Design of a Testing Setup for Diffusion Coefficient Measurement

Design Activity No. 6: Embodiment Design Report

MECH 463 - Design 3: Mechanical Engineering Project

McGill University, Department of Mechanical Engineering

GROUP 20

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Table of Contents

List of Figures

List of Tables

1. Executive Summary

This report highlights the major design specifications for the test rig used to measure the diffusion coefficient. Epoxy resin has been chosen as the tank material due to its convenient manufacturability through 3D printing, high melting temperature and transparency. The tank dimensions have been defined using final element analysis (FEA). Gaskets and bolt specifications have been defined through specific stress calculations to prevent any leaking during the experiment. A magnetic heating plate has been chosen as the heating mechanism due to its ability to combine both heating and stirring. Heating plate selection has been done and verified with heat transfer calculations, both at unsteady and steady-state conditions. Finally, an estimate of the total costs has been provided to ensure the feasibility of the design.

2. Introduction

The goal of this project is to assist the Graduate Biomechanics Laboratory team at McGill University in their effort to improve the performance of drug-eluting stents and prevent the formation of blood clots in arteries. More precisely, the goal is to create an experimental setup to measure the release kinetics of the stent coating compounds. Measuring the diffusion coefficient will help the Graduate Biomechanics Laboratory team in improving their stent design and choosing the right compound.

This report presents the criteria that was selected to evaluate a set of generated concepts. The choice of each criterion is justified while being paired them with a relevant metric to ensure an objective evaluation. As discussed in DAN-5, this process helps understand the rationale and the steps taken to choose the best concept to measure diffusion coefficient between two liquids.

A Pugh Matrix was used to compare the three concepts. This tool helped evaluate each concept and choose the concept that is best fit to the needs of this project.

In this report, the final concept is presented with its final specifications. New parameters are considered such as temperature and size which allowed for layout and material selection. Some changes were made with respect to the concept selected in DAN-5 and justification for these changes are addressed.

3. Problem Definition

Specifically, the experimental setup must allow the user to measure the diffusion coefficient of the chemical compound. When released from the stent, the compound releases into the vascular tissue and into the plasma. Hence, the experimental setup must have a membrane to mimic the vascular tissue.

A typical yet very efficient way to measure the diffusion coefficient is the Diaphragm Cell method. This process consists of two containers with respective volumes, separated by a porous membrane [2]. Solutions of different compositions and concentrations are placed on either side of the membrane and stirring begins. Both solutions will interact, and the diffusion process will occur for a measured period of time. At time t, the solutions are then withdrawn, and both concentrations are measured. The diffusion coefficient is then measured using the following formula:

$$\overline{D}_{t,c} = \frac{1}{\beta t}\ln\left[\frac{(c_1 - c_2)}{(c_3 - c_4)}\right]$$

Where c1 and c2 are initial concentrations of the solutions and c3 and c4 are incidentally the final concentrations. β is the cell calibration constant [2], which is dependent on the volume of both compartments, the effective thickness of the diaphragm [1], as well as the total area open for diffusion. Therefore, this method presents a simple way to measure the effective diffusion coefficient.

A few key factors allow this method to be feasible: both compartments must be well stirred before diffusion process begins, knowledge of the solute and solvent's properties are required to proceed with analysis, and an important calibration with a solute of known diffusion coefficient is required to determine the porosity of the membrane, which is then used to calculate the effective diffusion coefficient of the compound at hand [2].

The chosen experimental setup must provide accurate results regarding the diffusion coefficient. Failure to do so will prevent from correctly assessing the effectiveness of the chemical compound. Ideally, the setup is lightweight and compact to allow for easy handling and transportation if needed.

The costs of manufacturing the experimental setup must fit in the allowed budget. Note that a manufacturing budget of 2000$ is allocated for this project. 3D printing may also be used within a budget of about 1000$.

4. Evaluation Criteria

The table below illustrates the criteria used for the evaluation of the concepts generated. The table contains a justification for each criterion along with the metric used. If quantitative data is unavailable for a certain metric, any qualitative information will be used in the Pugh table for comparison.

Table 1: Performance Criteria Metrics.

Metric	**Justification**	**Evaluation Technique**
1. Leakage	Leakage is the primary driver of error for diffusion coefficient measures. To achieve the best results, an instrument that inherently minimizes leakage will be chosen.	Theoretical liquid lost (mL).
2. Measurement Accuracy	The accuracy of the measurement itself is a primary metric for the choice of instrument. A high measurement accuracy will ensure the tested diffusion coefficient will have a high degree of confidence.	Percent Error (%) between theoretical and experimental diffusion coefficients.
3. Size of Instrument	Smaller instruments are preferred. A smaller instrument typically entails a simpler design, and lower cost of manufacturing.	Size (m^3) of instrument.

4. Versatility	Versatility is an imperative quality for a strong design. A versatile instrument would allow for the membrane to be changed easily, and for many membrane shapes to be used.	Number of membranes that can be used.
5. Cost of Manufacturing	A cheaper instrument is preferable. Easier to iterate upon, and scale if needed by multiple teams.	Estimated Cost ($).
6. Ease of Manufacturing	Instruments that are easier to manufacture are preferable. This will make the process easier for the milling and 3D printing teams and will make the concept better to iterate upon.	Total estimated time to produce.
7. Steering or Passive	Some measurement techniques require more monitoring than the rest. A technique that requires less human input is preferable. This will reduce possible errors, and time take for those testing.	Total estimated time of human input.
8. Ease of Use	A less challenging concept is preferable. This will make results more repeatable across teams, and reduce time taken for knowledge transfer between individuals.	Arbitrary measure of difficulty on a scale of 1-5.
9. Modular	It is preferable if parts are independent of one another. If the instrument can be broken down into distinct parts, this will make iteration of specific functionality more effective. It is cheaper and easier to iterate upon the specific part failing, than the entire instrument.	Number of unique parts.

