{2}\right)^2 = 95\mu m^2 = 9.5 * 10^{-11} mm^2$$

$$A_{Phantom} = w * h = 1.3225mm^2$$

$$n_{Particles} = \frac{m_{Total} * N_A}{M} = 15.63 * 10^7 particles$$

$$d = 11\mu m$$

$$\rho = 1.06\left(\frac{g}{mL}\right)$$

$$w = 1.15m$$

$$h = w$$

$$m_{Total} = 0.1g$$

$$N_A = \text{Avgoadro's Number}$$

$$PD(\%) = \frac{(n_{particle} * A_{particle})}{A_{phanom}} = 0.011\%$$

Through the calculations above and the assumptions of what is going into the system we found that 0.011% of particles will be seen within the camera.

This calculation will be validated and updated in the future when a raw PIV frame is captured. We will count the visible particles in the image either manually or using PIVlab. We will then compare the same equation of $PD(\%) = \frac{(n_{particle} * A_{particle})}{A_{phanom}}$ with the new $n_{Particles}$ number and areas to this mathematical modeling and see what changed and how to adjust.

3.3.6 Minimum Wall Thickness – Clinton Nelson

When manufacturing a silicone phantom we asked the question, is there a minimum thickness between the outside of the phantom and the hollow inside vessel as seen in figure 9. This thickness could influence the strength of the silicone and if the minimum happened to be large, how does the thickness effect data collection that will be uploaded to PIVlab.

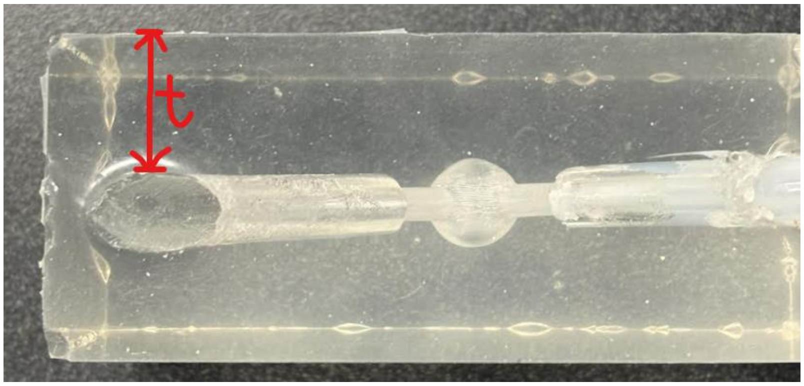


Figure 9: Side view of example phantom

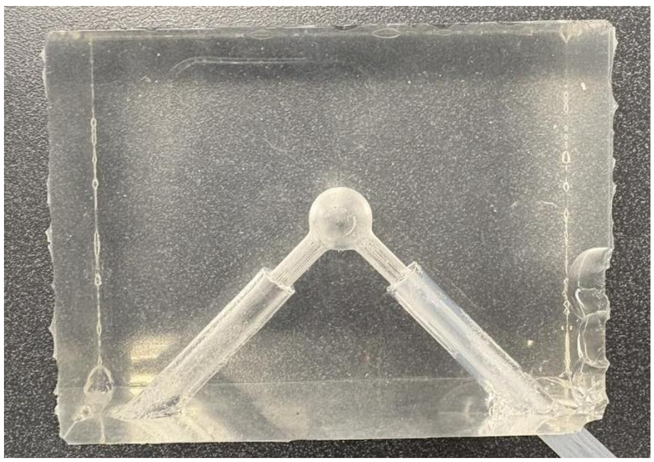


Figure 10: Front view of example phantom

$$\textbf{Hoop Stress: } \boldsymbol{\sigma} = \frac{\mathbf{Pr}}{\mathbf{t}}\ [\mathbf{35}]$$

$$\mathrm{P} = \text{Internal Pressure} = 0.015995\left(\frac{\mathrm{N}}{\mathrm{mm}^2}\right) = 120\mathrm{mmHg}$$

The internal pressure was taken from physiological pressure of 120 mmHg, this was then converted to N/mm^2 or MPa.

$$\mathrm{r} = \text{Radius} = 2.5\mathrm{mm}\ \text{(average vessel radius)}$$

$$\sigma_{\text{allowable}} = 1.5\text{MPA (given from silicone properties [33])}$$

We then rearranging the hoop stress equation we solved for t-thickness

$$\mathrm{t} = \frac{\mathrm{Pr}}{\sigma_{\text{allowable}}}$$

When plugging in corresponding values we get a thickness of

$$t = 0.0262\text{mm}$$

From the Hoop Stress equation, we used dimensions of a vessel to model our phantom as well as the internal pressure. We then took the properties of silicon to get the allowable stress to then be plugged into the Hoop equation to get a thickness of 0.0262mm.

