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Preliminary Study on GF/Carbon/Epoxy Composite Permeability in Designing Close Compartment Processing

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Preliminary Study on GF/Carbon/Epoxy Composite Permeability in Designing Close Compartment Processing

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Abstract. This project involves discovering how the permeability effect inside a close compartment in processing. After the appropriate pressure range was found, the close compartment was designed by studying the relationship between pressure output and the flow rate. A variety of pressure ranges have been used in this test to determine the effective pressure range that can be applied to the manufacturing process. Based on the results, the suitable pressure ranges were found between 55 psi to 75 psi. These pressures have been chosen based on the area covered on the product surfaces and time taken to penetrate the proposed area. The relationship between pressure and flow rate have been found to be directly proportional until 75 psi only. In conclusion, 70 psi for the proposed design of close compartment mould is suitable to be used to fulfill the required area of 120 mm square within 90 seconds.

1. Introduction

This was an industrial-related project as an initial study for pull-winding process which would be employed to manufacture fiberglass or carbon, composite poles or tubing. On-site observation showed high inconsistency quality of composite part, rejection rate of composite products and excessive mixed resin waste. One of the suspected reasons being was the processing environmental condition such as high humidity. Hence, a close compartment processing concept was designed to solve this industry problem – an automated resin infusion-fiber drying system (RIFiDS) was proposed. One of the goals of this study was to create a new technology that can be integrated to the current pull-winding process line. Nevertheless, the most significant outcome of this preliminary study is that such proposed close compartment system has never been utilized commercially in the current pull-winding process and because of that, the proposed system is a novel technology.

The causes to these industry problems are schematically illustrated in Fig.1 below:



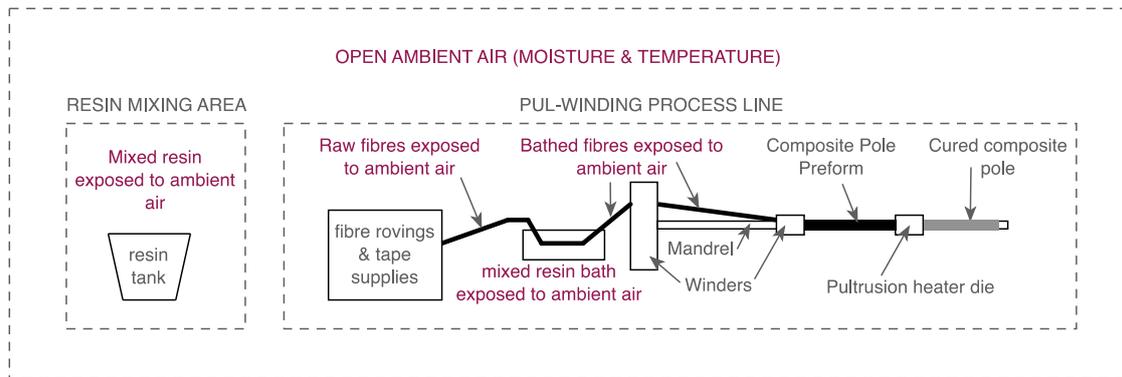


Figure 1. Suspected moisture ingress problem in the actual processing line

The resin flow in a laminate is one of the major contributors to void formation, transportation, and growth (Kardos, Duduković, & Dave, 1986). During processing, because of pressure application and decreased viscosity of resin, excess resin between fibers in tows and adjacent plies move, causing voids to swipe out of the laminate (Shan, Hongqiang, Zhengping, & Hao, 2014). The resin flow mainly occurs due to applied pressure gradients and viscosity changes. The resin flow rate is controlled by the resin and surrounding pressure of the laminate, resin viscosity, specific permeability, porosity of the fiber bed and laminate dimensions (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016). Resin flow in laminate is quasi-static and transient in nature (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016) and (Schaefer, Werner, & Daniel, 2014). The initial viscosity of resin in liquid stage is influenced by size of molecular extension (α) and temperature (T) hence as resin approaches the gelling point, viscosity rises rapidly and resin flow ceases (Van Velthem, et al., 2015).

