Design and Model Optimization of Cross-Media Fiber Heat Exchanger (CHX)

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Introduction and Motivation:

This document is an internship report discussing the optimization of the design and model of the Cross-Media Fiber Heat Exchanger, also known as CHX. The CHX is a novel heat exchanger that utilizes polymers as the main structure and/or fluid channels and high conductivity metallic fins as the heat transfer surfaces. The CHX is better than the standard finned heat exchangers in being more thermally efficient, cost effective and lighter in weight [1].

It becomes important to further optimize its features for better performance in the industry. The design needs to be optimized to make it lighter, stronger and more thermally efficient. Various materials need to be explored and checked for compatibility and the performance of the CHX before it is actually 3D printed. This project work involves both experimental as well as computational work to accomplish the goal.

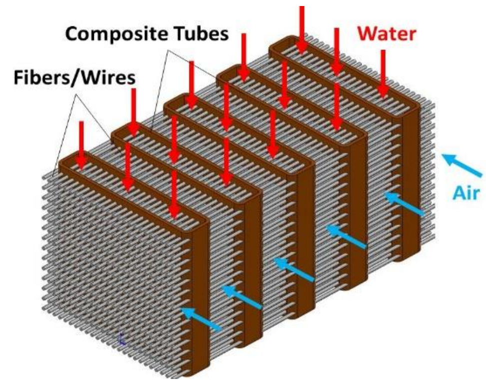


Figure 1: Element of Water-Air Cross-Media Fiber Heat Exchanger [1]

Polymer Database:

The unit cell of a CHX is made up of metal fiber, a polymer wall and a coating layer. The high conductivity metal fiber acts as a bridge for heat transfer between the two fluid channels without any physical connections between the channels. The polymer wall provides mechanical stability and a barrier to separate the two fluid channels. The coating has multiple roles. It acts as a complementary adhesive to join the metal fiber and the polymer wall, make the structure defect free by blocking all the cracks and adding to the mechanical strength and stability of the CHX.

The materials to be used for the fiber, wall and the coating need to be decided. The potential candidates are compiled in Appendices 1-4 with all their physical, mechanical and thermal properties. Out of all the properties, the most important properties are:

1. Density
2. Young's Modulus
3. Poisson's Ratio
4. Tensile Yield Stress
5. Tensile Ultimate Stress
6. Coefficient of Thermal Expansion, Linear

The wall material candidates can be bought from the company, 3DXTECH.

The experiments were performed using Polyurethane as the coating and the results compiled and compared to the desired outcomes (discussed in the next section). However, Parylene C is the best choice for the coating (discussed in later sections). VSI Parylene is the company which can deposit the coating onto the heat exchanger samples by a technique called chemical vapor deposition (CVD) at the desired thickness. The polyurethane was originally dip coated onto the samples but CVD is preferred because it is capable of creating thin polymer coats of uniform thickness. Coating thickness of the polymer deposited using dip coating cannot be controlled to a large extent and strongly depends on the human efficiency. Hence to get a coating thickness of 40-50 microns, CVD is the best option.

Arrhenius Model- Age Prediction:

Reliability Tests:

The reliability test is the determination of the effect that the exposure to heated water has over time on the pressure containment of the vessel. This can be used to determine the lifetime of the heat exchanger samples under any desired service temperature.

The small heat exchanger samples were printed using 3D printing by a 2nd generation 3D printer. The wall material was ABS and the fiber was Al 6061. The samples were then dip coated with polyurethane. Polyurethane acts as an adhesive to bond the fiber and the wall firmly and enhance the mechanical strength. Four coatings of polyurethane were applied thus resulting in a total thickness of 40 microns. The samples were then left to dry to ensure that the coating has been cured. They were then divided in three batches and were subjected to temperatures of 60°C, 70°C and 80°C respectively. A number of samples, nine per group, were removed from the oven after a fixed interval (72 hours). Small metal rods were stuck in them using epoxy as channels for water inlet. They were then tested for their degradation by measuring the pressure handling capacity using the static pressure pump shown in Figure 2. The average pressures at which the air and water side coatings of the aged samples broke and the water leaked out were noted. This concludes the experimental part of the reliability tests. The next section on the Arrhenius Model Prediction covers the analysis of the pressure data gathered by conducting these tests.

Refer to the Appendix 5 for the complete procedure to conduct the above experiment.

Refer to Appendix 8 for the pressure data gathered from the reliability test.

Figure 2: The static pressure pump along with the heat exchanger samples beside it

Arrhenius Model Prediction:

An Arrhenius model analysis was done to predict the lifetime of the heat exchanger samples [2].

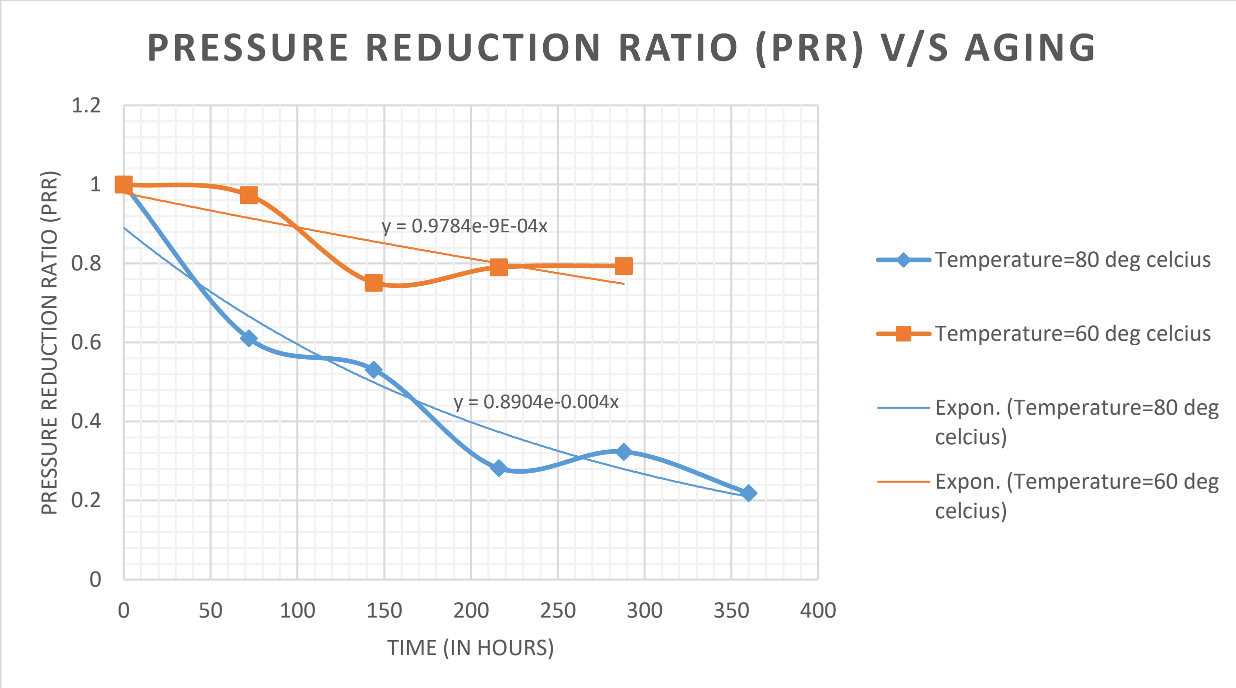


Figure 3: PRR v/s the time the samples were aged at different temperatures

We can use the trendline equations in Figure 3 and find the time taken to reach a particular degradation level (PRR) at the desired service temperature.

Steps to calculate the lifetime of a sample:

1. Calculate the Pressure Reduction Ratio (PRR) for the averaged data (Appendix 8) at a particular temperature. It can be calculated using the formula:
   $$PRR = \frac{\text{Pressure handling capacity after aging at a particular temperature}}{\text{Original pressure handling capacity of the unaged sample}}$$
2. Plot the PRR values against the aging time to obtain the graph in Figure 3
3. Plot an exponential trendline for the data
4. Decide the degradation ratio. We considered a PRR of 0.1 which means that any sample whose PRR was less than 0.1 was assumed degraded
5. Use the trend line in Figure 3 to calculate the times at which we get a PRR of 0.1 for both the temperatures. These are the time taken for the samples to degrade
6. Calculate ln(1/time to degrade) and 1/temperature (time is in hours and temperature is in K)
7. Plot the corresponding points to obtain the graph in Figure 4
8. Take the inverse of the service temperature (in K) and calculate the value of ln(1/time to degrade) from the equation of the line in Figure 4 corresponding to PRR=0.1
9. Find the value of time taken to degrade at this service temperature

Sr. No.	PRR	Temperature (in °C)	Time taken to degrade (in days)
1	0.1	40	595.82
2	0.1	60	105.59
3	0.1	70	47.98
4	0.1	80	22.78

Table 1: Lifetimes of samples, corresponding to PRR=0.1, at different service temperatures