By getting a minimum thickness of 0.0262mm, we found that the pressure on the inside of the phantom model does not affect the silicone enough to cause it to break. This informed our design because now we can focus on the visibility of the silicone and what thickness is best for data collection without having to worry about a rupture in the model because of a high internal pressure.

This mathematical model was validated via textbook problems and applying lessons taught in mechanics of materials and machine design. We will further validate the thickness with testing the physical model and fitting it best to the refractive index of our blood analog mixture.

3.3.7 Phantom Cost Analysis – Ryan Abelman

In the first analysis of the Phantom Cost, the team took a broad approach without knowing the specifics of the materials, process, or size of the object.

$$PPU = \left(\frac{C_f}{n}\right) + C_v + t(C_L)$$

The variables involved in this initial equation are as follows:

$$PPU - Price\ Per\ Unit$$

$$C_f - Fixed\ Costs$$

$$n - Quantity$$

$$C_v - Variable\ Costs$$

$$t - Labor\ time\ (hours)$$

$$C_L - Hourly\ Labor\ Cost$$

Without actual numbers early in the project, the team had to assume numbers that were believed to be in the realm of what we could use. The initial calculations were also done relative to the whole 5.5 kg of silicone to be purchased. These values included:

$$C_f = \$200.00$$

$$n = 1, 5, 10, 20, 25$$

$$C_v = \$50.00$$

$$t = 7.5\ hrs\ or\ 1.5\ hrs$$

$$C_L = 15.5\frac{dollars}{hr}(minimum\ wage\ at\ NAU)$$

Plugging in these values into an excel equation helped to create Table 1 below.

Quantity (n)	Cost of Normal Cure Time (7-8hrs)	Cost of Faster Cure Time (1-2hrs @ 120F)
1	366.25	273.25
5	206.25	113.25
10	186.25	93.25
20	176.25	83.25
25	174.25	81.25
50	170.25	77.25
100	168.25	75.25
150	167.58	74.58
200	167.25	74.25

Table #1: Analysis #1 of Phantom Cost

After Presentation 1, some concerns with validation of these values and how they would be applied in the project were brought forth in feedback. How high the costs were depending on the time and curing did not completely make sense and the quantity produced was not plausible. To account for these concerns, a revised calculation of the analysis was completed.

3.3.8 Revised Phantom Cost Analysis – Ryan Abelman

With a greater understanding of how the process for the Phantom unit would be created, the actual size of it, and the feedback in mind, adjustments were made to the values and the PPU equation itself.

$$price\ per\ unit\ (PPU) = \left(\frac{C_f}{n}\right) + C_v$$

This equation was adjusted with the assumptions that we did not need to incorporate the hourly labor cost because the team would not be paid during the process of making the unit. Also, if a heating mechanism was incorporated, the cost would be in the Fixed Cost rather than having the actual time the curing takes affect the cost.

$$C_f = \$5.00\ (non - heated)\ or\ \$7.00\ (heated)$$

Furthermore, after studying more about the Fixed and Variable cost, we decided to consider the Variable cost to come from the volume of a unit produced. This was done through dividing the total milliliters available in the 5.5 kg silicone order (5500mL) by the volume of 392 mL to find the number of units we could produce.

# of units available to produce = 14

Then using the total cost of one order, we could find the price per volume:

$$price\ per\ unit\ volume = \frac{\$196.25}{14} = \$14.02$$

Using that value, we could then assume the Variable cost.

$$C_v = \$17.06 \text{ (includes another \$3.00 for miscellaneous items)}$$

Now applying these new values to the new equation, we found more accurate and appliable results for our group, seen in Table 2 below.

Quantity (n)	Normal Curing at Room Temperature	Faster Curing(1-2hrs @ 120°C)
1	\$22.02	\$24.02
2	\$19.52	\$20.52
3	\$18.69	\$19.35
5	\$18.02	\$18.42
10	\$17.52	\$17.72

Table 2: Analysis #2 of Phantom Cost

With the feedback, we developed a more reasonable cost with reasonable quantities that we could produce and validate. These values show that if we have the time to wait early on in production, then we can save a couple of dollars, once we increase quantity though the prices begin to even out. In validating, these numbers come from actual values and ultimately make sense when thinking about the size of the object being created, compared to the values found in 3.3.8.

4 Design Concepts

Chapter 4 details the extensive process our group underwent to select the best designs and methods to be used for our first manufactured prototype. This process was completed using functional decomposition charts 4.1, concept generations 4.2, and the methods we used to select the best design 4.3 and 4.4.

4.1 Functional Decomposition

Figure 11 depicts a black box model for manufacturing a single silicone phantom model. The black box model is a useful tool for simplifying a decomposition model by only showing the inputs and outputs of the process. The arrows on either side of the black box represent the specific method of the input with materials represented by a thick black arrow, energy represented by a thin arrow, and electronic signals represented by a dashed line. The paths can be seen in more detail in figure 11. The black box model was important when generating our preliminary bill of materials as we can see every item needed to create a single silicone phantom.