There are two major mathematical models for resin flow in laminate. The first one is based on the theories of soil mechanics, considering the fiber bed of the laminate as a porous solid. The other follows lubrication theory (Van Velthem, et al., 2015). Models are based on soil science, which assumes a pressure gradient across the vertical and horizontal direction of the laminate. While (Grigoriev, Krasnovskii, & Kazakov, 2014) assumed a linear pressure gradient, (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016) and (Ghnatios, Chinesta, & Binetruy, 2013) considered nonlinear pressure gradients. Resin flow in a laminated composite is laminar and low Reynolds number flow (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016). The porous medium combined with a low Reynolds number ($Re \leq 10$) flow can be characterized by Darcy's Law (Partha, Vimal, & Mishra, 2016). As a porous medium, flow inside the laminate is described by Darcy's law and requires the knowledge of fiber network permeability, viscosity, and pressure gradient of the resin during cure. According to Darcy's law, resin velocity (V) inside laminate is as per equation below:

$$V = \frac{k \Delta P}{\mu L} \quad (1)$$

where μ is the viscosity, ΔP is pressure gradient of the resin, k is the fiber bed permeability and L is the length of fiber bed. Although Darcy's law is suitable for one dimensional flow, this equation can be applied to three-dimensional flow as well (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016). (Grigoriev, Krasnovskii, & Kazakov, 2014) and (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016) use Darcy's law to model resin flow in laminates during cure. The fiber bed permeability (k) is analogous to the conductivity of the porous media. The more permeable the fiber bed, the less resistance resin faces to flow. According to soil science, permeability is the specific discharge per unit hydraulic gradient (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016). Permeability of the fiber bed may change with time due to an applied external load that changes the structures and texture of the porous bed. As the fiber volume fraction changes during compaction, therefore, fiber bed permeability is a function of fiber volume fraction. (Sánchez, Artero-Guerrero, Varas, & López-

Puente, 2016) described the permeability of laminate fiber bed using Carman-Kozeny equation as follows:

$$k = \frac{r_f (1-V_f)^3}{4K V_f^2} \quad (2)$$

Where r_f and K are the fiber radius and Kozeny constant, respectively. Anisotropy of the fiber bed permeability is determined by the Kozeny constant in three principle directions. The principle directions of the laminate are shown in Fig. 2. Since fiber bed is assumed to be transversely isotropic, permeability in fiber (1,x) and transverse (2,y) directions are different. (Ghnatios, Chinesta, & Binetruy, 2013) found axial and transverse Kozeny constant to be $K_1=0.7$ and $K_2=17.9$ for different fiber volume fractions. (Rouhi, Wysocki, & Larsson, 2015) reported a Kozeny constant for transverse permeability of $K_2=11$ for $0.5 < V_f < 0.75$ and observed substantial decrease in K_2 at higher fiber volume fractions from their permeability experiment. They obtained axial permeability $K_1=0.35$ and 0.68 for silicone oil and water respectively, indicating the effect of fluid properties on fiber bed permeability. Since laminate contains layers of varying permeability, layers having the highest permeability govern the resin flow (Schaefer, Werner, & Daniel, 2014). Combining the void ratio and effective stress relationship with Carman-Kozeny equation provides a relationship of permeability with the effective stress. Fig. 3 showing fiber bed permeability decreases with the increase in the effective loading.

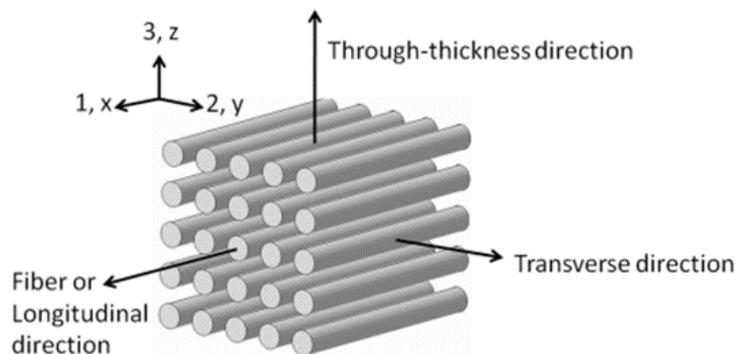


Figure 2. Unidirectional fiber bundle with direction convention. (Ghnatios, Chinesta, & Binetruy, 2013)