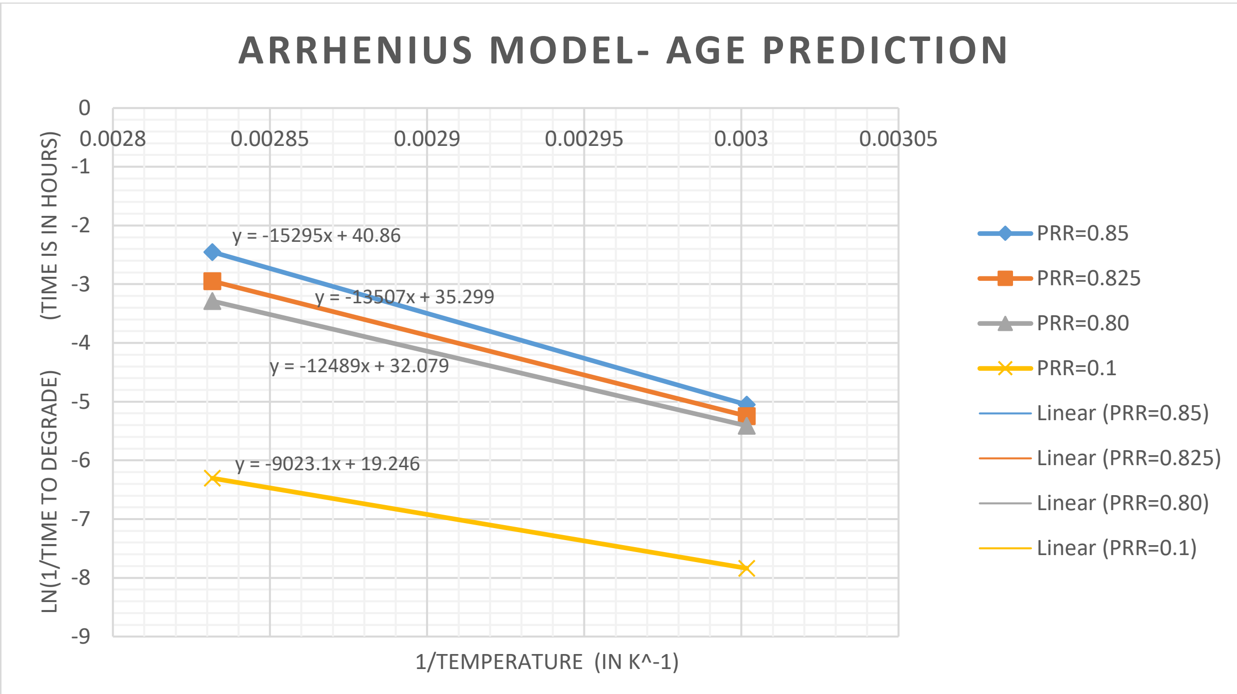


Figure 4: Arrhenius Plot to predict the Lifetimes (corresponding to different PRR)

Note: It can be seen that only the data corresponding to temperatures 60°C and 80°C are plotted in Figure 3. This is because the data corresponding to 70°C showed abnormal behavior. The PRR should decrease down from unity as time progresses but that was not observed so it was decided to reject the particular data set. The random variation was observed because the coating was not properly applied on the samples. The initial coating thickness was too large and not enough time was given for it settle on the samples before the second layer of coating was applied. So the control samples were relatively weaker than the aged samples because the coating had not been cured. But the aged samples held a larger pressure because the coating got enough time to cure before the samples were tested. Also, the coating was not applied uniformly on all the samples which resulted in random behavior of PRR.

ANSYS Simulations:

Simulations were done using the ANSYS "Static Structural" Analysis System. It is necessary to conduct simulations to choose the materials to be used for printing the CHX, and determine the optimum dimensions of the model to ensure appropriate stress handling capacity before the new modified samples are actually printed and tested using the reliability test discussed in the above section. Conducting experiments is both time consuming and costly, so it was easier to perform the simulations first in ANSYS.

The properties of the potential candidates for wall, coating and fiber materials (Appendices 1-4) were used and fed into the Engineering Database of Static Structural.

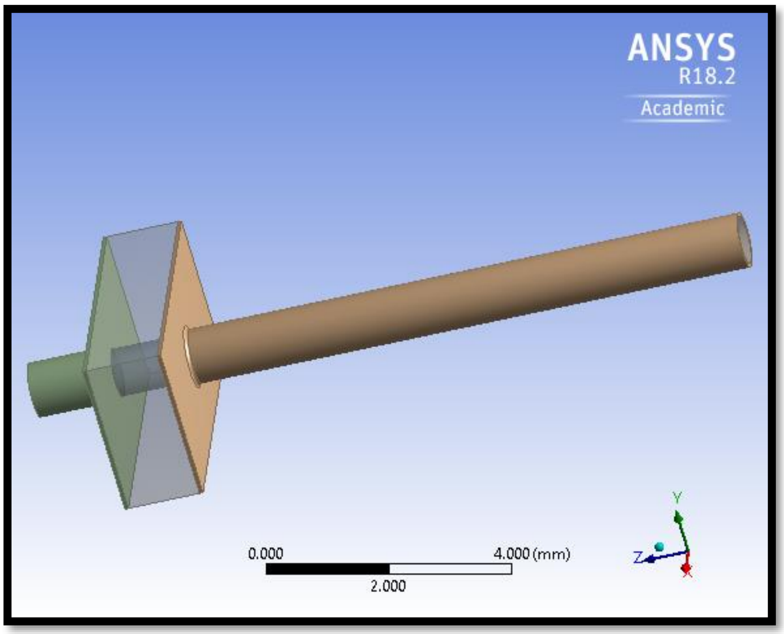


Figure 5: Unit cell designed in the "Design Modeler"

A single unit cell of the heat exchanger was designed in the "Design Modeler" with the dimensions being parametrized. Appropriate boundary conditions were applied and the materials for the wall, coat and fiber were chosen in the "Mechanical".

Initial dimensions:

Sr. No.	Properties	Dimension (mm)
1	Wall thickness	1.5
2	Coating thickness	0.05
3	Water side fiber length	2
4	Air side fiber length	10
5	Fillet radius	0.05
6	Fiber Diameter	0.8

Table 2: Initial dimensions of the Unit Cell

These dimensions were later varied to observe their effect on the stresses in the structure. The parametric study is explained in Appendix 9.

General Boundary Conditions:

1. Gauge Pressure on Water side= 450 psi (3.1 MPa)
2. Temperature of the entire unit cell= 70℃
3. Fixed support at the midpoint of the fiber's water side face
4. Symmetry- 6 identical units were assumed to be placed around symmetrically

Stress probes were placed on the water and air side coating, fiber-coating interface, wall-coating interface and 10 microns inside the coating to measure the maximum equivalent Von-Mises stress.

The initial simulations aimed towards determining the materials of the wall, fiber and coating. Changes in stresses were observed by changing the Young's modulus of the wall and coat material.

Wall Material Determination:

Conditions for the simulations:

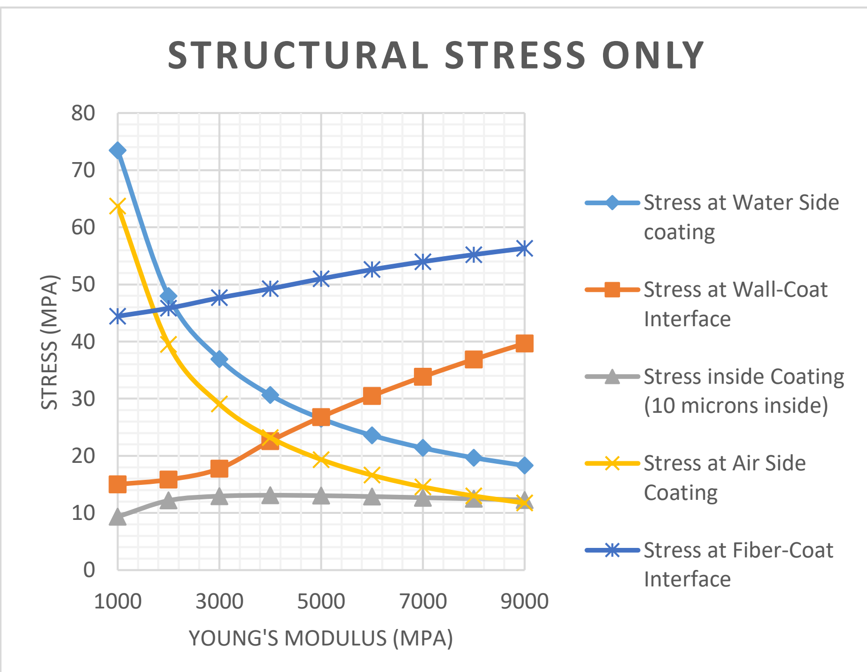
1. Wall thickness: 1.5 mm
2. Coating thickness: 50 microns
3. Coating is Parylene C
4. Fiber is Aluminum 6061
5. Gauge Pressure: 450 psi (for structural stress)
6. Temperature of the entire unit cell: 70°C (for thermal stress)

The following table helps in deciding which yield tensile limit to consider the rupturing of the wall, coat or fiber interface(s).