Figure 11: Black Box design

Figure 12 is a detailed plan for manufacturing a singular silicone phantom. Unlike the black box model, the decomposition model shows the entire manufacturing process in detail. This model is useful to the team as it provides a detailed flow chart of the processes and tools needed to manufacture a model.

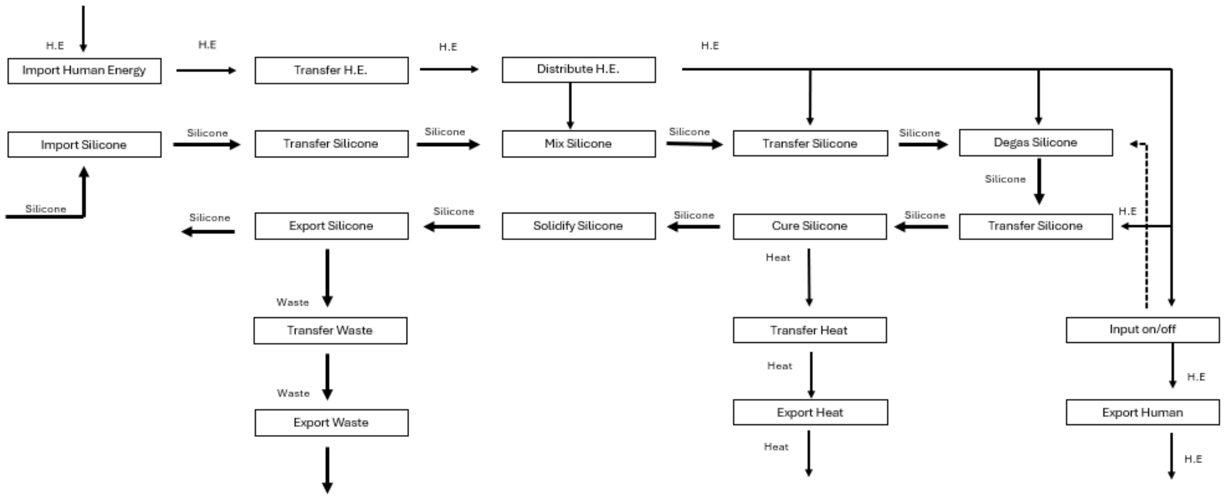


Figure 12: Decomposition Model

4.2 Concept Generation

A. **Face shape of silicone block –** This is the shape of the final silicone phantom block. For example, in figure 9, the phantom shape is rectangular. This is an important aspect to see which shape decreases the use of unnecessary material, and which affects visibility of the hollowed inner vessel model.

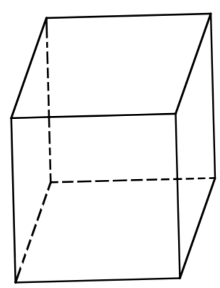


Figure 13: Square phantom shape

The concept design for the face shape of the silicone phantom block was a square. This model works well for smaller phantoms but if we had to increase the length of the vessel inside the model then we would also have to increase the height of the phantom to match the square shape.

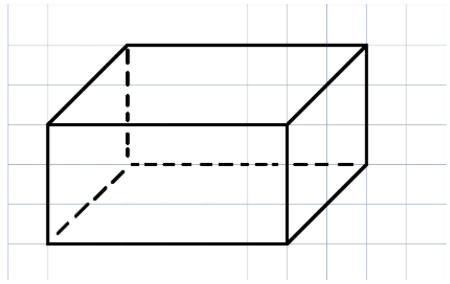


Figure 14: Rectangle phantom shape

We have the rectangle next which will also be used as a shape for our phantom model. This design will roughly be the same dimensions as a phone but a bit thicker. This is the likely model we want for both the phantom and vessel model because it optimized the size of the vessel model and decreasing cost on material used.

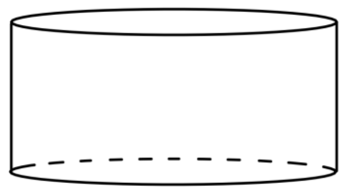


Figure 15: Oval face phantom shape

The oval shaped model will have a cylindrical body and will have the vessel model run along the length in the center. There will likely be less material needed for this model, but we believe this would be difficult to observe unless viewed from above with the molding process being inefficient as well.