5. Evaluation of Alternative Concepts and Final Concept Design

5.1. Alternative Concepts

Multiple concepts were created based on the evaluation criteria described in Section 4. Three concepts were generated which are each based on the diaphragm cell diffusion method. The three concepts are shown below.

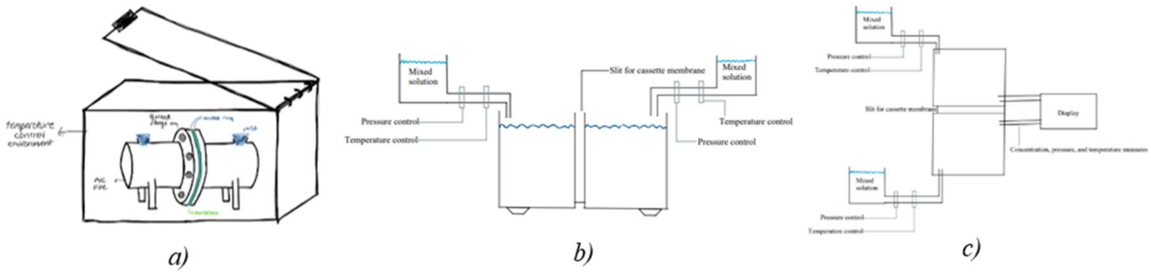

Figure 1: a) Concept 1. b) Concept 2. c) Concept 3.

Concept 1 is made of two PVC pipes with flanges and gaskets to secure a circular section of membrane tissue. Each pipe serves as a tank to hold the solutions being examined. The setup is placed in a boxed in which the temperature can be controlled. This concept uses bolts to ensure sufficient compression of the gaskets to prevent leakage at the membrane.

Concept 2 consists of a rectangular tank separated into two sides to hold the solutions. A slit would be made in the tank allowing the user to slide the membrane, compressed by gaskets, into the tank. This concept focuses on the versatility aspect by having a cassette like mechanism allowing for the membrane to be changed easily. The solutions pressure and temperature would be controlled in separate beakers before being poured into their respective tanks.

Concept 3 features a vertical experimental setup in contrast to the horizontal setups in the previous designs. Like concept 2, the pressure and temperature of the solutions is controlled in external beakers. Additionally, this method includes a display with aims to make the monitoring of pressure and temperature as easy as possible.

5.2. Concept Evaluation

As discussed in DAN-5, to objectively evaluate the three concepts, a Pugh Matrix was generated. Each criterion was given a weight to quantify its importance based on the team's discussions and consultation with the advisor. Each concept was given a number from 1 to 3 for each criterion, 1 being the worst and 3 being the best. The grade attribution was done acknowledging that the designs were defined at a very preliminary phase.

Table 2: Pugh Matrix Comparing the Three Concepts.

Criteria	Weight	Concept 1	Concept 2	Concept 3
Leakage	20	3	2	1
Measurement Accuracy	20	2	2	3
Size of Instrument	10	3	2	1
Versatility	10	2	3	2
Manufacturing cost	15	3	3	1
Ease of manufacturing	10	3	2	1
Steering or Passive	5	3	2	3
Ease of Use	5	2	3	3
Modular	5	2	3	2
TOTAL SCORE		**260**	**235**	**175**

Results from the Pugh Matrix show that concept 1 has the highest total score with 260 points followed up close by concept 2 with 235 points. Concept 3 shows disappointing results, with a score of only 175 points.

5.3. Final Concept Selection

As our main objectives were to provide minimal leakage, low manufacturing cost and maximum measurement accuracy, these metrics held the most importance when comparing each method. The results of the Pugh matrix provided concrete results which led to the conceptual design of our final concept. While concept 3 had some promising features surrounding accuracy, ease of use, and human input, it would be far too challenging to implement for a prototype. The ease of manufacturing as well as the leakproof features from concept 1 are evidently a key feature for the design of the testing setup. Concept 2 is strong due to the temperature and pressure regulation, along with the modular design. Components of both concept 1 and concept 2 are integrated into the final design.

Concept 1 scored well on manufacturing cost, size of instrument, ease of manufacturing and human input. It also has the highest score for leakage. This is due to the bolted flange joint which greatly reduces any potential leakage. We believe this design component would be imperative for a final design, provided leakage is one of the most important metrics. Thus, we decided upon using concept 1’s body for the testing chamber. As shown in Figure 2 , this includes the double flange clamp design with a modifiable middle membrane piece.

Concept 2 scored well on versatility, manufacturing cost, modularity, and ease of use. Specifically, our team liked the individual control of temperature and pressure for each solution. Not only does this externalization help with regulation, but magnetic mixers can also be added to the separate tanks, and the design is more modular which promotes iterative design. As shown in Figure 2, the final design will intake the temperature and pressure regulated tanks from concept 2.

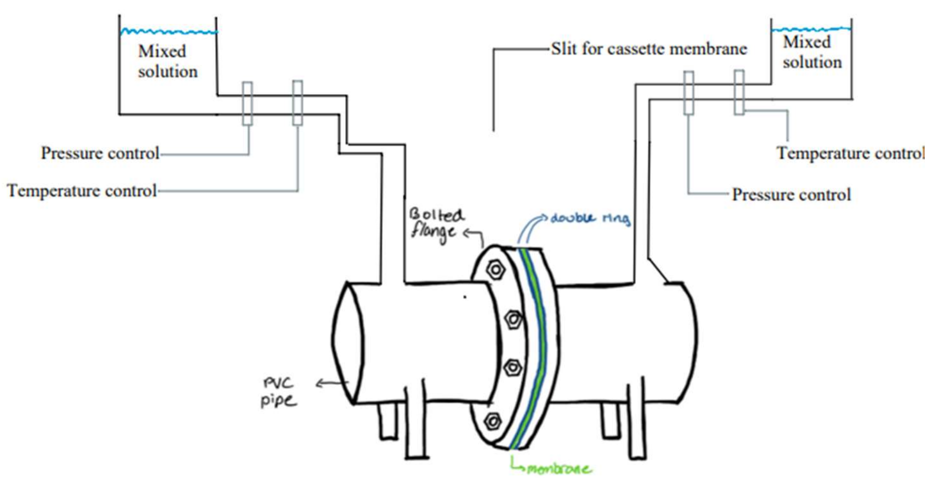

Figure 2: Sketch of Final Conceptual Design.