Stress	Material whose Yield Tensile Strength needs to be considered
Stress at Water Side Coating	Coating
Stress at Air Side Coating	Coating
Stress inside Coating	Coating
Stress at Wall-Coat Interface	Wall
Stress at Fiber-Coat Interface	Fiber

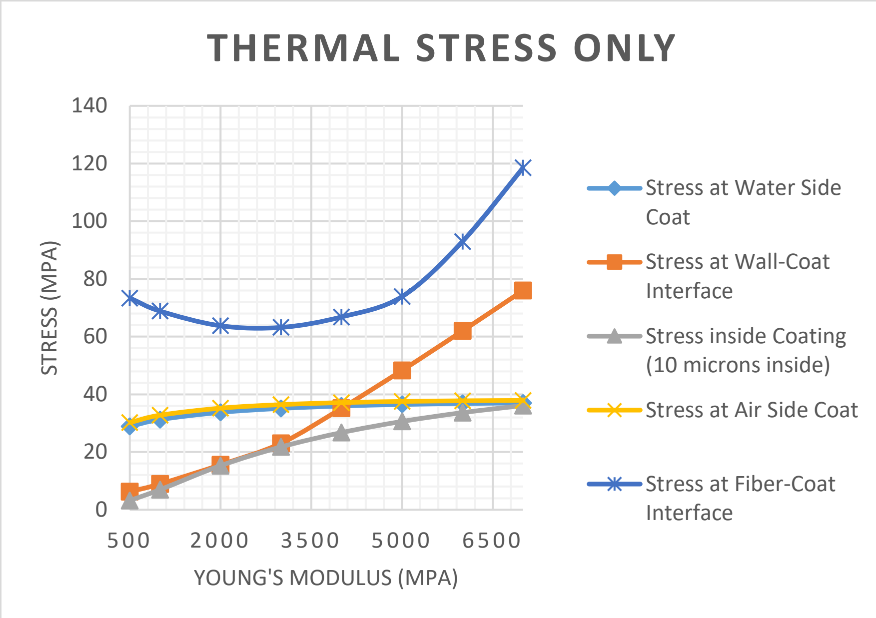
Table 3: Material whose Yield Tensile Strength needs to be used to determine stress handling capacity

The following 3 Figures depict the variation of stress with change in Young's modulus of the wall.



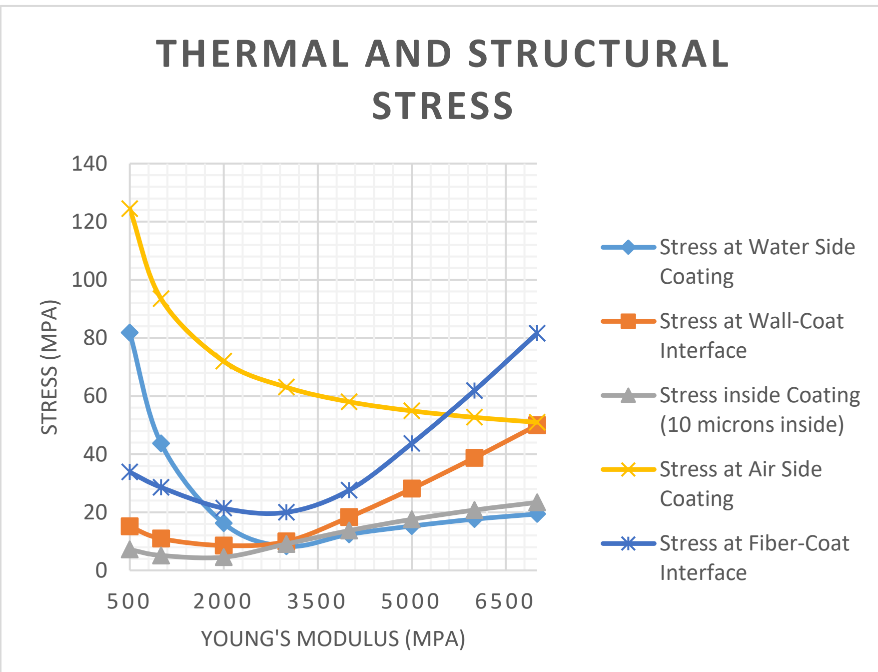
Structural Stress Only- The yield tensile strength of the coating and the wall materials are between 50-55 MPa typically and that of Aluminum fiber is 276 MPa. So, it needs to be ensured that the stress at the water side coating, air side coating, inside the coating and wall-coat interface is below 55 MPa. It can, therefore, be concluded that a material whose Young's Modulus greater than 2000 MPa should be used to avoid rupturing the air side and the water side coating.

Figure 6: Stress Analysis by varying Young's Modulus of the Wall under "Structural Stress Only"



Thermal Stress Only- From the Figure 7, it can be seen that the stresses increase with increase in Young's modulus. However, the stress in the coating remains way below the limit at all times. It is, therefore, suggested to use a material whose Young's Modulus is below 5000 MPa to avoid rupturing the wall-coat interface as the wall will typically yield at around 55 MPa.

Figure 7: Stress Analysis by varying Young's Modulus of the Wall under "Thermal Stress Only"



Thermal and Structural Stress: From the Figure 8, it can be recommended that the preferred material is the one with Young' modulus greater than 5000 MPa to avoid rupturing the air side coating. The other stresses are way below their limits. The best material choice would be PSU because it has a Young's Modulus of 7300 MPa, a high enough yield tensile strength (52.8 MPa), high glass transition temperature (185°C) and is cost effective compared to other polymers.

Figure 8: Stress Analysis by varying Young's Modulus of Wall under "Thermal and Structural Stress"

Fiber Material Determination:

The wall material decided for the use is PSU. The next task is choosing the fiber material. The fiber needs to be a high conductive material so Aluminum and Copper are considered. After running the simulation, comparison between Aluminum and Copper shows that the structure experiences a similar stresses in both the situations. So Aluminum should be used for applications where weight is an important factor as Aluminum (density: 2.7 g/cc) is much lighter than Copper (density: 8.93 g/cc). Copper should be used where space and compactness is an important factor as its thermal conductivity is more than twice that of Aluminum.

	Aluminum 6061	**Copper**
Stress at Water Side Coating	10.883 MPa	11.91 MPa
Stress at Wall-Coat Interface	31.998 MPa	35.867 MPa
Stress inside Coating (10 microns inside)	15.929 MPa	18.021 MPa
Stress at Air Side Coating	66.547 MPa	66.62 MPa
Stress at Fiber-Coat Interface	59.89 MPa	67.365 MPa

Table 4: Stress Comparison between Aluminum 6061 and Copper

Conditions for the simulation:

1. Wall: PSU; Coating: Parylene C
2. Wall Thickness: 1 mm; Coating Thickness: 40 µm
3. Hydrostatic Gauge Pressure: 450 psi; Temperature of the unit cell: 70℃

Coating Material Determination:

Parylene, acrylic and epoxy are preferred over other polymers as they have low Coefficient of Thermal Expansion (CTE). It is desired to have a coating with low CTE to ensure low expansion and thus inducing less stress in the structure. However, the melting point of acrylic is too low between 85℃-105℃. Hence, it is not an ideal choice too. Simulations are run to study the effect of change in Young's Modulus on the stress induced at no thermal stress.

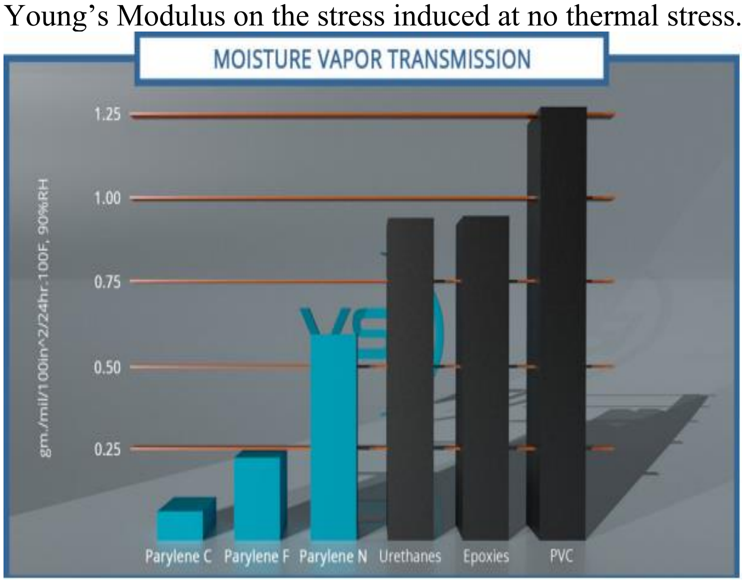


Figure 9: Comparison of Moisture Vapor Transmission [5]

It can be concluded from Figure 9 shows that a material whose Young's modulus is greater than 1000 MPa should be preferred to avoid rupturing of the Wall-Coat Interface. The fiber can handle much higher stresses so the stress at the fiber-coat interface is not an issue. Parylene is a better choice over epoxy because it has a lower moisture vapor transmission which is necessary as we are dealing with water as one of our fluid channels and want to minimize the water transmission to avoid corrosion of wall and fiber.