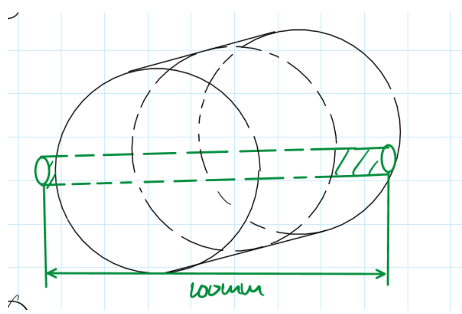


Figure 16: Circle phantom shape

Lastly, we have a shape with a circular cross section and a cylindrical body. The vessel model will run along the length of the model in the center. Similar to the oval design, it may be difficult to cast and observe. The vessel inside would have extra length added onto the inlet and outlet to combat the curvature of the face, typically the vessels have a hard cut off line of the inlets and outlets.

B. **Material of outside silicone mold –** One of the steps in the silicone molding process is to cast silicone around an inner core model, once the silicone has cured it will be removed. The material of this outside mold is important because it needs to hold the silicone in a shape long enough for it to cure and not leave any texture on the silicone.

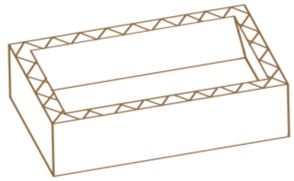


Figure 17: Cardboard material

For this concept we have cardboard being the housing for the silicone model as it cures from pouring. This would likely be the cheapest option, and we can always buy more if needed. However, we believe it would provide poor-quality housing for our mold. Leakage may also be a problem with casting, and the removal process may leave cardboard residue on the silicone.

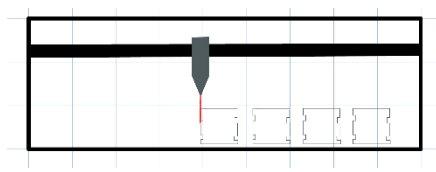


Figure 18: Laser cut acrylic

Next, we have Laser cut acrylic which will be acrylic cut into desired lengths and thicknesses to then be assembled to house the curing silicone. This will most likely be the best option to make the housing and get precise results. This method may be the most expensive due to the machines and materials needed. However, we would be able to reuse the mold if the length of the phantom stays the same. Unfortunately, if the length is altered, we would have to have another laser cut acrylic made which increases the cost.

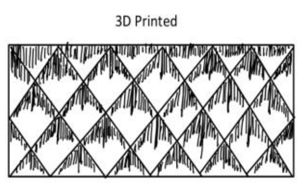


Figure 19: 3D Printing

As seen in figure 19, the 3D Printed mold will be a polymer-based material which will be printed to lengths needed to house our silicone. 3D printing is another likely option and not as expensive as other options allowing the team to get as good of results but with the risk of being melted by the heat of the poured silicone.

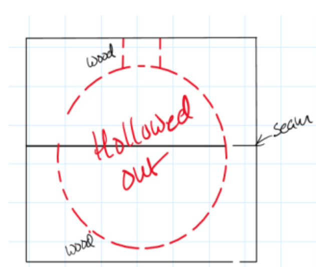


Figure 20: Wood material

Now we have wood being the housing for the silicone which will be milled or hand carved from two solid blocks of needed lengths and thickness to then be assembled at the seam. Wood is not expensive, but it is also not as cheap as some other options. It would be good housing for the poured silicone but with the temperature of the silicone once poured and the grain of the wood it will likely burn the wood and melt into the grain and may cause the wood to be replaced often. The wood will have to be very smooth as the goal is to have smooth outside of the silicone.

C. Male mold material – The male inner mold is probably the most variable aspect of this design. Each material has pros and cons of using it, varies in prices, and are all removed in a different way. This material will allow the inner vessel model to be more intricate, which is important for the model to be physiologically accurate. The ease of removal of this core will ultimately determine how repeatable this manufacturing process is and how fast a phantom can be made.

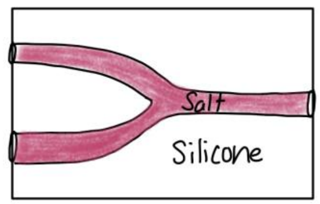


Figure 21: Inner core material, salt

For the vessel model inside the vessel will chose a salt core as one of the male molds which will be dissolved once the silicone has cured fully around the core. A salt core is good and inexpensive material but to mold it and keep it structured to then pour around it may be difficult. Another con is that the salt may cause porous indents along the inside of the silicone where we want it to be smooth. These indents will cause variation in the flow data which is not wanted.

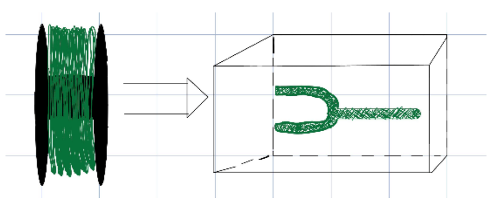


Figure 22: Inner core material 3D printing with PLA

Next, we have PLA which will be 3D printed and placed inside the housing before pouring the silicone. It will be dissolved using an ethyl acetate solution. This option is a good precise way to get a detailed vessel model within in the phantom but the need for a special solution to dissolve the PLA is expensive and proper safety measures are needed when handling ethyl acetate.