6. Design Embodiment

In this section of the report, the use of models, simulation results and research will help determine the final design specifications. The concept described in Section 5.3 represents the basic idea, however, at this stage multiple modifications were brought to the design. Further discussion with the client led our team to the conclusion that pressure control is not necessary for the scope of this project. Diffusion measurement will likely not be measured at great pressures; therefore, it is sufficient to only have a form of temperature control in the experimental setup.

6.1. Tank Dimensions

The layout of the experimental setup remains horizontal like what is shown in Figure 2. Having a horizontal setup compared to a vertical one has the advantage of neglecting the effect of the gravitational field, making calculations simpler, and results more accurate.

Originally, the two tanks had a cylindrical shape, however, it was decided to go with half-cylinders instead. Half-cylinders have a flat base which would serve as the heating surface. Unlike a circular bottom, a flat one enables the use of a magnetic stirrer in each tank as a mixing method. The top of the tanks remains circular to benefit from some of the advantages of round edges on fluid flow. Round edges are shown to keep the velocity of fluid flow more uniform compared to sharp edges [3]. The heating and stirring systems are discussed in later sections, it is simply important to understand the reasoning behind the choice of the tank geometry.

One of the client's requirements is that the size of the membrane sample remains between a diameter of 2.5cm and 3.5cm. To achieve this, given the shape of the tank is not circular, each tank will have an opening of 3.5cm on the side.

The dimensions of the half-cylinder tank were chosen to be larger than the 3.5cm diameter opening. The diameter of the half diameter is 7cm and its length is 10cm. This way the tanks are not too small and can be easily handled. The thickness of the walls was chosen arbitrarily to be 2mm.

The method of attaching the tanks together with the gaskets and the membrane is the same as the final concept presented in Section 5.3. Flanges are necessary to allow the passing of bolts through the tanks, the gaskets, and the membrane.

Due to the complexity of the tank geometry, these parts must be 3D printed. 3D printing allows the team to turn the flange and the tanks into one part. To better visualize the parts, an exploded view of the design is showed in Figure 3.

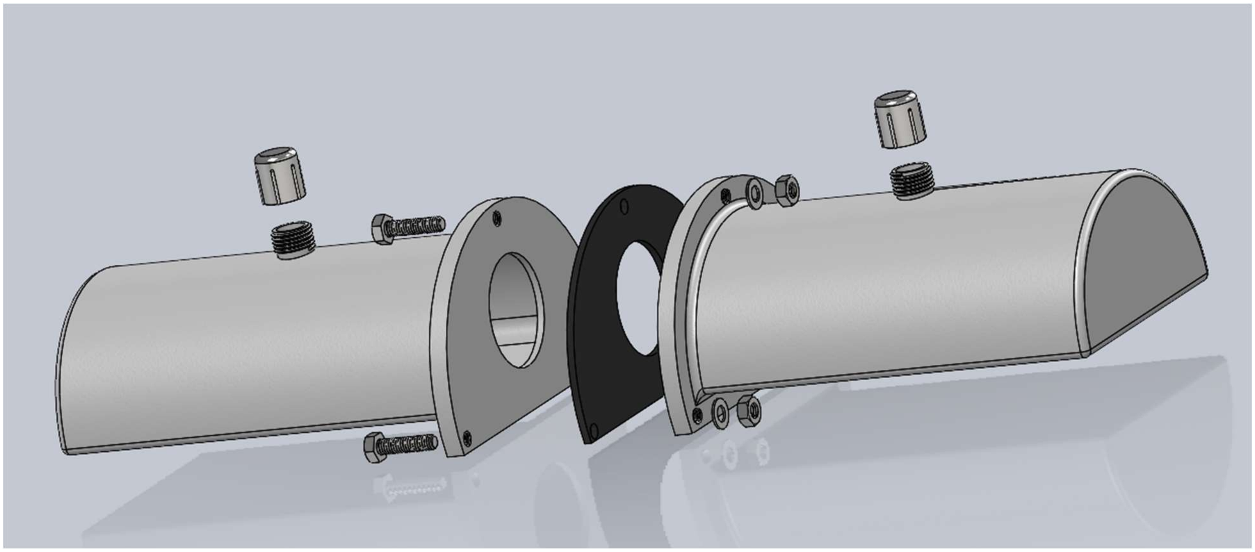

Figure 3: Exploded View of CAD

Fillets were added on the inside of the tanks to avoid have sharp corners where the fluids will be.

The dimensions of the parts will be confirmed through further analysis of other aspects of the experimental setup.

6.2. Material Selection

One of the most important aspects to this experiment is the material of the vessel. As described above, the dimensions of the tank are quite small and compact, meaning the material needs to be durable and robust. The temperature at which the experiment takes place is especially important for material selection, since all degradation, deterioration and melting should certainly be avoided. Since this experiment is mimicking the diffusion through a cellular membrane in the human body, the experiment will be held at approximately 37ºC, corresponding to the average human body temperature.

The apparatus will be resting on a hot plate, which will allow the user to maintain an internal experimental temperature of 37ºC. Thus, the material chosen will not only have to withstand this desired experimental temperature, but it must also withstand the required external heating temperature of the vessel to obtain this internal 37ºC.

Moreover, to allow the user to visualize the experiment and note any observational changes, it is essential to have a transparent tank. After analysis and discussion, a good tradeoff between a small, robust, durable model and one that is transparent is quite difficult to obtain due to the small dimensions of the experimental setup. Therefore, instead of ordering parts and assembling them to create the apparatus, it will instead be 3D printed.