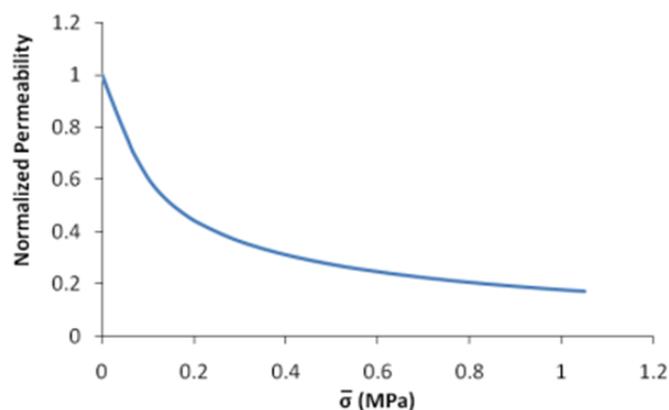


Figure 3. Permeability and effective stress relationship. (Sánchez, Artero-Guerrero, Varas, & López-Puente, 2016)

Many factors can affect the liquid drop size such as liquid properties, nozzle capacity, spray pressure and spray angle. Nozzles should be placed as close as possible to the beginning of the transfer point as possible (Prakash & Jhavar, 2014). The force of the moving preform in this study helps the resin in penetrating the preform as it moves through the transfer point (De La Haza, Andrey, & Samokrutov, 2013). Fig.4 showing the flat fan type is the best type for resin penetration and sharp uniform pattern to the preform. The liquid is shaped into a fan-shaped sheet of fluid. This can be comprised of droplets or a more or less coherent sheet of water like a waterfall. Flat fans can have a spray angle of between 15 and 145 degrees depending on the nozzle design. Another study also showed the flat fan pattern that creates a flat sheet of spray, with medium velocity and large drop size. It is excellent for covering an area when there is a relative motion between the nozzle and target such as pull-winding (Tseng, Raudensky, & Lee, 2016). This preliminary study utilizes the nozzle to break the liquid into droplets and form the spray pattern (Lujaji, Boateng, Schaffer, Mtui, & Mkilaha, 2016) Another study shows that the standard flat-fan nozzle normally operates between 30 psi and 60 psi – with an ideal range of 30 to 40 psi.

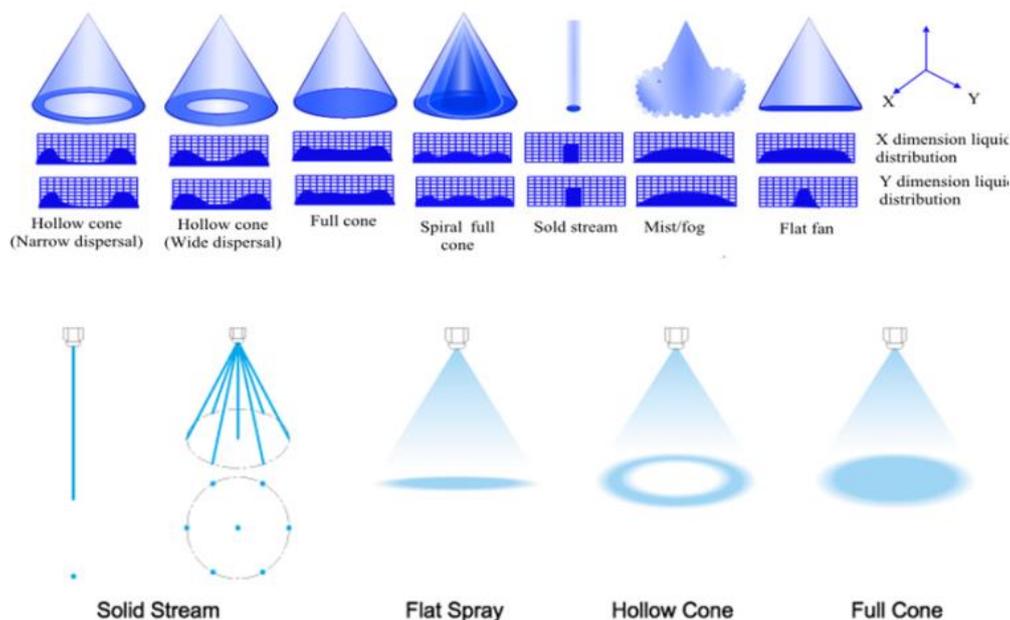


Figure 4. Spray pattern (BETE Fog Nozzle, Inc., 2017)

