LIQUID INJECTION MOULDING TECHNOLOGY: PUSHING THE LIMITS, IF ANY

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INTRODUCTION

Application of Liquid Injection Moulding technology is steadily growing, and major advances in materials, preforming and flow analysis technology (see [1] for example) have resulted in a process that can compete technically with prepreg technology at much lower cost. At the other end of the spectrum, resin infusion technology is successfully used to laminate very large parts, like bridges and mine sweepers. Infusions of several tonnes in a single shot are no longer an exception. The increasing size and complexity of parts injected puts high demands on robustness, stability and accuracy of flow analysis software and raises additional issues, like gravity, process monitoring and control.

One of the obstacles for infusion of large parts is the height limit of 6 meters. We developed a new technology that allows infusion of continuous reinforcement under a single bag in multiple steps where the quality of the laminate on the weld lines is guaranteed. This technology uses membrane material in combination with a special configuration of vacuum lines (to lift the resin) and feeding lines.

In order to simulate this solution using flow analysis, gravity has been taken into account at the level of the partial differential equations, so that it enters the Finite Element and Control Volume discretisation naturally. This paper will discuss the consequences of using membrane material to apply vacuum in the resin infusion process, explain why additional measures are needed to make it work in practice and the model we developed to describe the full process. Results will be presented from testing the new technology at lab scale, investigation of the structural integrity of the weld(s) and a full scale test: a section of 6 meter long, 8.5 meters high and 10 meters wide.

The second, more practical, issue is how to mix and degas the quantities of resin necessary for infusion of large high objects. We will present this as a case: a project that has been carried out at the SNSZ shipyard in St. Petersburg: infusion of a 62 meter hull, where a total amount of resin of 20930 kg was infused in two shots of 14865 kg and 6065 kg respectively. In cooperation with 2KM Germany, equipment was developed to degas and mix the resin. The injection machines are controlled with the use of a pressure sensor close to the part which allows to compensate for the pressure loss in the feeding tubes (over 20 meters long).

THEORY

In order to model the Vacuum Infusion process, we need the ability to model sections with and without reinforcement. More detailed information – including the theory behind the non-isothermal reactive calculation (temperature and conversion) can be found in [2] and [3].

Flow equations

With gravity terms included, Darcy's Law - which well describes the flow of resin through reinforcement, [4] - generalised to three dimensions and the continuity equations are:

$$\underline{u} = -\frac{\underline{\underline{K}}}{\eta}\left(\underline{\nabla} p - \rho_r \, \underline{g}\right) \tag{1}$$

$$\underline{\nabla} \cdot \underline{u} = 0 \tag{2}$$

Here, $\underline{u}$ is the local flux density (or superficial velocity), $\underline{\underline{K}}$ is the permeability tensor, η is the resin viscosity, p is the pressure in the resin, ρ_r is the (local) resin density and $\underline{g}$ is the gravity vector. Substitution of Darcy's Law (1) in equation (2) results in:

$$\underline{\nabla} \cdot \left(\frac{\underline{\underline{K}}}{\eta}\left(\underline{\nabla} p - \rho_r \, \underline{g}\right)\right) = 0 \tag{3}$$

This equation is often referred to as the 'pressure equation', because the pressure (a 3D scalar quantity) is the only unknown.

For sections without reinforcement, the equations for a Generalised Newtonian Fluid apply. At the pressures typically used in the Vacuum Infusion process, the resin behaves as an incompressible fluid, so we can assume that the density is constant, which leads to the well-known Navier-Stokes equations:

$$\rho \dot{\vec{v}} = -\vec{\nabla} p + \vec{\nabla} \cdot \underline{\underline{D}}^{d} + \rho \vec{g} \tag{4}$$

Unified GHS/RTM model formulation

The restriction to thin-walled sections makes it possible to introduce a number of simplifications in the Navier-Stokes equations which lead to the so-called Generalised Hele-Shaw (GHS) model [5], better known as the 2½D model:

The pressure gradient in thickness direction can be neglected because it is much smaller than the pressure gradient in the (local) plane. Analytical integration of the Navier-Stokes equations (4) over the thickness, leads to the following, much simpler, formulation for the pressure problem on a GHS shell element:

$$\vec{\nabla}^{*} \cdot \left(S \cdot \vec{\nabla}^{*} p - \underline{G}^{*}\right) = 0, \tag{5}$$

$$S = 2\int_0^h \frac{z^2}{\eta} dz \qquad \underline{G}^{*} = 2\underline{g}^{*} \int_0^h \frac{z}{\eta} \int_0^z \rho \, d\zeta \, dz \tag{6}$$

Integration of equation (3) with gravity forces included over the thickness leads to a similar result for the RTM shell element:

$$\vec{\nabla}^{*} \cdot \left(\underline{\underline{S}} \cdot \vec{\nabla}^{*} p - \underline{G}^{*}\right) = 0 \tag{7}$$

$$\underline{\underline{S}}^{*} = 2\int_0^h \frac{\underline{\underline{K}}^{*}}{\eta} dz \qquad \underline{G}^{*} = 2\int_0^h \frac{\underline{\underline{K}}^{*}}{\eta} \cdot \rho \underline{g}^{*} dz \tag{8}$$

We now have a generalised model for the calculation of pressure (and resulting velocities) in 3D volume (Darcy flow only), 2D shell (Darcy and Hele-Shaw flow) and 1D beam (Darcy and Poiseuille flow) elements (details about the FEM implementation can be found in [6]).