The material chosen is epoxy resin, a common print material that has a thermal conductivity of 0.2 W/mK [6], and the thermal resistance of epoxy resin is approximately 200 ºC [7]. Generally, epoxy resins also have incredible strength, ranging from 3500 – 6000 psi in tensile strength [5], and compressive strength of approximately 10 000 psi [8]. In addition, epoxy resin is a transparent material, therefore ideal for our apparatus. In further sections of this report, analysis will be made to prove that the experiment will never externally heat to a value greater than the heat resistance of epoxy resin, and that the stress applied to the material will never exceed its allowable stress.

6.3. Finite Element Analysis

To confirm the thickness of the vessel, finite element analysis was conducted. We explored the stress that the bottom of the vessel will experience due to water pressure. Provided how small the vessel is, we expect the stress exerted upon the container to be minimal. However, this analysis is still an imperative component of the design process and allows us to quantify our safety factor against this stress. To begin, we gathered the material properties of our chosen material, epoxy resin, and inputted into our model. The notable properties of epoxy resin are as follows:

Table 3: Material Properties of Epoxy Resin (from SolidWorks).

Property	Value	Units
Elastic Modulus	350266.1365	Psi
Mass Density	0.03974001	lbs/in^3
Poisson's Ratio	0.35	
Tensile Strength	4061.056655	Psi
Compressive Strength	15083.92472	Psi

With the appropriate material parameters inputted into the model, we now need to fix the geometry, and input the stress that the device will experience. The stress was calculated using $P = \rho g h$, where:

$$P = \rho g h = \left(\frac{997kg}{m^3}\right)\left(\frac{9.81m}{s^2}\right)(0.035m) = 342.32N/m^2$$

Assuming a constant distributed load of $342.32N/m^2$, we then fixed the geometry of the device, as the bottom of the plate, not including the flange. Then, allowing the mesh to automatically generate using the Solidworks Simulator, the job was run. The results are shown below:

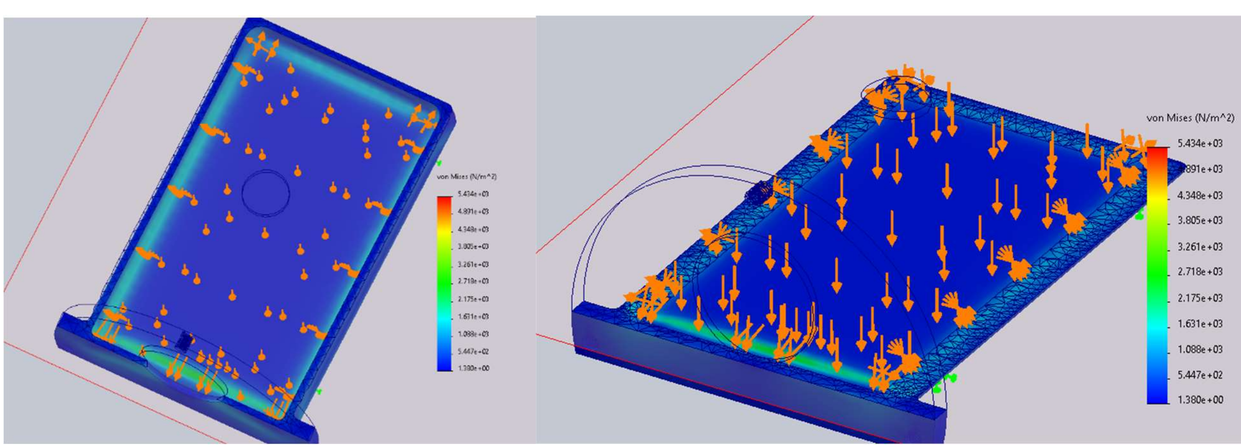

Figure 4: Von Mises Stress Mesh of Device (View 1,2).

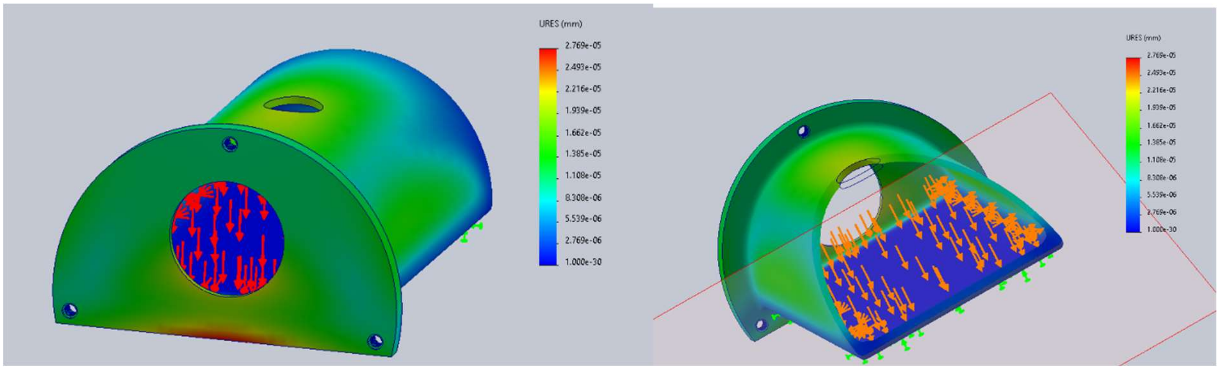

Figure 5: Displacement Mesh of Device (View 1, 2).