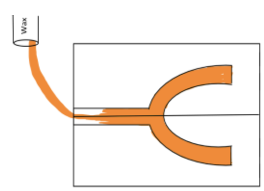


Figure 23: Inner core material, wax

We have Wax as another male model which will be modeled to desired diameters and length before phantom use, once silicone is poured and cured around the wax it can be broken up and melted out using a heat gun. This is a decent option to use but it comes with extra costs of having to create a mold just for the wax and then the wax will be used inside the phantom. Creating the molds for the wax will be difficult once the vessel models become more intricate and wax may not be as strong as it needs to be in order to pour the silicone around it.

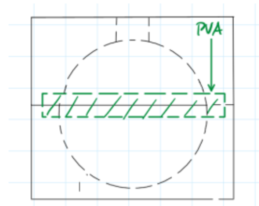


Figure 24: Inner core material 3D printing with PVA

Lastly, we have PVA, PVA is a 3D printing material that stands for Polyvinyl alcohol. This material is water soluble which is a low-cost option for removing the inner male mold from the phantom. By using 3D printing, we can model intricate vessels that are very precise and easy to remove. The only downside to this material is that it is the most expensive to purchase but there are no other expenses when using it.

D. Outside box mold assembly – The outer box assembly corresponds with how the outer mold of the silicone casting shape will hold together. It is important that the silicone does not leak and this outer mold is easily able to be disassembled.

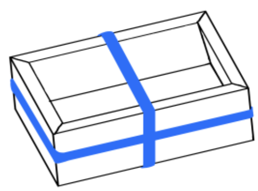


Figure 25: Rubber band hold

For what will be holding our assembly together we have rubber bands as an option which means we have several rubber bands wrapped around each side of the housing holding it all together to cure. Once the silicone has cured the bands will be released and the housing pulled apart. The rubber bands are a good and inexpensive option that are reusable, but they do not allow for precision when holding the silicone housing together and may not be able to hold enough pressure to prevent leakage when the silicone is curing.

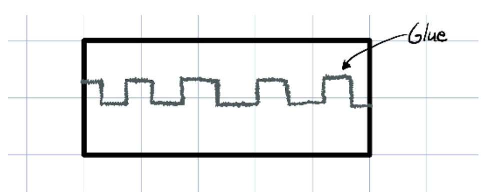


Figure 26: Outer box adhesive with glue

Next, we have Glue. The glue will be applied on the seams of the housing walls. Once curing is complete, heat will be applied to loosen the glue, and the walls will be pried apart to release the mold. Glue is another inexpensive option, but it depends on the structure of the outside housing of the assembly, and the temperature of the silicone may cause the glue to melt or not adhere correctly.

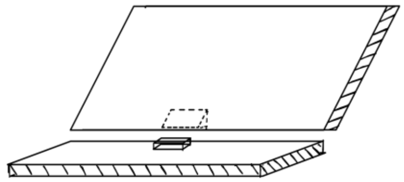


Figure 27: Pins to hold outer box together

We now have pins which will most likely be a part of the 3D printed housing. Extrusions and extruded cuts on parts of the wall will piece together and hold the housing together during silicone curing. Once cured the walls can be pried apart and reused again and again. Downside to this is that overtime the cuts may wear down and become loose, therefore leading to leaks and there is a chance of the walls breaking if too much force is needed to pry apart the pieces.

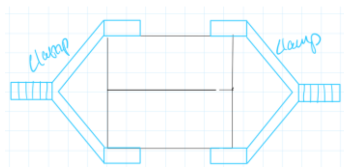


Figure 28: Clamps to hold outer box together

Last in the concept generation we have clamps, depending on the housing design clamps will be placed on the corners of the housing to hold the seams tightly for the silicone to cure. Once done clamps will be released and the mold pulled from the housing. With the clamps it's a good option to hold everything together of varying housing sizes over time but the housing will have an open top making it difficult to clamp each side of the wall together.

Concept Generation Table

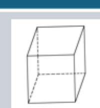
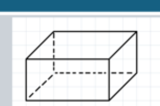
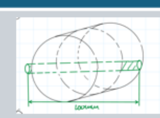
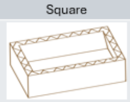
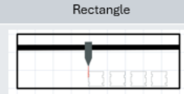
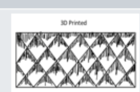
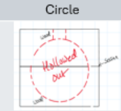
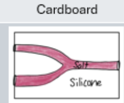
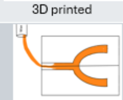
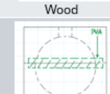
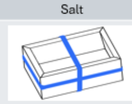
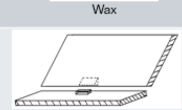
	1	2	3	4
A Shape of silicone block	 Square	 Rectangle	 Oval	 Circle
B Material of outside silicone mold	 Cardboard	 Laser cut acrylic	 3D printed	 Wood
C Male mold material	 Salt	 PLA	 Wax	 PVA
D Outside box mold assembly	 Rubber band	 Glue	 Pins	 Clamps