2. Methodology

Basically, the work requires the resin to be automatically metered and mixed so that consistent batch of resin quality would be obtained and then, the mixed resin was infused or injected or compressed directly to the composite preforms without excessively exposing the preform to the ambient air. This will eliminate moisture absorption problem that was causing inconsistent quality of fabricated composite part. Furthermore, the mixed resin will be infused as per required only; hence, it eliminates the excessive mixed resin waste. The raw material of glass fiber carbon fiber has been provided by TenAsia Corp. Sdn Bhd. The stacking sequence of fibers and epoxy were also based on recommendation from TenAsia Corp. Sdn Bhd. Both, the raw material identification and stacking sequence was considered as confidential by TenAsia Corp. Sdn Bhd. The sample dimension in this study was 12 inch by 12 inch sample. Initially, the fiber was laid flat on the glass, and then a metal plat mold was put on the fiber surface to avoid the preform from shifting. The spray process takes place in the mock-up close compartment. The spray gun was used to spray and the nozzle position was placed 3 inch high from the fiber surface. The container was design to prevent splashing of excessive resin.

The pressure used was 50, 55, 60, 65, 70, 75 and 80 psi respectively. Each of different pressure testing was conducted for 2 minutes. Metal plate was used to position the nozzle at 3 inches away from the preform. Hence, in this study a fan spray pattern was introduced by adjusting the nozzle. This spray pattern was been recorded every 30 second for 2 minutes. Fig. 5 showing steps in samples preparation.

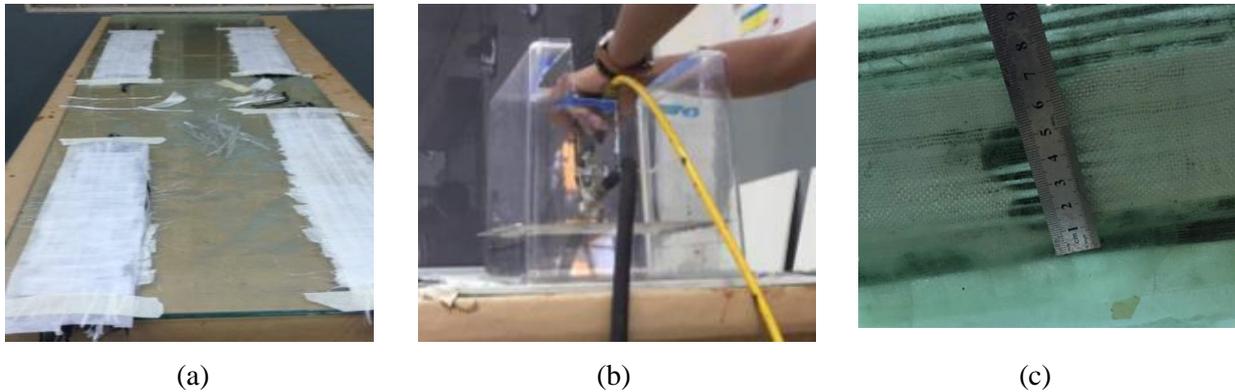


Figure 5. (a) Preform preparation, (b) Spray pattern adjustment and (c) Permeability behaviour of the preform sample.

The close compartment was designed initially by using Perspex material (temporary mold) then later will be fabricated using metal. The mold has been designed in order to avoid preform exposure to the environment. The close compartment was also designed to reduce waste and emission for a cleaner and healthier environment. In this study an injection spray resin and compression resin concept was also introduce in the close compartment. The mold was designed to ensure resin penetration to the sample. Hence, this design was chosen to avoid environmental exposure to the fabrication. The internal design of the compartment was design in a circular form to avoid resin residual and also for ease of mold maintenance by the operator. In order to avoid the human error during the assembly of the mold, the guide pin was designed as a reference. In this design, a drain outlet was located at the bottom of the mold in order to remove the excessive resin during the resin spray stages. The excessive resin will flow down to the trap chamber to be reused back to the system. Expected drawback of this close compartment design is the possibilities of having resin clog at the drainage outlet and also at the nozzles area will be expected in long run. Continuously maintenance must be done to this close compartment to avoid the clog. The nozzle was designed at less than 0.4 inch as such to produce the flat fan pattern spraying.

3. Result and Discussion

Preliminary findings showing for every 120 second at 50 psi the resin spread will cover 110 cm² area, 55 psi will cover 137.5 cm² area, 60 psi will cover 146.4 cm², 65 psi will cover 162.5 cm² area, 70 psi will cover 184.6 cm² area, 75 psi will cover 129.8 cm² area and at 80 psi the resin spread will cover 103 cm² area. The best range of pressure was between 60 to 70 psi. In this study, 75 and 80 psi are not used as the resin will change into mist thus preventing it from being absorbed by the preform. Findings are shown as per Fig. 6 below.