Among the different Parylene polymers, Parylene C would be the preferred one. Parylene D has poor distribution in the deposition process. Parylene F has a slower deposition and has costly raw material. Parylene N is molecularly more active than Parylene C during the deposition process, which results in slower deposition, thus increasing the machine costs for thick layers [5]. Hence, the ideal choice would be Parylene C as it has a high enough Young's Modulus, Yield Tensile Strength, and low Coefficient of Thermal Expansion.

Conditions for the simulation:

1. Wall: PSU; Fiber: Al 6061
2. Wall thickness: 1.5 mm; Coating thickness: 50 microns
3. Gauge Pressure: 450 psi; No thermal stress

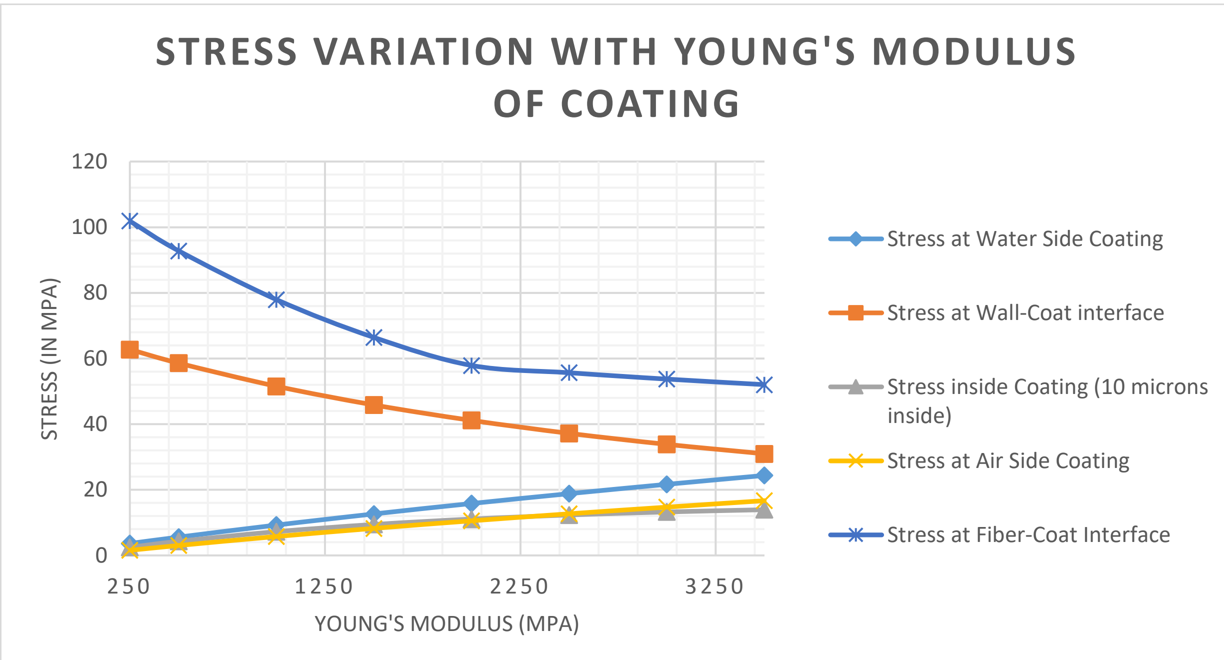


Figure 10: Stress variation with Young's Modulus of the Coating under Structural stress only

Design Optimization:

Once the materials are decided, the next task is to optimize the design dimensions.

Wall and Coating Thickness

The design is first optimized by varying the coating and the wall thicknesses and observing the interaction effect by using the 2 factorial design method. This method is used when optimizing a particular parameter, stress in this case, with respect to two parameters, wall and coating thickness for our case.

The range of wall thickness considered is: 1 mm - 1.5 mm
The range of coating thickness considered is: 30 microns – 60 microns

The MATLAB code to obtain the interaction equations for various stresses and generate the following graphs in Figures 11, 12 and 13 is in Appendix 10.

Results:

1. With Structural Stress only (Figure 11) – It can be concluded that the more the thicknesses, the less is the stress.
2. With Thermal Stress only (Figure 12) – It can be concluded that the more the wall thickness, the more the stress observed. This seems justifiable as more the thickness, more will be the elongation due to the rise in temperature and hence more is the stress induced. The increase in coat thickness, however, helps reduce the stress.
3. With Thermal and Structural Stress (Figure 13) - It is seen that a coating thickness of 40 microns and wall thickness of 1 mm should have a stress of around 55 MPa at the air side coating. The water side does not experience a breaking stress for the given range of wall and coating thickness. Hence, it can be concluded that wall thickness of 1mm and coating thickness of 40 microns is the best design as we want our design to survive pressures just up to 450 psi.