Figure 4 highlights the maximal Von Mises Stress the device may experience [4]. Von Mises Stress is expressed with the following equation, in terms of the principal stresses $\sigma_1, \sigma_2, \sigma_3$,

$$\sigma_{von\ mises} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_2)^2}{2}}$$

The theory states that a ductile material will start to yield when the von Mises Stress becomes equal to the stress limit. In most cases, this yield limit is set to the ultimate tensile strength of the material. For epoxy resins, the tensile strength can range from 5000-6000psi [5]. From the given chart, we see the maximal von mises stress experienced is approximately 3260Pa, which is 0.47psi. This is many orders of magnitude less than the ultimate tensile strength that could be experienced, which validates the thickness chosen for the design. In the second figure, Figure 5, we see the maximal displacements that may be experienced because of this loading. The maximal displacement that would potentially occur would be at the bottom edge of the flange. This displacement would only be a value of 0.00002755mm, which is negligible, and confirms what we concluded from the stress analysis.

6.4. Gaskets and Bolts

Gasket stress is a very important parameter when describing the load of a bolted joint surface, especially since each material responds differently to applied stresses. The first consideration when selecting the material of choice for the gasket is the temperature at which will be exposed to. Temperature can quickly change the characteristics of the material, hence affecting its maximum allowable stress and quickly deteriorating the gasket. Since the experiment at hand will be mimicking the process of diffusion through the human body, the steady state temperature of the experiment is held 37°C, corresponding to average body temperature. This is a non-limiting factor where most materials will be compromised well above the average body temperature of a human.

The next important concept to evaluate is the material's durometer status, which is a standard way to measure material hardness [9]. Soft materials tend to range from 0-50 on the Shore A scale and harder materials tend to range from 50-100. This scale describes the material's ability to resist indentation, which in turn specifies sealing performance. Ideally, the gasket must be soft enough to fill the gap between the two flanges, but hard enough to withstand the pressure it will encounter [10].

In this experiment, there isn't a required internal pressure needed to maintain. Thus, as long as the membrane is sealed between the two flanges and that the gasket is preventing the apparatus from leaking, the experiment should be a success. Therefore, the material being used is natural rubber. On the durometer scale, this equates to the 40 mark for Shore A, which resembles the hardness of an eraser at the tip of a pencil. This will allow the material to compress, without failure, and seal the joint between both flanges without an issue.

Moreover, the typical service temperature for natural rubber ranges from -55°C to 82 °C, which is way beyond the scope of this experiment. An elastomer without fabric, having a value on the durometer scale less than 75 will have a gasket factor of 0.5m and a minimum design seating stress of 0 psi [11]. The minimum design seating stress is the minimum compressive stress on the contact area of the gasket that is required to provide a seal at an internal pressure of 0.14 bar [12], which means that for a minimum compression of the flanges, the natural rubber will create an effective seal, free from any leak. Since this minimal compression causes an effective system, the torque applied will never amount to a value that may indent or deform the natural rubber permanently [11].

Of course, the flanges should be tightened moderately, but enough so that the apparatus is indeed well structured. However, there isn't a minimum stress required to prevent leakage due to the material chosen, and if tightened reasonably (2-3 bolt rotations after feeling initial resistance), there will be not any hazard regarding failure of the apparatus or of the gasket itself.

To justify this assumption, a sample calculation is shown:

The ASME Unfired Pressure Vessel Code states the initial bolt load required to seat a gasket sufficiently as $W_{m2} = pbGy$ [11], where y is the minimum design stress.

To maintain a residual compression load on the gasket that is sufficient to assure a tight joint, ASME defines this bolt load as $W_{m1} = \left(\frac{p}{4}\right) G^2P + 2bpGmP$, where P is the design pressure of the experiment [11]. Since our experiment does not need to be pressurized, and our minimum design stress is 0 psi, both W_{m1}, and W_{m2} amount to 0 psi.

Next, the minimum bolt area is described as follows:

$$A_{m1} = \frac{W_{m1}}{S_a}, A_{m2} = \frac{W_{m2}}{S_a}$$

$$A_{m1} \geq A_{m2},\ \ A_m = A_{m1}$$

$$A_{m2} \geq A_{m1},\ \ A_m = A_{m2}$$

As A_{m1} and A_{m2} are both 0, we conclude that there in no minimum required bolt area A_m needed to contain stresses in this experiment.

Thus, bolts can be selected arbitrarily. Our selection is Class 8.8 Steel Hex head screws [20] which have a minimum cross-sectional diameter of 0.0033mm = 0.01299in. Thus, a minimum cross-sectional area of 0.0001325 in^2.

$$A_b = (Number\ of\ bolts)x\ (Minimum\ cross\ sectional\ area\ of\ bolt)$$

$$A_b = (3)x\ (0.0001325)$$

$$A_b = 0.000397\ in^2$$

Finally, the maximum unit load $S_{g,max}$ on the gasket bearing surface is equal to the total maximum bolt load divided by the actual area of the gasket.

$$S_{g,max} = \frac{A_b S_a}{\frac{p}{4}[(OD)^2 - (ID)^2]}$$

$$S_{g,max} = \frac{0.000397\ * 110000}{\frac{p}{4}[(2.165)^2 - (1.181)^2]}$$

$$S_{g,max} = 16.88\ \frac{lbs}{in^2}$$

To tighten the bolts, a wrench of approximately 6 inches in length can be used. Assuming a force applied to the wrench of about 10 lbs:

$$Torque = F\ x\ D = 10lbs\ x\ 6in = \ 60\ in - lbs$$

$$Actual\ stress\ applied\ to\ gasket = \frac{F}{A} = \frac{10\ lbs}{6.26in^2} = 1.6\ \frac{lbs}{in^2}$$

As we can observe, the actual stress applied is nowhere near the maximum load on the gasket. The safety factor is of approximately 10. Therefore, there is no concern when discussing gasket failure.

6.5. Heating Transfer Analysis

The diffusion coefficient of a substance is greatly dependent of its temperature. Hence, incorporating a heating system in the test rig is imperative to accurately reproduce the flow in an artery. For this design, water has been chosen as the fluid inside the testing rig. Using water will give use a general idea of the heat transfer analysis inside the test rig, hence it is assumed it will be similar if other liquids are used inside the tank.

