Vacuum Source Volumetric Flow and the Vacuum Infusion Process

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SUMMARY: Vacuum infusion processing has enjoyed a resurgence of interest in recent years as a primary mode of fabrication over traditional open mold processing. This renewed interest is driven by economic, environmental and engineering concerns as closed mold processing is recognized as being a cleaner, more efficient process than open molding. To facilitate vacuum infusion implementation, process simulation models are often used to gain an understanding of and to optimize the processing parameters for a given part. Simulation models to date derive resin flow characteristics, i.e. velocity, in part by way of the pressure gradient at the resin flow front. Although these simulations have been found to be generally accurate further process optimization may be realized through consideration of the effects of the vacuum source's volumetric flow rate on the infusion process. This paper seeks to lay the groundwork for future model development by expanding our understanding of these effects and their implications.

KEYWORDS: vacuum source volumetric flow; *Darcy Weisbach Friction Factor Equation*; extended *Bernoulli* equation.

INTRODUCTION

While composites find their roots in closed mold processing modern derivatives such as resin transfer molding (RTM) and were born of the desire to reduce the acquisition costs associated with aerospace composites. Generally what we think of as vacuum infusion processing (VIP), be it surface infusion or interlaminar infusion, are second order derivatives of RTM developed with the intention of meeting the cost/performance profile of a commercial (aka open mold) composite. Process simulation models for VIP naturally followed a like path from RTM. While significant model development specific to VIP is prevalent throughout the literature [1-3], no mention is made of the vacuum source volumetric flow rate relative to the resin flow rate. Rather, motive force is defined specific to the established pressure gradient at the flow front between the vacuum and the resin. However, numerous field accounts of varied infusion rates with different pumps and vacuum tube diameters, other variables remaining constant, led us to believe otherwise.

RESEARCH OBJECTIVE & APPROACH

Clearly the discovery of a correlation between vacuum source volumetric flow rate and resin flow velocity would, at a minimum, impact seemingly rudimentary decisions such as vacuum pump selection, and could ultimately shift our approach to process implementation enabling broader application within the market. Thus our research sought to determine whether or not the volumetric flow rate of a vacuum pump make a difference in the resin flow velocity and parallel infusion rate, and if so, determine how might we account for this in future models.

To approach the question a standard vacuum/laminae cell was developed in which resin flow velocity was characterized via distance over time. Two such experiments would be performed wherein all variables within the cell were maintained constant, bar the cells vacuum tube inlet diameter. In this manner the volumetric flow rate afforded by the pump was altered between the experiments.

EXPERIMENTAL

The standard vacuum/laminae cell is shown schematically (top view) in Figure 1 where the laminae consisted of 600 g/m^2 chopped strand mat/Polybeam™ 720/600 g/m^2 chopped strand mat measuring 304.8-mm in width by 2133.6-mm in length. The general assembly of the standard cell is representative of interlaminar infusion, shown schematically in Figure 2, where the Polybeam™ 720 is a reinforcing interlaminar infusion media. Referring again to Figure 1, upon assembly of the laminae (1), a single vacuum port (3) was fitted adjacent to the flow medium, and spiral cut tubing (2) for resin input was fitted on the opposite edge of the flow medium. The cell was set up such that the ensuing flow front path would run perpendicular to the lamina length. A flexible vacuum bag was then fitted and sealed about the laminae, the resin input tube sealed with a clamp and vacuum drawn. To facilitate flow front progression time demarcation a clear vacuum bag was used.

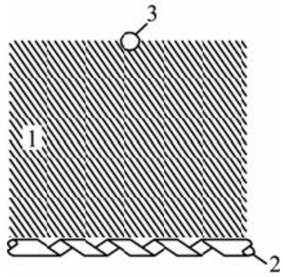

Figure 1.