Table 3: Compiled Concept generation denoting each concept with a letter (based on row) and number (based on column)

4.3 Selection Criteria

This selection process was only based on the subsystem of the manufacturing of the silicone phantom model. Based on the engineering requirements the only two that involve this process would be the clarity of the silicone after casting and the validation process at the very end. Clarity of the silicone is very important so the removal of the inner male mold or the outer housing must not leave any material residue or yellow the silicone. Validation involved the process of testing medical devices on the model; this involves having a smooth inside to the phantom model and an intricate vessel design that is physiologically similar.

Other requirements include ease of core removal and material usage. The hardest part of this manufacturing process is the removal of the inner male mold. This must include leaving no damage to the inside of the silicone during removal and the removal that takes the least amount of time in order to make this process more repeatable. Material usage is also important to cut down on costs. There will already be material usage for the housing of the silicone casting process and the inner male mold, if there is any way to not add another material or step to the process that would cut down on costs and time.

4.4 Concept Selection

After the concept generation table was created, four designs were put together, one by each member of this team. Each design consists of one concept from each of the four categories including, shape of silicone block, material of outside silicone mold, male mold material, and outside box mold material.

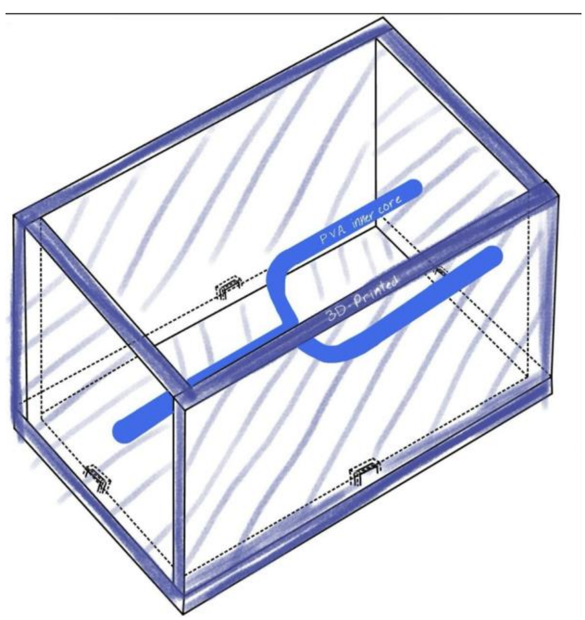


Figure 29: Design 1

Design 1 consists of a rectangle silicone shape, 3D printed outer mold material, PVA 3D printed inner male mold, and pins to hold the outer mold together. A2, B3, C4, D3

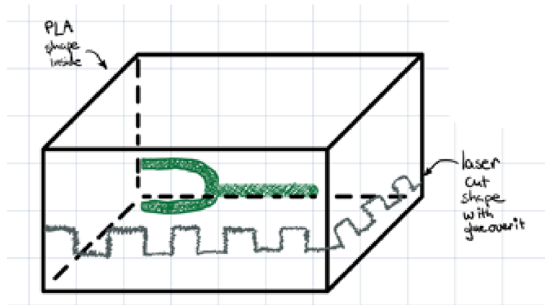


Figure 30: Design 2

Design 2 consists of a square shaped box for silicone casting, laser cut acrylic material of the outer mold, PLA 3D printed inner male mold, and glue to hold the box together. A1, B2, C2, D2

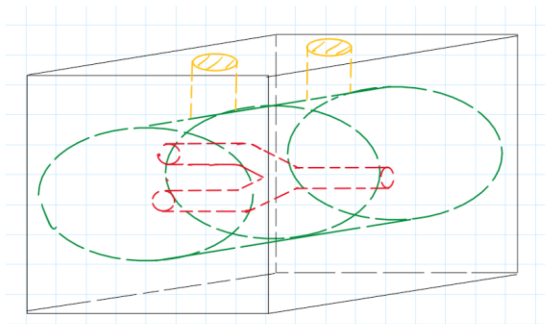


Figure 31: Design 3

Design 3 consists of a circle face shape of the silicone with the rest of the mold being a cylinder, Wood outer mold material during silicone casting, a wax inner male mold, and clamps to hold the outer mold together. A4, B4, C3, D4