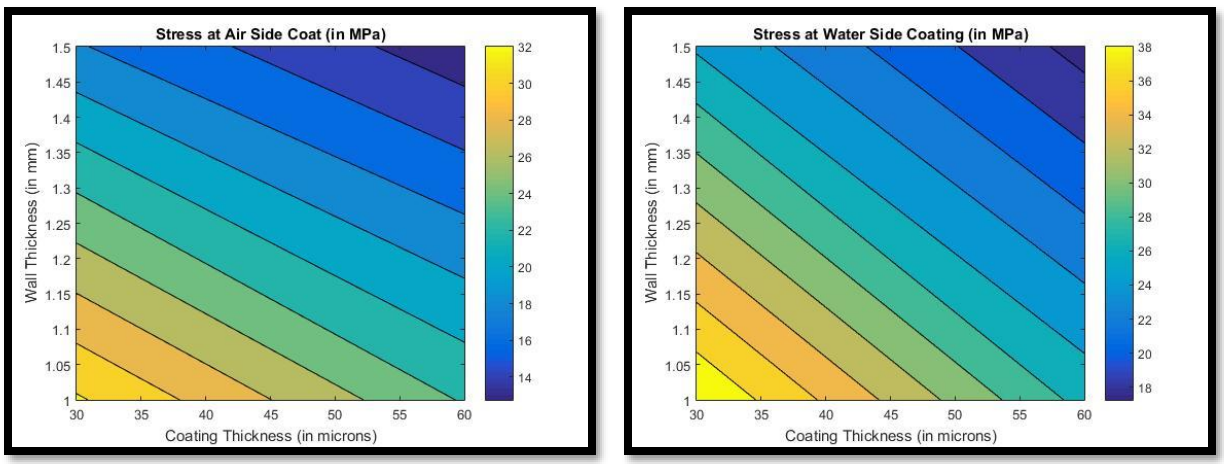


Figure 11: Only Structural Stress

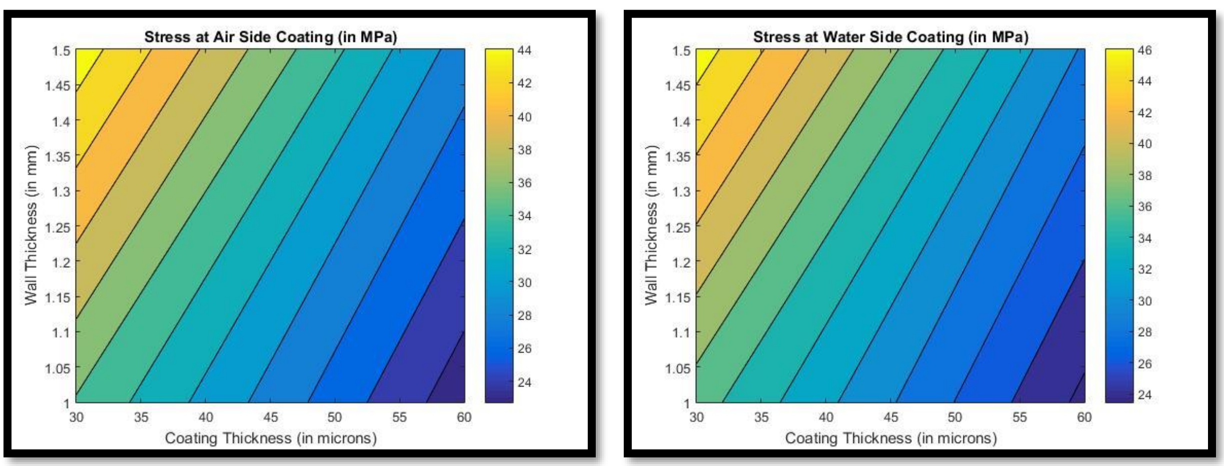


Figure 12: Only Thermal Stress

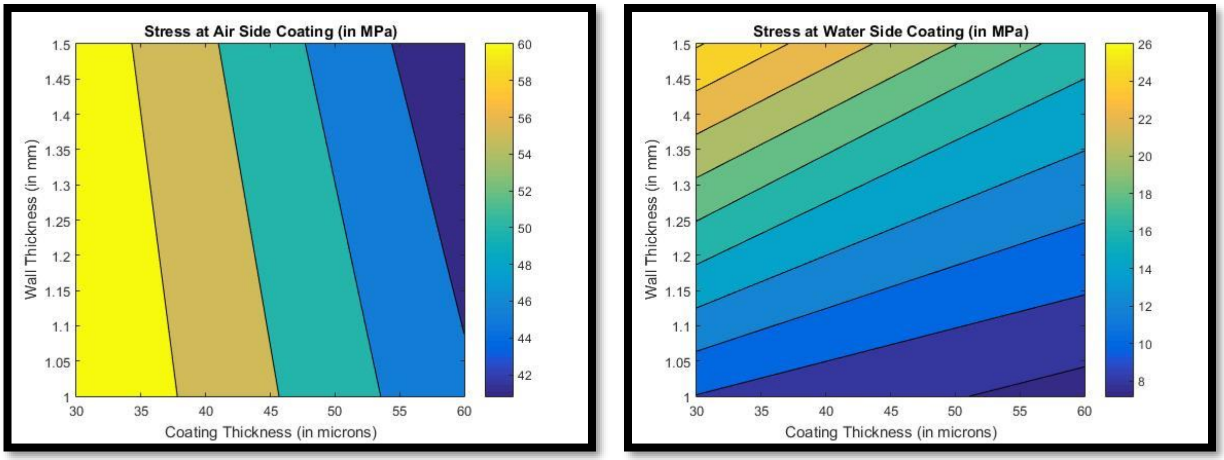


Figure 13: Both Thermal and Structural Stress

Fiber Diameter:

The next task after deciding upon the wall and coating thickness is to optimize the fiber diameter subject to thermal and hydrostatic stresses. The wall dimensions change according to the fiber diameter. The wall width/fiber diameter ratio is constant at 6 and wall height/fiber diameter is constant at 3.25.

Conditions for the simulation:

1. Wall Thickness: 1 mm; Coating Thickness: 40 microns
2. Wall: PSU; Coating: Parylene C; Fiber: Al 6061
3. Gauge Pressure: 450 psi; Temperature of the unit cell: 70°C

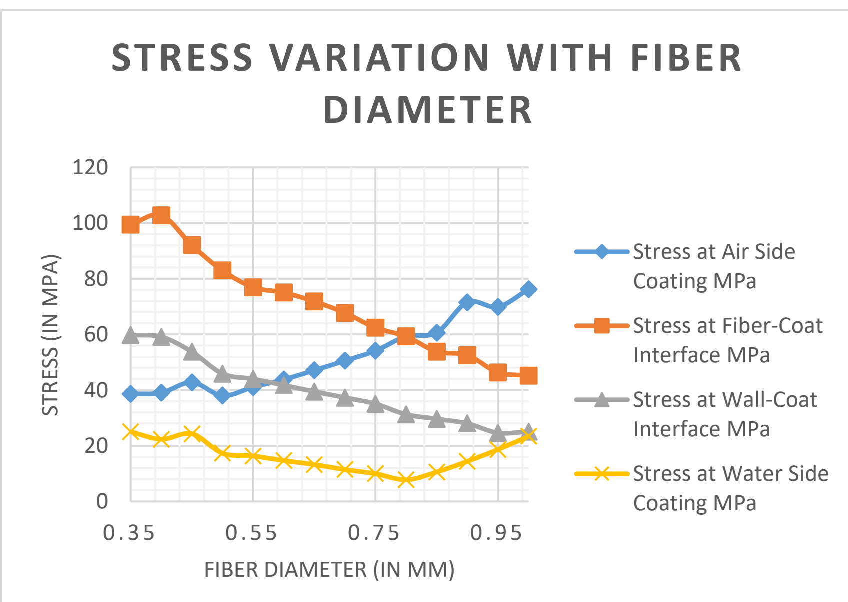


Figure 14: Variation of stresses with fiber diameter

It is advised to use a fiber with a diameter less than 0.75 mm to avoid rupturing the air side coating. The PSU wall fails at 52.8 MPa so the recommended fiber diameter is between 0.50 mm to 0.75 mm. Although reducing the fiber diameter reduces the heat transfer through one fiber, we can fit more unit cells in the same space with reduced fiber diameter (as the wall dimensions also decrease with fiber diameter). So, the ideal diameter is 0.5 mm.

Variable Hydrostatic Pressure at a Constant Temperature of 70℃:

It becomes important to study the effect of hydrostatic pressure on the stresses experienced by the structure as the CHX will not always be subjected to such a high pressure of 450 psi.

Conditions for the simulation:

1. Wall is PSU
2. Coating is Parylene C
3. Fiber is Al 6061
4. Temperature of the unit cell: 70℃
5. Wall thickness: 1.2 mm
6. Coating thickness: 60 microns

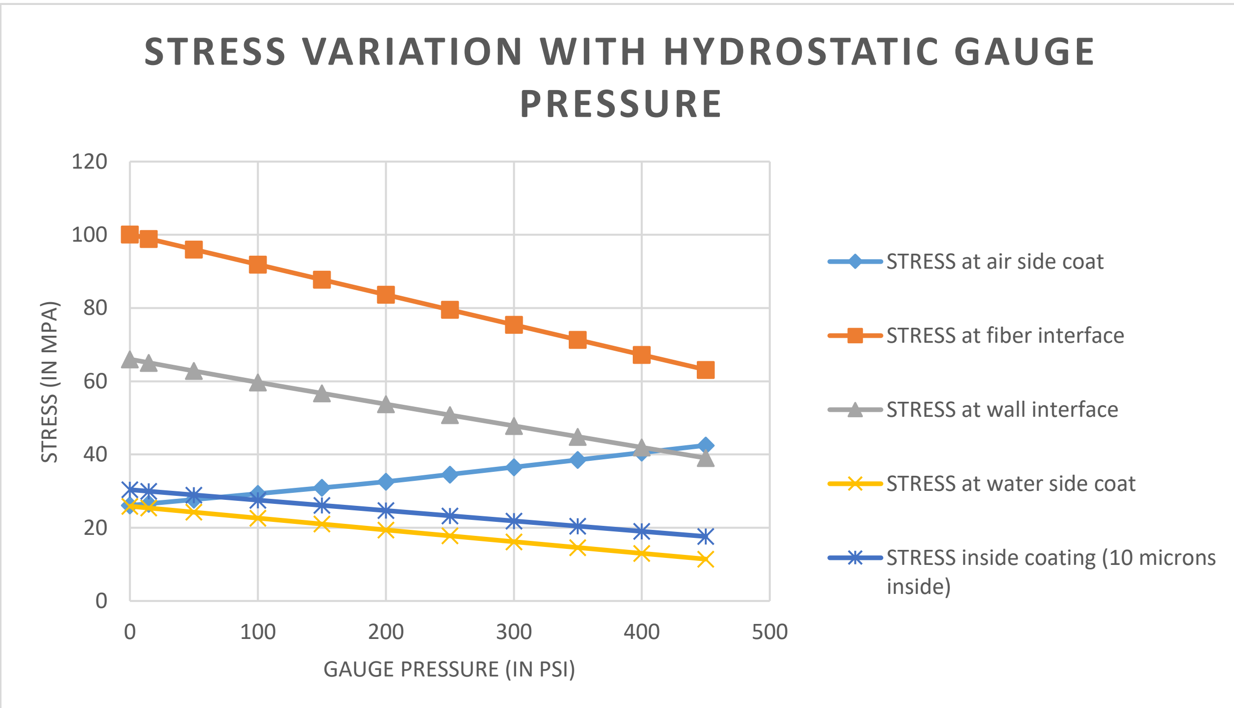


Figure 15: Stress variation with variable hydrostatic pressure and a fixed temperature

It can be seen in Figure 15 that all the stresses (except on the air side coating) decrease on increasing the hydrostatic gauge pressure. The possible explanation can be: the fiber, the wall and the coating expand due to the increase in temperature but the hydrostatic pressure on the water side prevents their free expansion. So, the net elongation is less than that without the hydrostatic pressure. The air side coating experiences a greater stress to compensate for this relaxation on the water side.