The first step in designing the heating system was to choose if the heater would be either external or submerged in the flow. Both alternatives have their pros and cons. Submerged heaters are more efficient, since they are directly in contact with the flow, hence the fluid heating time is shorter. However, submerged heaters are prone to corrosion, which makes them more damaged and less efficient over time. Corrosion can also contaminate the fluids on the test rig. On the other hand, external heaters, such as jackets or heating plates, are more durable since they are not in contact with the flow, but the heating process might take longer because the heat must go through the base wall of the test rig before reaching the water.

To simplify the design and prevent damage due to corrosion, it has been decided to go with an external heating source. The choice was then between a jacket heater and a heating plate. A heating plate has been chosen, since it would enable to look through the test rig during the experiment, unlike the jacket heater.

The following calculations have been performed to ensure that the selected heater can provide the required power to keep the water at 37 °C. Two cases have been analyzed:

<u>Case 1: Water heating process (unsteady heat transfer)</u>

First, one must ensure that the heater is able to warm the water to the required temperature T_f in a reasonable time. Since these calculations are raw approximations to ensure proper heater sizing, the following assumptions can be made for simplification:

- All the heat coming from the plate is transmitted to the water
- The heat loss from the water to its surroundings is negligible
- The initial water temperature T_i is the same as the ambient air temperature (=25 °C = $298\ K$)
- Desired water temperature $T_f = 37°\text{C} = 310\ K$
- The water must be heated in Δt = 10min = 600s
- Radiation heat transfer in negligible

The average power required to heat the water can be calculated with the following formula [13]:

$$\dot{Q} = mc\frac{\Delta T}{\Delta t} = mc\frac{(T_f - T_i)}{\Delta t}$$

Where $\dot{Q}$ is the average rate of heat transfer provided by the heating plate in W, m is the mass of water to be heated in kg and c is the specific heat capacity of water in J/(kg*K)

Since the test rig has a half-cylindrical shape, the mass of water can be found with the following formula:

$$m = \rho V = \rho\frac{\pi}{8}{D_i}^2 L$$

Substituting for m:

$$\dot{Q} = \rho\frac{\pi}{4}{D_i}^2 Lc\frac{(T_f - T_i)}{\Delta t} = (1000)\frac{\pi}{8}(0.07)^2(0.12)(4184)\frac{(310 - 298)}{600} = \mathbf{19.32\ \ W}$$

Most magnetic plate heaters are rated between 150 and 300W. Hence, any plate heater will have more than sufficient power to heat the water in the test rig.

The total mass of water that needs be heated is also found:

$$V = \frac{\pi}{8}(0.07)^2(0.12) = \boldsymbol{0.000231\ m^3 = 0.231\ L}$$

<u>Case 2: Steady-state heat transfer between heater and water extremity</u>

One must also ensure that the chosen heater can also provide enough power to keep the water at the desired temperature. Once again, since these calculations are a raw approximation, the following assumptions can be made for simplification:

- Water temperature T_{water} is uniform due to the agitation provided by the mixing (310 K)
- Perfect thermal contact between the heater and the test rig
- The heater has a temperature $T_{heater} = 50°\text{C} = 323\ K$
- Radiation heat transfer is negligible

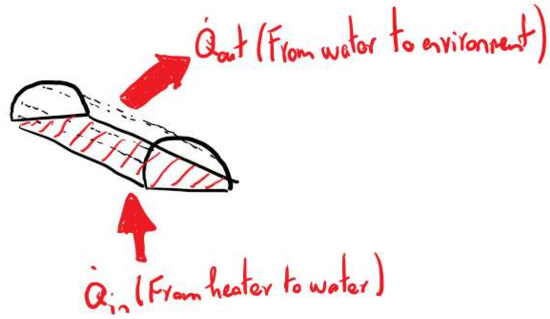

Figure 6: Steady-state energy balance on testing rig

Resistance analogy will be used to solve this heat transfer problem [13].

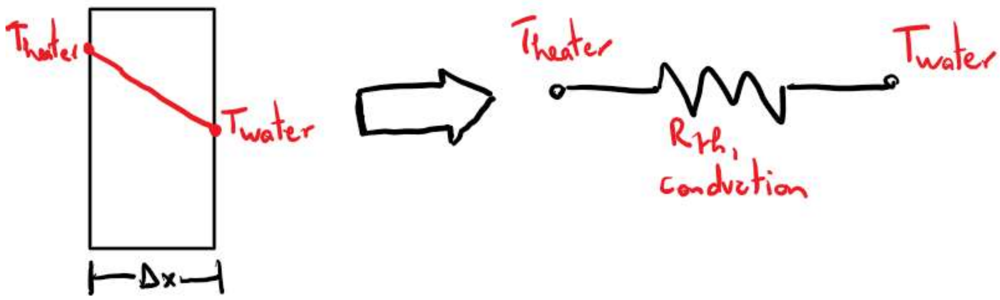

Figure 7: Steady-State resistance analogy between heater and test rig

The following equation will be used to approximate the steady-state rate of heat transfer from the heating plate to the water:

$$\dot{Q} = \frac{kA}{\Delta x}(T_{heater} - T_{water}) = \frac{kwL}{\Delta x}(T_{hea} \quad - T_{water})$$

Where $\dot{Q}$ is the steady-state power required by the heater in W, k is the thermal conductivity of the test rig material in W/(m*K), w and L are the test rig's base width and length in m and Δx is the base thickness of the test rig in m.

Solving for $\dot{Q}$ gives:

$$\dot{Q} = \frac{(0.2)(0.07)(0.12)}{(0.002)}(323 - 310) = \mathbf{10.92\ W}$$

Results show that any basic commercial magnetic plate heater can provide the required power to keep the water at 37°C. The results also prove that the dimensions selected for the tank (width, length, and thickness) are adequate.