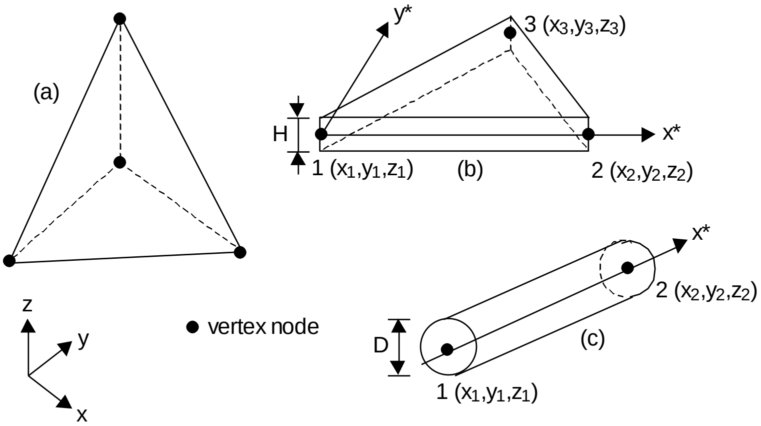


Figure 1: Basic element types for the unified GHS/RTM formulation, (a) 3D linear tetrahedron (Darcy flow only), (b) 2D linear triangular shell and (c) 1D linear runner (tube); where x* and y* denote the local co-ordinates and (x_i,y_i,z_i) the global co-ordinates.

PERMEABILITY MEASUREMENT

In order to use the flow model presented in the previous paragraph, the minimum amount of material data needed to do an isothermal flow simulation are the following parameters: resin viscosity η, resin density ρ_r, reinforcement porosity (not explicitly mentioned yet, but necessary to determine the volume for resin) and reinforcement permeability tensor $\underline{K}$. Methods to measure the resin properties are well established, and porosity is also easily determined. Measuring permeability is relatively simple, but doing it accurately is very difficult because permeability is very dependent on porosity.

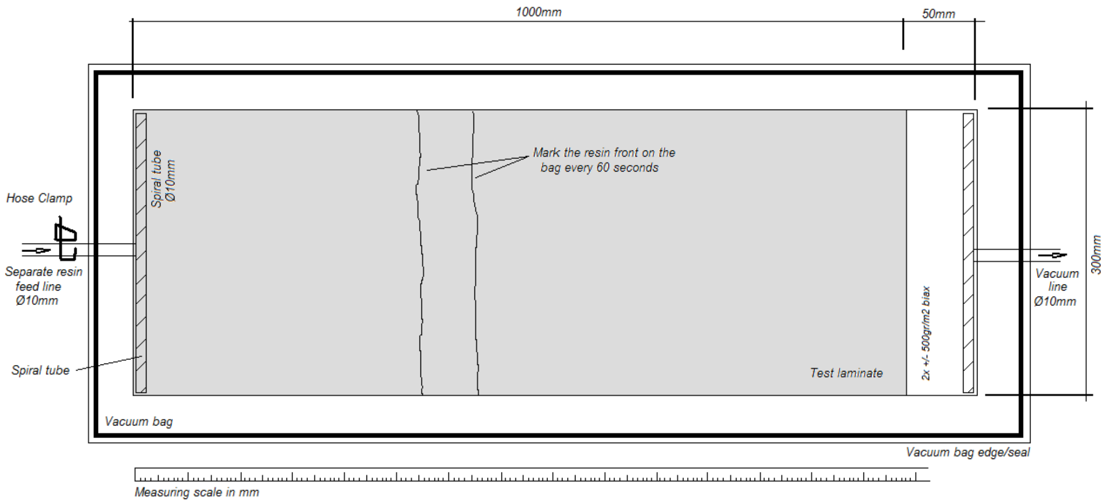


Figure 2: Standardized strip injection test for permeability measurement.

Therefore, we developed a standardized way to measure permeability, schematically shown in figure 2. During the strip injection test, the position of the flow front is recorded in time. This is sufficient information to calculate the permeability in flow direction. In case of anisotropic (e.g. triaxial NCF or unidirectional fibres) the measurement needs to be repeated in different directions.

INJECTION STRATEGIES

Choosing the best injection strategy is important to ensure that the reinforcement is properly impregnated without voids, or worse, air being trapped and within a given time frame. The reinforcement has to be completely wetted out before the resin starts to gel.