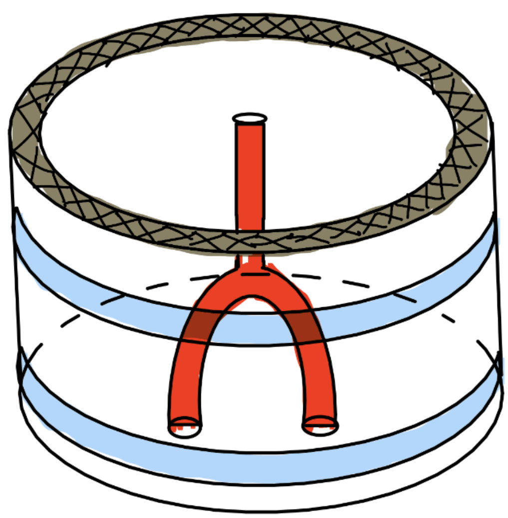


Figure 32: Design 4

Design 4 consists of an oval face shape silicone mold, the outer mold will be made of cardboard, a salt inner male core, and outer mold will be held together via rubber bands. A3, B1, C1, D1

Each design was put into a Pugh chart with one design being denoted as the datum. Design 3 was selected as the datum because it was the middle ground with each of the concepts and felt the rest could compare as either better or worse based on the selection criteria to this design.

Pugh Chart

Concept/ Criteria	Design 1	Design 2	Design 3	Design 4
Clarity Of Silicon	S	S	Datum	S
Validation	+	+		+
Ease of Core Removal	+	-		-
Material Usage	S	+		-
Sum +	2	2	Datum	1
Sum -	0	1	Datum	2
Sum S	2	1	Datum	1

Table 4: Pugh chart, comparing each design to the datum with an S meaning it compares similarly, + being positively or better than, or – as negatively

Each design was then put into a decision matrix with a weight relating to each of the criteria. Then each design was rated on a scale of 1-100, 100 being it fulfills that criteria fully. The rating, shown in the unweighted column, would then be multiplied by the weight of the criteria, as shown in the weighted column, and each weighted value would be summed to get the total value for that design. The design with the highest value scored the best according to the criteria and is now the selected design.

Decision Matrix

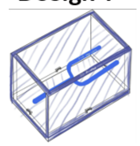
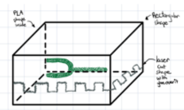
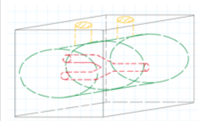
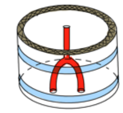
Criteria	Weight	Design 1 		Design 2 		Design 3 		Design 4 	
		Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Clarity Of Silicon	0.3	90	27	70	21	60	18	90	27
Validation	0.2	90	18	70	14	90	18	60	12
Ease of Core Removal	0.4	90	36	80	32	70	28	50	20
Material Usage	0.1	90	9.0	40	4.0	90	9.0	40	4.0
Total:	1.0	Sum:	90	Sum:	71	Sum:	73	Sum:	63

Table 5: Decision Matrix

According to the decision, matrix design 1 scored the best based on the four criteria. Design 1 consists of a rectangle silicone shape which decreases the amount of silicone used in the model, 3D printed outer mold material which has a smooth finish and low-cost option, PVA 3D printed inner male mold easiest core to remove, and pins to hold the outer mold together.

In the future multiple designs may be tested and each process will be evaluated when prototyping to truly see which one is the most repeatable and easy to assemble.