Model Recommendation:

Property	Recommended Material/Dimension
Wall	PSU
Coating	Parylene C
Fiber	Aluminum 6061/Copper (depending on the requirement)
Wall Thickness	1 mm
Coat Thickness	40 µm
Fiber Diameter	0.50 mm

Table 5: Recommended Dimensions for the Unit Cell

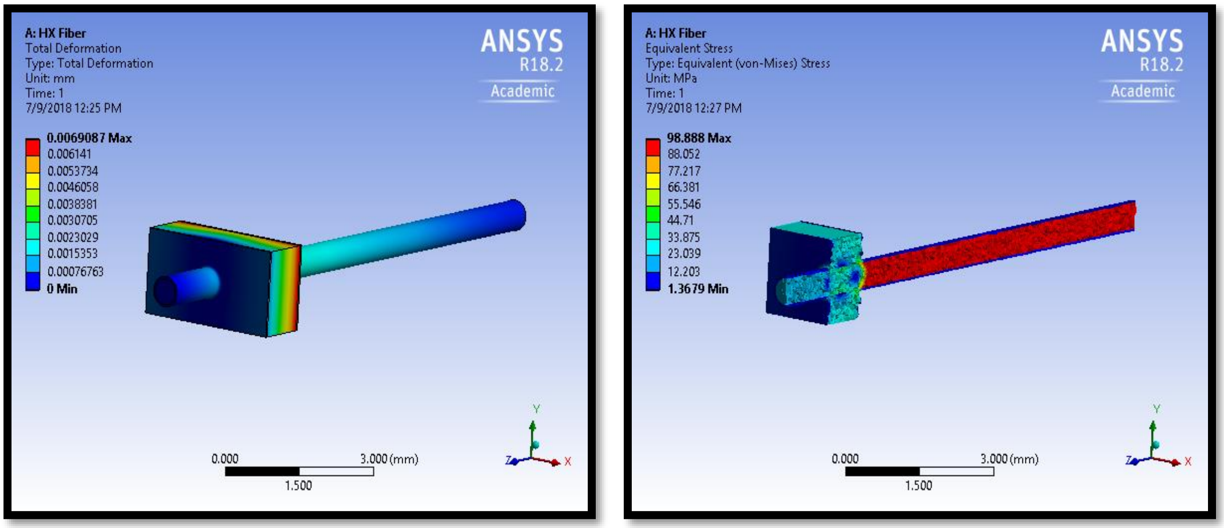


Figure 16: Total Deformation and Equivalent Stress under both Thermal and Structural Stress

It can be concluded from Figure 16 that the major stress lies inside the fiber, which it is capable of holding. The deformation of the structure is in microns with the major deformation being at the wall.

Conditions for the simulation:

1. Wall: PSU; Coating: Parylene C; Fiber: Aluminum 6061
2. Gauge Pressure: 450 psi; Temperature of the unit cell: 70°C
3. The dimensions are the ones which are recommended in the Table 5

3rd Generation 3D Printer:

The samples are printed using the 2nd Generation 3D Printer. It is a slow printer and hence takes a lot of time to print one batch. A faster and more efficient machine would save a lot of time and efforts. This machine is the 3rd Generation 3D Printer. The work to setup the printer is currently in progress. The original components of the printer were made up of a material called polylactide (PLA). It has a glass transition temperature of 60°C, so all the parts of the printer needed to be replaced by Ultem, which has a higher glass transition temperature of over 200°C, because the service temperature is over 60°C. The electronic circuits also had to be rewired. The current limit of the stepper motor drivers was also set up to avoid supplying excess current to the stepper motors and thus unnecessarily heating them up. The current limit was set to 1.3 A.

Experimental Setup:

The final task after printing the CHX using the 3rd Generation 3D printer will be to experimentally test the heat exchanger for thermal efficiency. The structural efficiency will be checked with the reliability tests discussed previously. An experimental setup is currently being built to test the parameters like pressure drop, heat transfer, heat transfer per unit mass flow rate, etc. through the CHX. Various parts like pressure transducers, air mixing chambers, steam pressure regulators, small heat exchangers, motor pumps, etc. were researched on the internet and bought to build the setup.

References:

[1] Hymas, D. M. (08-24-17). Invention Disclosure CHX and MFC

[2] Koerner, R. M., Lord, A. E., & Hsuan, Y. H. (1992). Arrhenius modeling to predict geosynthetic degradation. *Geotextiles and Geomembranes, 11*(2), 151-183. doi:10.1016/0266-1144(92)90042-9

[3] MatWeb http://www.matweb.com/

[4] 3DXTECH https://www.3dxtech.com/

[5] VSI Parylene: https://vsiparylene.com/

[6] Wikipedia: https://www.wikipedia.org/

Appendix 1:

Name of polymer	Glass Transition Temp	Melt Temp	heat deflection temperature (66 psi)	heat deflection temperature (261 psi)	CTE Linear	Thermal Conductivity at 25 °C	Continuous Use Temperature (CUT)	Extruder temp	Enclosure temp	Bed temp
PEKK (PolyEtherKetoneKetone)	162°C	335°C	-	164 °C	39.7 µm/m-°C	0.25 W/m-K	260°C	345 - 375°C	70 - 150°C	120 - 140°C
PEEK	143°C	343°C	309 °C	295 °C	30.4 µm/m-°C	1.14 W/m-K	240 - 260°C	380 - 410°C	70 - 150°C	130 - 150°C
PEI (Polyether Imide)	186°C-217°C	367 °C	208 °C	201 °C	36.0 µm/m-°C	0.344 W/m-K	199 °C	350 - 380°C (all-metal extruder)	warm to hot environment (185°C)	140 - 160°C
PPSF/PPSU (Polyphenylsulfone)	220°C	367 °C	216 °C	205°C	88.0 µm/m-°C	0.297 W/m-K	307 °C	360 - 390°C (all-metal extruder)	heated enclosure or in a warm build	140-160°C
PSU (Polysulfone)	185°C	348 °C	189 °C	175°C	47.5 µm/m-°C	0.268 W/m-K	299 °C	350 - 380°C (all-metal extruder)	heated enclosure or in a warm build	140-160°C
PPS (Polyphenylene Sulfide)	85°C	285°C	-	136 °C	53.3 µm/m-°C	0.297 W/m-K	-	315 - 345°C (all-metal extruder)	60 - 90°C	120 - 160°C
PVDF (Polyvinylidene fluoride)	-36.4 °C	165 °C	113 °C	83.6 °C	135 µm/m-°C	0.193 W/m-K	150°C	245-265°C	-	90 - 110°C
Polycarbonate (PC)	147°C	286 °C	93.0 - 174 °C	85.0 - 230 °C	68.3 µm/m-°C	0.204 W/m-K	-	280-310°C	Recommend using a printer with an enclosure	110 - 120°C
Polycarbonate + Acrylonitirle Styrene Acrylate Alloy PC/ASA	126	255 °C	113°C	85.0 - 122 °C	81.8 µm/m-°C	0.173 W/m-K	-	260 – 280°C	Recommend using a printer with an enclosure	110 - 120°C
polycarbonate + acrylonitrile butadiene styrene PC/ABS	137	235 °C	126°C	99.0 °C	71.4 µm/m-°C	0.234 W/m-K		270 – 290°C	Recommend using a printer with an enclosure	110 - 120°C

Table 1: Thermal properties of material candidates for Wall [3] [4] [5] [6]

Appendix 2:

Name of polymer	Density	Young's Modulus	Poisson's ratio	Shear Modulus	Yield Tensile Strength	Ultimate Tensile Strength	Shear Strength	Hardenss Rockwell M
PEKK (PolyEtherKetoneKetone)	1.30 g/cc	4.07 GPa		1.44 GPa	-	103 MPa	-	86.0 - 88.0
PEEK	-	24.9 GPa			342 MPa	385 MPa	128 MPa	90.0 - 125
PEI (Polyether Imide)	-	8.68 GPa			115 MPa	130 MPa	78.5 MPa	85.0 - 118
PPSF/PPSU (Polyphenylsulfone)	1.29 g/cc	2.51 GPa	0.40	0.645 GPa	70.4 MPa	70.9 MPa	46.9 MPa	80.0 - 86.0
PSU (Polysulfone)	1.24 g/cc	7.30 GPa	0.417	-	52.8 MPa	86.6 MPa	62.1 - 68.9 MPa	68.0 - 92.0
PPS (Polyphenylene Sulfide)	-	3.65 GPa	-	-	-	149 MPa	-	84.0 - 95.0
PVDF (Polyvinylidene fluoride)	-	1.62 GPa	-	-	44.3 MPa	168 MPa	-	62.0 - 115
Polycarbonate (PC)	1.21 g/cc	2.41 GPa	0.3	-	62.4 MPa	61.3 MPa	-	65.0 - 118
PC/ASA (Polycarbonate + Acrylonitirle Styrene Acrylate Alloy)	1.15 g/cc	2100 MPa	0.332	-	57.1 MPa	52.9 MPa	-	-
PC/ABS (polycarbonate + acrylonitrile butadiene styrene)	1.14 g/cc	2200 MPa	0.3		56.5 MPa	53.2 MPa		72.0 - 97.0

Table 2: Mechanical properties of material candidates for Wall [3] [4] [5] [6]

Appendix 3:

Name of Polymer	Melting point	Coefficient of thermal expansion	Thermal Conductivity at 25ºC (W/m/K)	Young's modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Ultimate Tensile Strength (MPa)	Coefficient of friction	Density (g/cc)
PTFE polytetrafluoroethylene	285 - 300 °C	150 µm/m-°C	-	0.5	-	23	28.0	0.05–0.10	2.2
Parylene C	290ºC	35 ppm/ºC at 25ºC	0.08	2.8	0.4	55.2	69	0.29 static and dynamic	1.289
Parylene N	420ºC	69 ppm/ºC at 25ºC	0.13	2.4	0.4	42.1	48	0.25 static and dynamic	1.11
Parylene F	435ºC	45 ppm/ºC at 25ºC	0.1	3	0.4	52	55	0.35 static 0.39 dynamic	1.652
Parylene D	380ºC	38 ppm/ºC at 25ºC	-	2.62	0.4	62.05	76	0.33 static 0.31 dynamic	1.418
Parylene AF4	>500ºC	36 ppm/ºC at 25ºC	0.1	2.55	0.4	34.47	52	0.15 static 0.13 dynamic	1.32
Acrylic	85-105	55-205 ppm/ºC at 25ºC	0.17-0.21	0.014-0.069	-	-	48.26-75.84	-	1.19
Epoxy	-	45-65 ppm/ºC at 25ºC	0.13-0.25	2.41	-	-	27.58-89.63	-	1.11-1.40
Urethanes	170	100-200 ppm/ºC at 25ºC	0.11	0.007-0.689	-	-	1.21-68.95	-	1.1-2.5
Silicone	-	250-300 ppm/ºC at 25ºC	0.15-0.31	0.006	-	-	2.41-6.89	-	1.05-1.23

Table 3: Material candidates for Coating [3] [4] [5] [6]

Appendix 4:

Material	Density	Poisson's Ratio	Young's Modulus	Ultimate Tensile Strength	Yield Tensile Strength	CTE, linear	Thermal Conductivity
Aluminum 6061	2.7 g/cc	-	68.9 GPa	310 MPa	276 MPa	23.6 µm/m-°C	167 W/m-K
Copper	8.93 g/cc	0.343	110 GPa	210 MPa	69 MPa	16.4 µm/m-°C	398 W/m-K

Table 4: Material candidates for Fiber [3] [4] [5] [6]

Appendix 5:

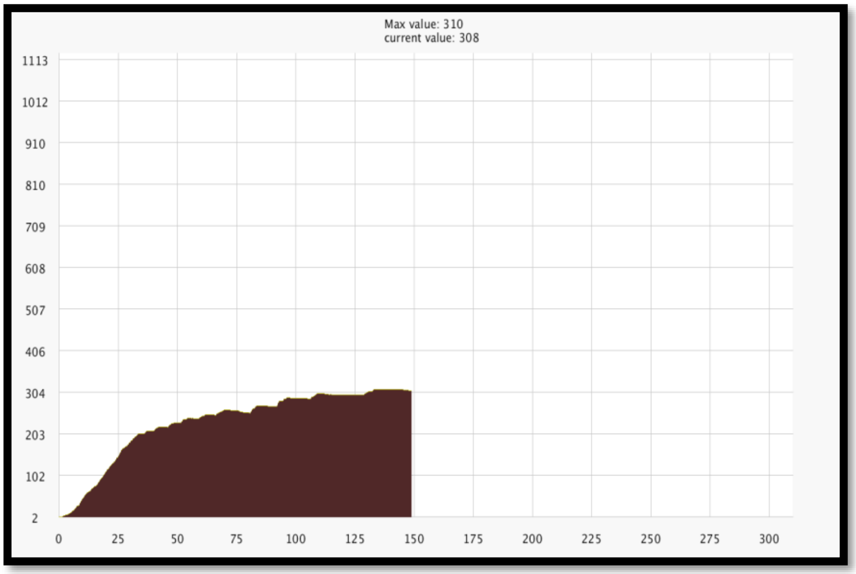
The method to determine the pressure handling capacity of the heat exchangers is as follows:

1. Hook up the Arduino with the sensor of the static pressure pump (shown in Fig 3) to read the analog sensor data. The static pressure pump has 3 wires coming out of the sensor. Make following connections:

Sensor Wire on the Static Pressure Pump	Connection Pin on Arduino
Red	5V
Black	Ground
White	Analog Pin A0

Table 7

2. Program the Arduino by uploading the code onto it (See Appendix 6 for the code)
3. Fill the static piston pump with de-ionized water
4. Connect the heat exchanger sample to the device by the metal rod end
5. Close the air escape valve located on the side of the pump. Suck out all the air in the sample by turning the pump in counterclockwise direction and then open the escape valve to create a partial vacuum. Close the valve once all the air has escaped.
6. Load the open source “Processing” software and run the code to read the data and to plot it in real time (See Appendix 7 for the code)
7. Gradually increase the pressure inside the heat exchanger sample, by rotating the pump in the clockwise direction, till it reaches 100 psi
8. From here onwards, increase the pressure in steps of 10 psi every 5 seconds
9. Observe the sample between the consecutive pressure increments for any water leakages
10. Stop the experiment once you see water leaking out of the wall. This implies that both the air and water side coatings have failed. Make a note of this pressure. This is the maximum pressure holding capacity for that particular heat exchanger sample
11. Note: There may be some instances where one can see the pressure dropping slightly over time even when no external pressure change has been applied. This can be attributed to the plastic deformation of the wall and the coating. This generally occurs at high pressures (over 250 psi)
12. Continue the experiment with other samples
13. Compile all the data in an excel sheet and calculate the average pressure holding capacity for samples aged at the particular temperature and for the given time
14. This data will later be used for the age prediction using the Arrhenius Model
15. Refer to Appendix 8 for the pressure data gathered from the reliability tests



A sample graph obtained using the Processing software to obtain the break point of the heat exchanger sample is shown in Figure 2. The Y axis is the pressure (in psi) and the X axis is the time elapsed while conducting the testing (in secs). The water side coating leaked at 310 psi for this particular case as recorded by the "Max value" on the top of the graph.

Figure 1: Real-time pressure variation inside the heat exchanger sample

Appendix 6:

```
//Arduino Code
int sensorPin = 0;
  int reading = 0;

void setup() {
  Serial.begin(9600);
}

void loop() {
  if(abs(analogRead(sensorPin)-reading)>1){
  reading = analogRead(sensorPin);
  Serial.println(reading);
  }
}
```

Appendix 7:

```
//Code to load onto "Processing" software
import java.io.FileNotFoundException;
import processing.serial.*;
import java.util.Scanner;

final int topSpace = 60;
final int botSpace = 60;
final int sideSpace = 80;
final int frameWdith = 1400; //width of screen
final int frameHeight = 800; //height of screen
final int xsep = 100;     //seperation between x axis markers
final int ysep = 61;     //seperation between y axis markers
final String filename = "testfile."; //file prefix
final int rate = 4;      //refresh per second
final int countInit = 1; //sets initial save count
final double timeInt = 1 / (double)rate;

String ret = "";
Serial myPort;     // The serial port float output = 0;
String userInp;
float output;
int inval = 0;
int max = 0;
int count = 0;
int xPos = sideSpace;


void setup () {
 frameRate(rate);
 size(1400, 800);
 println(timeInt);
 //println(Serial.list());
 myPort = new Serial(this, Serial.list()[0], 9600);
 // don't generate a serialEvent() unless you get a newline character:
 myPort.bufferUntil('\n');
 textSize(18);
 background(248, 248, 248);
 noStroke();
 reset();
}

void draw () {
 //draw data
 stroke(80, 40, 40);
 line(xPos, height - botSpace, xPos, height - botSpace - output); //bar
 stroke(200, 200, 20);
```

```
  point(xPos, height - botSpace - output);                //line
  fill(248, 248, 248);
  noStroke();//check
  rect(sideSpace, 0, width - 2 * sideSpace, topSpace);

  if (inval > max)
    max = inval;

  //display text
  fill(20, 20, 20);
  textAlign(LEFT, CENTER);
  text("Max value: " + toPSI(max), width/2 - 70, 15);
  text("current value: " + toPSI(inval), width/2 - 70, 35);
  ret += " " + toPSI(inval);

  //check for edge
  if (xPos >= width - sideSpace) {
    reset();
  } else {
    xPos++;
  }
}

void reset() {
  //different on first reset
  if (count != 0) {
    ret = "Max:\t" + max +  "\tTimeInterval:\t" + timeInt + ret;
    save(filename + (count + countInit - 1) + ".png");
    saveStrings(filename + (count + countInit - 1) + ".txt", split(ret, ' '));
    ret = "";
  }
  noLoop();
  count++;
  xPos = sideSpace;
  max = 0;
  frame.setTitle("Press any key to continue to trial count: " + (count + countInit - 1));
  background(248, 248, 248);
  fill(255, 255, 255);
  rect(sideSpace, topSpace, width - 2*sideSpace, height - botSpace - topSpace);

  textAlign(CENTER, CENTER);
  fill(20, 20, 20);
  for (int i = 0; i < (width - 2*sideSpace)/xsep + 1; i++) {
    textAlign(CENTER, CENTER);
    stroke(200, 200, 200);
    line(i * xsep + sideSpace, height - botSpace, i * xsep + sideSpace, topSpace);
    text(Integer.toString((int)(i * xsep * timeInt)), i * xsep + sideSpace, height - botSpace/2);
  }
  for (int i = 0; i < (height - topSpace - botSpace)/ysep + 1; i++) {
```

```
    line(sideSpace, height - botSpace - i * ysep, width-sideSpace, height - botSpace - i * ysep);
    text(toPSI((i * ysep * 924) / (height-topSpace - botSpace) + 99), sideSpace/2, height - botSpace - i
* ysep);
  }
}

void serialEvent (Serial myPort) {
  String read = myPort.readStringUntil('\n');

  if (read != null) {
    // convert to an int and map to the screen height:
    output = float(read);
    inval = (int) output;
    //println(inByte);
    output = map(output - 99, 0, 924, 0, height - topSpace - botSpace);
  }
}

void keyPressed() {
  if (key == 's')
    reset();
  else {
    loop();
    frame.setTitle(filename + (count + countInit - 1));
  }
}

int toPSI(int inp) {
  return (int)((double)(inp-99)/.82);
}
```