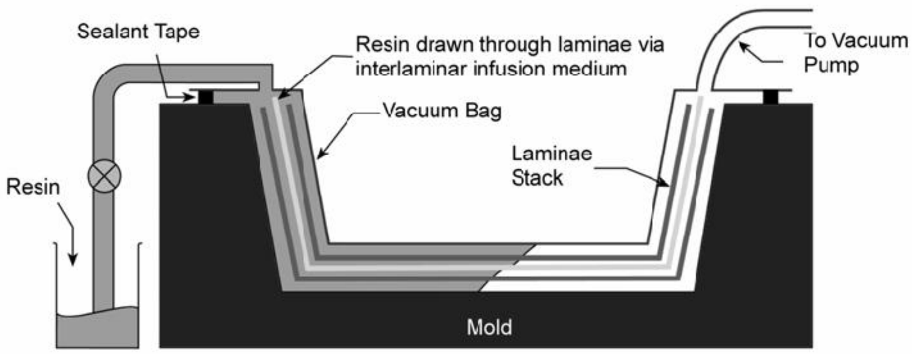

Figure 2. Interlaminar Infusion Illustration.

A gauge affixed to a standard resin trap read vacuum. When vacuum reached 96.5 kPa , the clamp was removed from the resin inlet tube, and the tube was subsequently placed in initiated polyester resin (~ 0.10 Pa•s). The resin clamp was reaffixed to the inlet tube when the resin front reached the vacuum port. Time interval demarcations were recorded every 30 seconds from the time of resin introduction to infusion completion. Two such experiments were performed wherein all variables within the cell were maintained constant, bar the cells vacuum tube inlet diameter. One experiment was run with a 19.05-mm ID vacuum tube as a control based on the pump inlet diameter (also 19.05-mm), and the other with a 9.525-mm ID vacuum tube. In this manner the volumetric flow rate afforded by the vacuum source was altered between the experiments.

RESULTS AND DISCUSSION

Figure 3 comparatively graphs the resin flow front velocity between that of the control (19.05-mm Vac.) and of the reduced (9.525-mm Vac.) vacuum source volumetric flow rate. One can clearly see a difference between the two. Given this measurement the question turns to whether or not the observed difference correlates to the change in volumetric flow rate.

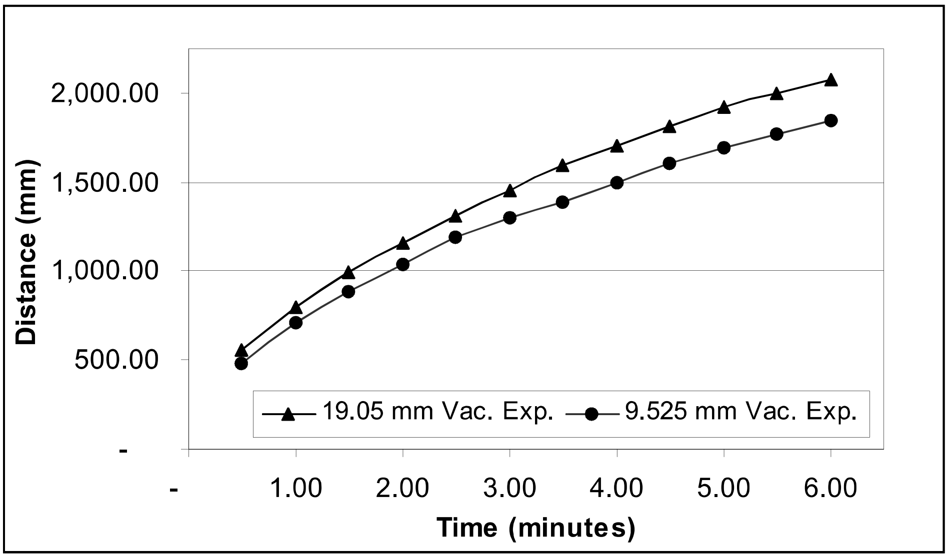

Figure 3. Infusion Rate Comparative.