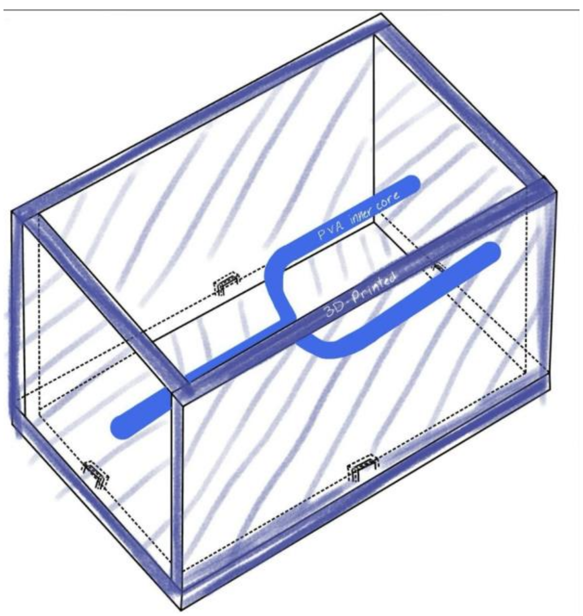


Figure 29: Design 1

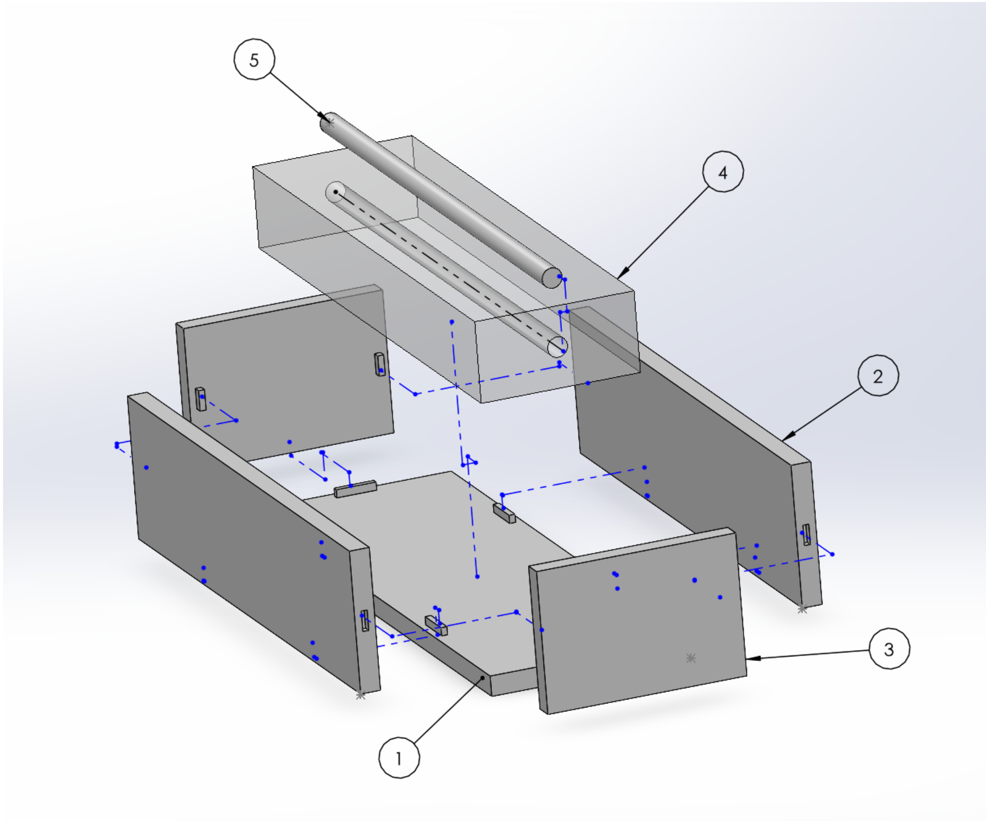


Figure 33: CAD model of final design with balloons and leader-lines

CAD design balloon labels:

1. Bottom plate made of 3D printing material with extruded pins.
2. Long side wall made of 3D printing material with extruded cut for pins to fit into.
3. Short Side wall made of 3D printing material with extruded cut on bottom and extruded pins on front face to fit with long side wall.
4. Rectangular clear silicone block (the phantom model).
5. PVA 3D printed inner core that will be dissolved out with water leaving a hollow inside of the phantom.

CONCLUSIONS

In this project we are trying to simulate interchangeable phantom models to be used alongside the BDL benchtop flow set up. Our capstone is the second version of the NAU's PIV project where the last team was able to design and construct a PIV set up with the necessary device to illuminate particles in thick silicone models and be able to capture flow regions to be studied. The BDL benchtop is used to test novel medical devices to treat strokes within the human vascular system. We plan for the Benchtop model to be used alongside the phantom model our group is currently designing to study flow in the vascular systems and collect the necessary data like velocities and stresses to combat serious medical problems like ischemic and hemorrhagic strokes.

We had a list of requirements we had to go over with our client, Jesse Wells, before we could start the overall design and planning or the project. We also had requirements for ourselves for the final design to be up to standards for the client. We met these requirements and placed them in our QFD chart and rated them on how important they are to the client and to the design itself. Some examples of the requirements we had are conversion time, time to go from PIV flow loop to standard loop, Clarity of Silicone, visibility when using cameras on the mold, Refractive Index, the matching of the solution to the mold without visible distortion, and Visibility of Particles, can the particle in the vessel be seen when the laser is on it as well as the camera.

In the end Design 1, figure 29 and 30, proved to be more suitable for the project based on the Pugh Chart, Table 4, and our Design Matrix, Table 5. Design 1 was composed of rectangular phantom shape, a structure material of a 3D printed Polymer, a male mold of PVA, and pins to hold the assembly together as the silicone cures. This and designs 2 and 4 were compared to design 3 which we chose to be our datum. The rest of the designs didn't prove to be efficient compared to the datum in the design matrix, table 5, where we decided to give design 3 an overall score to better compare the other three designs. After getting the scores, design 1 was the only one to outscore the rest of the designs based on the concept criteria. Design 1 will be the first prototyped design and if something needs to be changed the rest of the designs will be revisited. The next steps in this project will be applying all the mathematical modeling and the selection process to a physical model and we will manufacture a silicone phantom.

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6 APPENDICES

N/A there are no appendices in report #1