6.6. Stirring

Stirring is an essential aspect of the experimental setup design since mixing used to ensure uniform distribution of temperature during the diffusion experiment [14]. It also allows liquids to heat or cool more quickly and prevents boiling. In this case, the setup would benefit from faster heating. In the context of chemical solutions, stirring increases the rate of mixing [14]. Stirring speed should not be greater than 2000 RPM, after which diffusion measurements could be invalid [15]. The objective of the project being to measure diffusion coefficient of medication compounds, it is essential to have a stirring solution to ensure solutions are well mixed for the entirety of the experiment.

Magnetic stirrers are widely used in laboratories and consists of a magnet that produces a rotating magnetic field. The stir bar is immersed in the liquid which is place on a magnetic stirring system. The small size of stir bars make them easy to clean and sterilized [16]. Using this type of stirring system in the experimental setup would be quite simple. Furthermore, it would not require any additional holes to be made in the tanks, compared to other stirring solutions, reducing the risk of leakage.

6.7. Heating and Stirring System Selection

The selection of the heating and stirring system was made based on the requirements established in the previous section of this report. Magnetic stirring systems as discussed in Section 6.6, are generally coupled with a heating system. This type of device is suited for this design as a heating and stirring plate would be placed under each tank allowing the solutions to be heated and mixed simultaneously.

Another component that is essential for the diffusion measurement setup is to have a thermostat inside the solution of each tank measuring their respective temperatures. This would help ensure the temperature remains constant for the length of the experiment.

The selected device needs to satisfy the power and temperature requirements discussed in Section 6.5. Research led the team to select a magnetic stirrer hot plate with a temperature probe sensor as seen in Figure 8.

Figure 8: Digital Hotplate Magnetic Stirrer [17].

The device's specifications can be found in Table 5 in the appendix. This size of the heating plate is 17 x 17 cm which is larger than the area getting heated by one tank (7 x 12 cm). The power of the heating plate is 500 W, which is well above the requirement of 19.3 W for the plate to heat water to 37 degrees Celsius. The plates maximum heating temperature being 300 degrees Celsius provides a lot of flexibility to run experiments. The stirring speed is adjustable between

200-2000 RPM which is perfect considering it should not go over 2000 RPM. The stirring capacity is 2L which is well above the volume of one tank being 0.231 L (refer to Section 14).

7. Manufacturability

7.1. Fabrication Plans

The experimental apparatus will be composed of parts that are 3D printed, machined, and ordered. As seen in previous sections, the tank will be 3D printed, allowing customized dimensions and overall shape. Thus, our CAD files will be sent to the Cube at McGill and returned to our team once printed. As such, the flanges are part of the vessel, therefore reduces the number of separate parts in our design. Next, the gasket material will be ordered from the brand 'Small Parts' and delivered through a trusted distributor. The gasket will then be designed on CAD and sent to be machined at McGill. The last few parts of the assembly which are the bolts, washers and nuts will simply be ordered on McMaster-Carr.

7.2. Budget

Table 4 summarizes the costs associated with the purchase and manufacturing of the experimental setup for diffusion coefficient measurement. The table states where each part comes along with the cost. The cost estimate of 3D printed was estimated using a quote from a manufacturing company [18]. The machining budget of 2000$ allocated by McGill University will be respected and the client will have to purchase the other items.

Table 4: Cost of Products to Purchase and Manufacture.

Product	Number of Items	Process	Provider	Total Cost Estimate
Tank	2	3D Printing	McGill Cube	233 $
Rubber (gasket)	2	Purchase (to be machined)	Amazon [19] Machined in McGill Lab	11.25 $ + machining
Hotplate, stir bar & temperature sensor probe	2	Purchase	VEVOR [17]	191.98 $
Bolt	3	Purchase	McMaster-Carr [20]	31.68 $
Washer	3	Purchase	McMaster-Carr [21]	3.43 $
Nut	3	Purchase	McMaster-Carr [22]	3.33 $
Cap	1	Purchase	McMaster-Carr [23]	8.02 $
			Total	**482.69 $**

8. Conclusion and Remarks

In conclusion, this report outlines the main specifications for the design of the testing rig used to measure the diffusion coefficient. Every specification has been justified through diverse calculations, simulations, and careful assumptions. Some of these key analysis tools include finite element analysis (FEA), bolt and gasket stress calculations and heat analysis on the water inside the tank. In the next report, the agitation mechanism will be more thoroughly analyzed. In-depth calculations will be performed to make sure the flow inside the rig mimics the flow inside an artery. We will also further analyze the compatibility between the tank material and the magnetic agitator to ensure the magnetic field can get through the tank material.

9. References

[1] E.L Cussler : *Diffusion Mass Transfer in Fluid Systems,* Cambridge University Press, 2009

[2] See, D. M., White, Ralph E., "A simple Method for Determining Differential Diffusion Coefficients from Aqueous Electrolyte Diaphragm Cell Data at Temperatures Below 0^oC", https://scholarcommons.sc.edu/cgi/viewcontent.cgi?article=1376&context=eche_facpub, 1999.

[3] M. Khaki Jamei, M. Heydari Alashti, M. Abbasi, A. EbrahimNejad, and M. H. Taheri, "Impact of round edge on the duct fluid flow: analytical investigation," SN Applied Sciences, vol. 3, no. 4, Mar. 2021, doi: 10.1007/s42452-021-04434-6.

[4] "Maximum von Mises Stress Criterion - 2022 - SOLIDWORKS Help," *help.solidworks.com*. https://help.solidworks.com/2022/English/SolidWorks/cworks/r_Maximum_von_Mises_Stress_Criterion.htm.

[5] "Epoxy: A Complete Guide," *Copps Industries*. https://www.coppsindustries.com/epoxy-a-complete-guide/#:~:text=In%20general%2C%20the%20tensile%20strength.