The answer can be found by looking at the fundamentals of pumps in general. Pumps convert mechanical (rotational) energy into fluid (kinetic) energy, measured often as head. Head refers to the height of a liquid column which the pump could create using the kinetic energy that is generated. Vacuum producing devices maintain a system at a desired pressure or remove gas (fluid) from a vacuum system at a rate S_p, which is defined as a volume flow rate of gas per unit of time, $S_p = dV/dt$. Common units used for pumping speed are liters per second, cubic feet per minute (cfm), or cubic meters per second, all of which are expression of kinetic energy. Thus, as applied to our experiment, gas laws can be used to model the kinetic energy loss (or head loss) in our system, as attributed to the friction created by reducing the diameter of our vacuum tube.

The determination of frictional head loss can be attained through application of the *Darcy Weisbach Friction Factor Equation* (Eq. 1) as applied to our experimental set-up specific to the vacuum tube in question and our known pumping speed at the given pressure (96.5 kPa).

$$h_l = f\left(\frac{L}{D}\right)VP \qquad (1)$$

Where

VP = Pressure required to accelerate fluid from zero velocity to some velocity (V) and is proportional to the kinetic energy of the fluid stream.
L = length
D = diameter
f = friction factor

Through application of Eq. 1, in reducing the cross sectional area of the vacuum tube we find an 11.2089% drop in the systems kinetic energy, realized through the effective reduction in net CFM at the given pressure. Figure 4 graphs the 9.525-mm Vac. Predicted as derived through application of the 11.2089% kinetic energy loss against the control cure. Note the strong correlation between the 9.525-mm Vac Predicted and that of the experimental result.

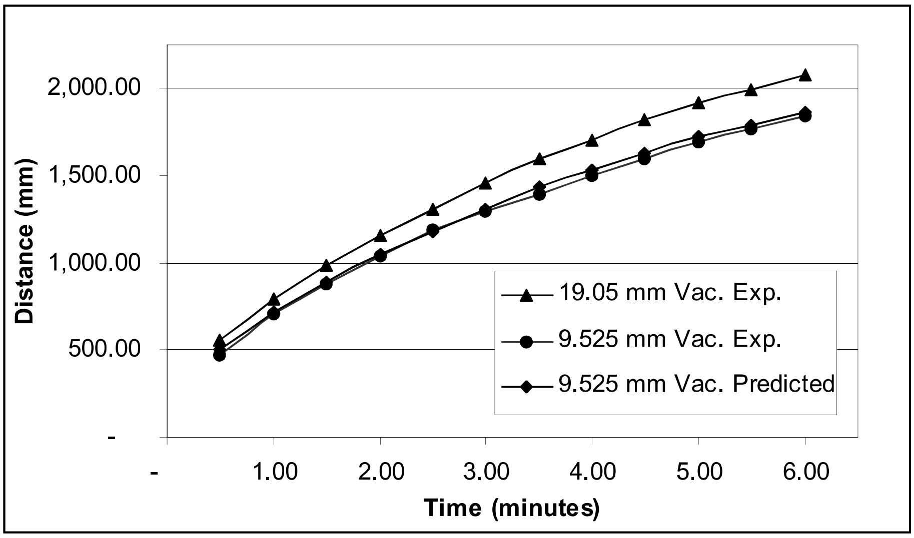

Figure 4. Infusion Rate Comparative vs. Predicted

SUMMARY AND CONCLUSION

The experimental results and model show good correlation and present compelling evidence regarding the role of vacuum source volumetric flow rate and resin flow velocity. From a practical standpoint one should consider the implication of flow rate in pump selection for a given application. Care should also be taken in infusion cell setup so as not to restrict the available kinetic energy (i.e. don't unnecessarily restrict the vacuum lines). Additionally care should be taken by those engaged in research activities where results may be skewed by differences in vacuum source volumetric flow rate (i.e. pre-form permeability testing).

With regards to simulation modeling our current research suggests that the role of vacuum source volumetric flow rate can be quantified by adding a term to Bernoulli's equation (2) to balance the pump energy (h_A)

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_A - h_L = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \qquad (2)$$

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