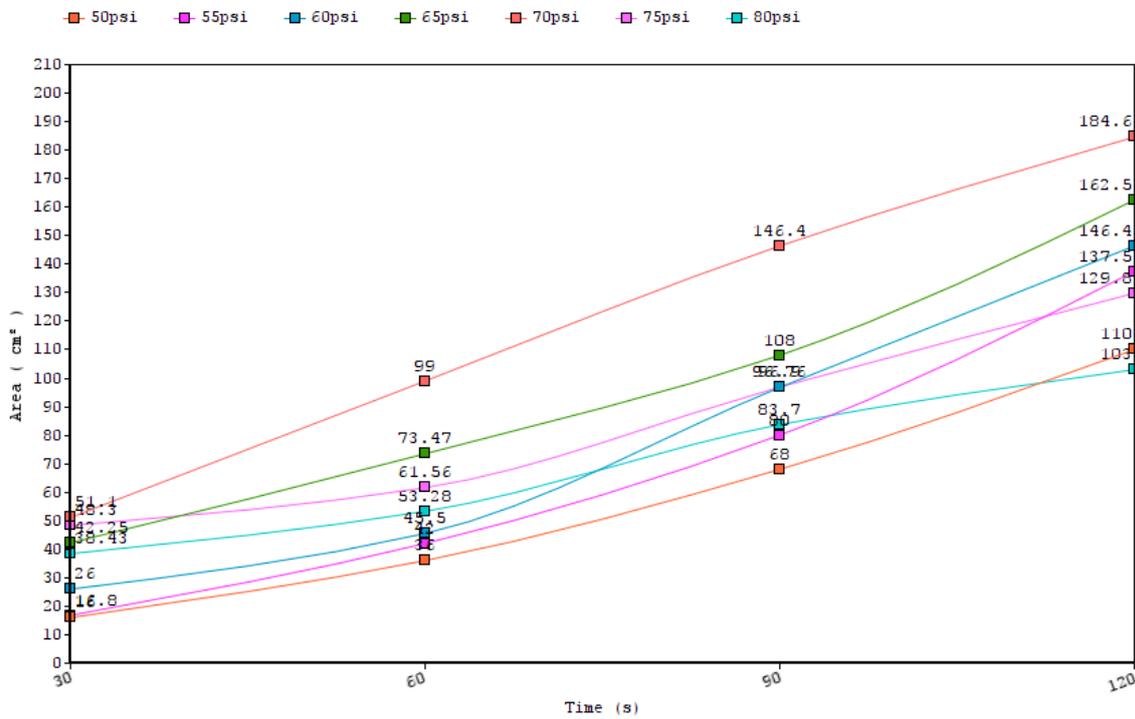


Figure 6. Relationship between pressure and area

Fig.7 show preliminary findings specifically for the first 30 second of the composite fabrication. At 50 psi the resin coverage was 16 cm², 55 psi was 16.2 cm², 60 psi was 26 cm², 65 psi was 42.25 cm², 70 psi was 51.1 cm², 75 psi was 48.3 cm² and at 80 psi the resin coverage was 38.43 cm². The pressure ranges suggested based on preliminary findings was 60 to 70 psi. The drop however happens between 75 to 80 psi because resin becomes mist.