Appendix 8:

Temp=60°C			Temp=70°C			Temp=80°C		
Sample ID	Pressure at Failure (psi)	Pressure Reduction Ratio	Sample ID	Pressure at Failure (psi)	Pressure Reduction Ratio	Sample ID	Pressure at Failure (psi)	Pressure Reduction Ratio
O2_1.1	475	1	O3_1.1	292	1	O1_1.1	463	1
O2_1.2	443	0.9729148	O3_1.2	297	1.487	O1_1.2	373	0.61051
O2_1.3	419	0.7517377	O3_1.3	270	1.232	O1_1.3	360	0.53136
O2_1.4	454	0.790269	O3_1.4	253	1.443	O1_1.4	410	0.28179
O2_1.5	415	0.7937947	O3_1.5	251	1.315	O1_1.5	462	0.32348
Average	441.2		O3_1.6	320	0.356	O1_1.6	502	0.21899
STD	22.31054		O3_1.7	231		Average	428.33	
			O3_1.8	243				
			O3_1.9	280				
			O3_1.10	248				
			Average	268.5				
			STD	28.234				
O2_2.1	502		O3_2.1	384		O1_2.1	236	
O2_2.2	363		O3_2.2	420		O1_2.2	263	
O2_2.3	459		O3_2.3	336		O1_2.3	276	
O2_2.4	401		O3_2.4	400		O1_2.4	271	
O2_2.5	412	Aged-1	O3_2.5	450		O1_2.5	302	
O2_2.6	413		O3_2.6	340	Aged-1	O1_2.6	231	Aged-1
O2_2.7	406		O3_2.7	492		O1_2.7	241	
O2_2.8	478		O3_2.8	371		O1_2.8	275	
Average	429.25		O3_2.9	401		O1_2.9	257	
STD	43.07479		Average	399.33		O1_2.10	263	
			STD	50.192		Average	261.5	
O2_3.1	352		O3_3.1	325		O1_3.1	167	
O2_3.2	370		O3_3.2	351		O1_3.2	278	
O2_3.3	389		O3_3.3	290		O1_3.3	192	
O2_3.4	290		O3_3.4	395		O1_3.4	207	
O2_3.5	340		O3_3.5	250		O1_3.5	321	
O2_3.6	393	Aged-2	O3_3.6	378	Aged-2	O1_3.6	246	Aged-2
O2_3.7	300		O3_3.7	284		O1_3.7	291	
O2_3.8	258		O3_3.8	302		O1_3.8	203	
O2_3.9	293		O3_3.9	401		O1_3.9	187	
Average	331.6667		Average	330.67		O1_3.10	184	
STD	48.29855		STD	53.54		Average	227.6	
O2_4.1	360		O3_4.1	321		O1_4.1	128	
O2_4.2	398	Aged-3	O3_4.2	390	Aged-3	O1_4.2	152	Aged-3
O2_4.3	329		O3_4.3	410		O1_4.3	120	

O2_4.4	395		O3_4.4	514		O1_4.4	134	
O2_4.5	318		O3_4.5	301		O1_4.5	132	
O2_4.6	320		O3_4.6	262		O1_4.6	125	
O2_4.7	362		O3_4.7	380		O1_4.7	123	
O2_4.8	341		O3_4.8	491		O1_4.8	106	
O2_4.9	315		O3_4.9	418		O1_4.9	97	
Average	348.6667		Average	387.44		O1_4.10	90	
STD	32.07024		STD	83.568		Average	120.7	
O2_5.1	393		O3_5.1	400		O1_5.1	100	
O2_5.2	367		O3_5.2	331		O1_5.2	97	
O2_5.3	370		O3_5.3	321		O1_5.3	154	
O2_5.4	342		O3_5.4	270		O1_5.4	192	
O2_5.5	320		O3_5.5	410		O1_5.5	90	Aged-4
O2_5.6	310	Aged-4	O3_5.6	200	Aged-4	O1_5.6	154	
O2_5.7	360		O3_5.7	401		O1_5.7	202	
O2_5.8	330		O3_5.8	370		O1_5.8	112	
O2_5.9	360		O3_5.9	475		O1_5.9	146	
Average	350.2222		Average	353.11		Average	138.56	
STD	26.69634		STD	82.72				
			O3_6.1	250		O1_6.1	103	
			O3_6.2	309		O1_6.2	91	
			O3_6.3	324		O1_6.3	81	
			O3_6.4	378		O1_6.4	92	
			O3_6.5	546		O1_6.5	101	
			O3_6.6	460		O1_6.6	71	Aged-5
			O3_6.7	389	Aged-5	O1_6.7	132	
			O3_6.8	282		O1_6.8	81	
			O3_6.9	496		O1_6.9	101	
			O3_6.10	380		O1_6.10	85	
			Average	330.29		Average	93.8	
			STD	95.544				

Table 8: Pressure Handling Capacity of the Heat Exchanger samples at various temperatures

The first data set corresponding to each temperature is the control data, implying no aging of the heat exchanger samples.
Aged-1: 72 hours
Aged-2: 144 hours
Aged-3: 216 hours
Aged-4: 288 hours
Aged-5: 360 hours

However, the Aged-4 for the 70°C data corresponds to 312 hours.

Appendix 9:

INPUT PARAMETERS:

The following input dimensions were parameterized and linked appropriately in ANSYS Static Structural so that the unit cell could be accordingly studied for stress distribution:

Sr. No.	Parameter	Dimension (in mm)
1	base_wall	= Half the value of the wall thickness
2	airsidewalloffsetnegative	= Negative of the base_wall dimension
3	coat_wall_thickness	= Coating Thickness
4	air_side_plane_offset	= Negative of Coating Thickness
5	outer_circle_diameter	= Fiber Diameter+2*Coating Thickness
6	water_circular_coat_length	= 2-base_wall-coat_wall_thickness
7	air_circular_coat_length	= 10-base_wall-coat_wall_thickness
8	fiber_diameter	= Fiber Diameter
9	diameter_plus_20_microns	= Fiber Diameter+0.02
10	face_split_radius	= Fiber Diameter/2
11	wall_width	= Fiber Diameter*6
12	wall_height	= Fiber Diameter*3.25

Table 5: Input parameters in ANSYS Static Structural

Note that the total length of the fiber is 12 mm, 2 mm being on the water side and 10 mm on the air side. That is the reason those numbers are used to determine water_circular_coat_length and air_circular_coat_length. Change them if modifying the total fiber length.

OUTPUT PARAMETERS:

The output parametric stresses are self-explanatory:

Sr. No.	Output Parameters (Stresses)
1	STRESS at air side coat
2	STRESS at fiber-coat interface
3	STRESS at wall-coat interface
4	STRESS at water side coat
5	STRESS inside the coating (10 microns inside)

Table 6: Output parameters in ANSYS Static Structural

Appendix 10:

```
%Matlab Code for 2-factorial design method
close all;
clc;
y=[ymin;ymax]; %define ymin, ymax in the command window: y is the wall thickness
x=[xmin;xmax]; %define xmin, xmax in the command window: x is the coat thickness
%define stress in the command window corresponding to the 4 combinations of x and y
contourf(x,y,stress); %plot the interaction contour graph

xlabel('Coating Thickness (in microns)');
ylabel('Wall Thickness (in mm)');
title('Stress at Wall Interface (in MPa)');

baseline=mean(mean(stress)); %average of all the 4 stresses

%calculate main effect of X (coating)
a_plus=stress(2,2)-stress(2,1);
a_minus=stress(1,2)-stress(1,1);
average_a=(a_plus+a_minus)/2;
main_effect_X=average_a/2;

%calculate main effect of Y (wall)
b_plus=stress(2,2)-stress(1,2);
b_minus=stress(2,1)-stress(1,1);
average_b=(b_plus+b_minus)/2;
main_effect_Y=average_b/2;

%interaction effect
interaction=(a_plus-a_minus)/4;

%interaction equation:
%stress=baseline+main_effect_X*coat thickness+main_effect_Y*wall thickness+interaction*wall
thickness*coat thickness
```