[6] "Thermal Conductivity of Epoxy esin Composites Filled with Combustion Synthesized h-BN particles", Chung, Shyan-Lung, Lin, Jeng-Shung, https://www.researchgate.net/publication/303406307_Thermal_Conductivity_of_Epoxy_Resin_Composites_Filled_with_Combustion_Synthesized_h-BN_Particles

[7] "What is the Heat Rating of Epoxy Resin," *Mas Epoxies*. https://masepoxies.com/what-is-the-heat-rating-of-epoxy-resin.

[8] "Epoxy Strengths Compressive Tensile Flexural Bond - Epoxy.com Education," *www.epoxy.com*. https://www.epoxy.com/strength.aspx

[9] "Custom & Standard Rubber Extensions", Elbex. https://www.elbex-us.com/sites/default/files/General%20Properties%20of%20Elastomers.pdf

[10] "5 Things to Consider When Choosing Material For Your Seal or Gasket," *www.jbc-tech.com*. https://www.jbc-tech.com/blog/posts/5-things-to-consider-when-choosing-material-for-your-seal-or-gasket/.

[11] "Gasket & Fastener Handbook", *Lamons Gasket Company*.

[12] "Gasket Factors 'M' and 'Y' 'M' -Maintenance Factor." https://www.goodyearrubberproducts.com/2012pdfs/garlock_fluid_sealing/files/assets/downloads/page0151.pdf

[13] J. Lienhard, "A Heat Transfer Textbook Third Edition." [Online]. Available: http://www.mie.uth.gr/labs/ltte/grk/pubs/ahtt.pdf

[14] "1.4B: Controlled Boiling," Chemistry LibreTexts, Aug. 11, 2020. https://chem.libretexts.org/Courses/SUNY_Oneonta/Chem_221%3A_Organic_Chemistry_I_(Bennett)/2%3ALab_Textbook_(Nichols)/01%3A_General_Techniques/1.04%3A_Heating_and_Cooling_Methods/1.4B%3A_Controlled_Boiling#:~:text=Stirring%20is%20often%20used%20with

[15] K. K. Altarawneh, "THE EFFECT OF STIRRING ON DIFFUSION MEASUREMENTS USING THE DIAPHRAGM CELL SETUP," Special Topics and Reviews in Porous Media: An

International Journal, vol. 6, no. 4, pp. 403–410, 2015, doi: 10.1615/specialtopicsrevporousmedia.v6.i4.70

[16] M. Loos, “Chapter 6 - Processing of Polymer Matrix Composites Containing CNTs,” ScienceDirect, Jan. 01, 2015. https://reader.elsevier.com/reader/sd/pii/B9781455731954000060?token=12E5187B5488D23D15A0EDA7CF7741D4A36EFE8808286B7551FF34F5FCE24B33CE6A59B5BA82C9ED2EB55D73960D9836&originRegion=us-east-1&originCreation=20221123204312).

[17] “VEVOR Magnetic Stirrer Hot Plate Digital Hotplate Magnetic Stirrer 2000 RPM 2L | VEVOR CA,” Vevor. https://www.vevor.ca/magnetic-stirrer-c_11062/vevor-magnetic-stirrer-hot-plate-digital-hotplate-magnetic-stirrer-2000-rpm-2l-p_010525136888?gclid=CjwKCAiApvebBhAvEiwAe7mHSNJvx0NeAVf_E0e7Pm8KDfoz5yJaGHnEpiQPXxLkezToiacUkWu7jBoCQ-AQAvD_BwE.

[18] “Hubs | On-demand Manufacturing: Quotes in Seconds, Parts in Days,” *Hubs*. https://www.hubs.com/?fbclid=IwAR12T3WD9iKi_FB5YuCuDencGqsrP2RA0kWqyaoIv-8MbtwwVxJoHWcql7I.

[19] “33-014-062-012-012 Pure Gum Rubber, 40A Durometer, Smooth Finish, No Backing, 0.062" Thickness, 12" Width, 12" Length, Tan : Amazon.ca: Industrial & Scientific,” *www.amazon.ca*. https://www.amazon.ca/33-014-062-012-012-Rubber-Durometer-Backing-Thickness/dp/B00P5VVCVK.

[20] “McMaster-Carr,” *www.mcmaster.com*. https://www.mcmaster.com/bolts/hex-head-screws-4/system-of-measurement~metric/length~16-mm/thread-size~m4/?fbclid=IwAR0y0APQuKrRNDQYNk7Su1lmyuR8qnXpFOq0o8bhK6rHl74-5Rkj3B3NmAw.

[21] “McMaster-Carr,” *www.mcmaster.com*. https://www.mcmaster.com/98689A113/?fbclid=IwAR3cydbC796jaHT54whlFTSpcKbXPUj_081ootixml_RG6Ac_Fk9azNGHAc.

[22] “McMaster-Carr,” *www.mcmaster.com*. https://www.mcmaster.com/90592A090/?fbclid=IwAR22MHJQ4XkSO5zW2vKhoF0vn6DsTLq9h-g2rc80iPfoR9s56ONsW2HOKbA.

[23] “McMaster-Carr,” *www.mcmaster.com*. https://www.mcmaster.com/1277K23/?fbclid=IwAR1bK0NAsMNdUCLO3nYIkgU21Y5hgdw_TGlLu3dSb9Yi3LFQRdlim8gVKmk.

10.Appendix

Table 5: Specifications of the Digital Hotplate Magnetic Stirrer [17].

Model	SH-3ABE1	Voltage	110V
Power	500W	Stirring Capacity	2L
Stirring Speed	200-2000 RPM Adjustable	Maximum Heating Temperature	572°F / 300°C
Permissible Temperature	122°F-608°F / 50°C-320°C	Temperature Display Accuracy	±0.1°C
Display	LED	Motor Rating Input	3W
Motor Rating Output	2.5W	Weight	5.5 lbs / 2.5 kg
Stirring Bar Size	2.2" x 0.4" / 5.5 x 1 cm	Heating Plate Size	6.7" x 6.7" / 17 x 17 cm
Size	7.1" x 12" x 5.5" / 18 x 30.5 x 14 cm	Certification	CE