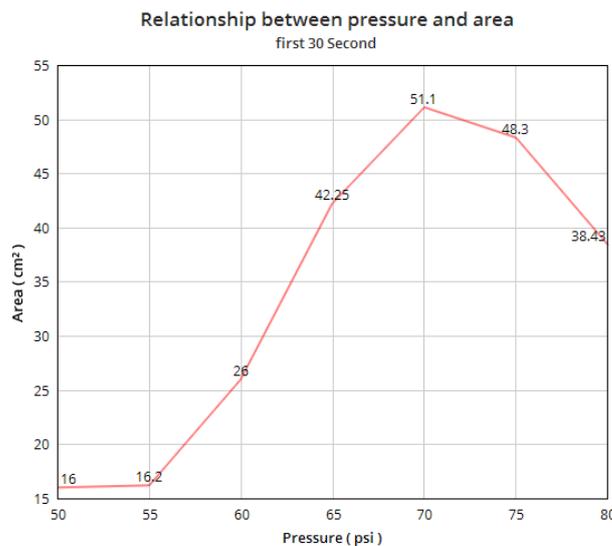


Figure 7. Pressure output observation at every 30 seconds

Overall finding was shown in Fig.8. Based on the preliminary results for duration of 120 seconds, the resin coverage at 50 psi was 118 cm², increasing the pressure at 55 psi resulted in resin coverage of 137.5 cm², at 60 psi was 146.4 cm², 65 psi was 162.5 cm², at 70 psi was 184.6 cm², at 75 psi was 121.8 cm² and at 80 psi was 103 cm². The suggested pressure range for 120 seconds was 60 to 70 psi. However, at both suggested pressure ranges the coverage area was already exceeding the preform product requirement.

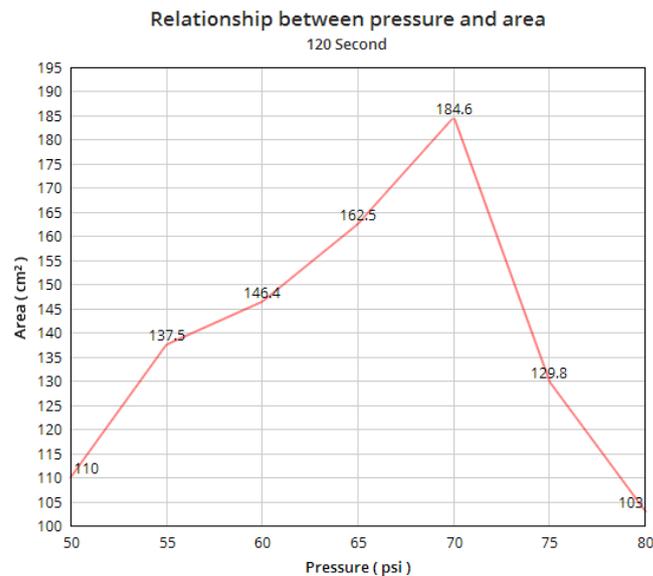


Figure 8. Preliminary findings for 120 seconds processing time

Fig.9 showing the close compartment concept, circular shape was designed for ease of cleaning and maintenance after used. This product has different type of diameter and the mold was designed separately into three parts for easy manageable change the mold size for specific product diameter. Circular shape was also designed to prevent cured resin retained after the processing completed in Fig.10. The size of circular shape was designed with small gap to ensure pressurize system will force-push in the resin into the fabric efficiently compared with large gap.

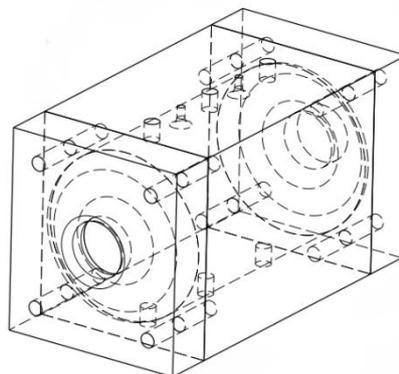


Figure 9. Close compartment with injected spray resin system for pull-winding process.

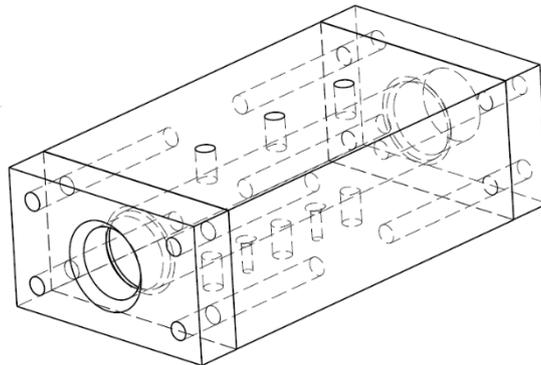


Figure 10. Close compartment with pressurize resin system for pull-winding process.

4. Conclusion

In conclusion, the appropriate pressure range in this preliminary study was identified between 55 psi to 75 psi. The design of the close compartment mold was to avoid exposure of the preform to the environment. Future investigation will involve the integration of close compartment e.g. Perspex mold, with fully operational pull-winding production line. In addition, the next stage of investigation will involve findings and observation comparison between experimental data to the actual condition of the manufacturing pull-winding system.

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