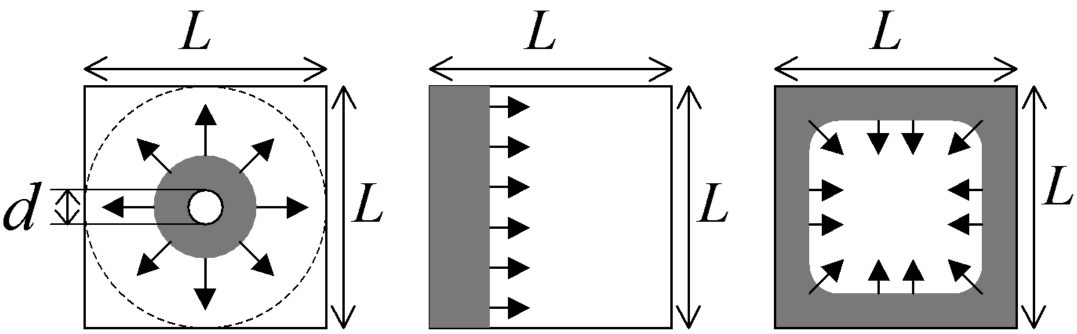


Figure 3: Three different injection strategies for a square plate with dimensions LxL. From left to right: point (slow to fast) injection (inlet diameter d), edge injection and peripheral injection.

Basically, all injection strategies, even the most complex ones, can be broken down into three basic methods (see figure 3): point, edge or peripheral injection. For those basic injection strategies, an analytical expression for the filling time can be derived [7], with a constant C that depends on the chosen injection strategy:

$$t_{fill} = C \cdot \frac{\eta L^2 \phi}{K \Delta p} \qquad (9)$$

The constant C depends on the chosen injection strategy and is given by:

- Point injection: $C = \frac{1}{16}\left[\varepsilon^2 + 2\ln\left(\frac{1}{\varepsilon}\right)\right] \qquad \varepsilon = \frac{d}{L}$
- Edge injection: $C = \frac{1}{2}$
- Peripheral injection: $C = \frac{1}{16}$

Peripheral injection is clearly the fastest method, while the injection time for point injection is very dependent on the diameter of the inlet. Therefore, injection time is very unpredictable. In addition, wetting out of the fibres takes place at the flow front, and peripheral injection results in the smallest variation in flow front speed. While this is not apparent from the analytical formula (9), it is an important parameter for the quality of the laminate. Therefore, peripheral injection is the preferred method.

Gravity and the ‘fishbone’ strategy

For the infusion of large parts, we have to deal with gravity. For every meter height difference, about 100 mbar of vacuum is lost: this is the force needed to lift up the resin. Infusing from top to bottom does not work because the air still under the bag will mix with the resin, resulting in a laminate with high void content. Using vertical feeding lines, combined with a feeding line in the length of a hull results in 3-sided configuration which is closest to the optimum (peripheral infusion) that can deal with gravity. Compared to typical SCRIMP technology, which consists of parallel lines which are opened in sequence, the advantages are:

- Any bubbles that get into the tubes will quickly travel up to the highest point through the vertical feeding lines.

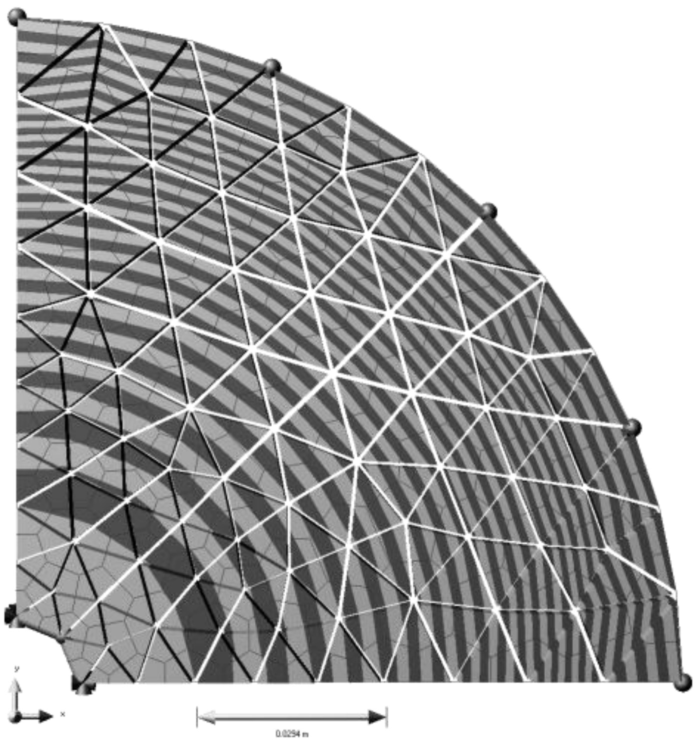
- There are no delays, because it is not necessary to wait for the resin front to arrive at the next feeding line before it can be opened. This allows for relatively slow filling locally with better wet out of the reinforcement as a result.
- Reduced man dependence, because there is no need to manage the resin feeds. This strategy works with a single feed, which is opened at the start of the infusion and closed when the part is full.

Therefore, the fishbone strategy is simply the preferred method from an engineering point of view based on the flow physics.

ACCURACY OF FLOW ANALYSIS

Application of the flow analysis software requires a good knowledge of the accuracy of the predictions. The numerical accuracy of the FEM/CV algorithm that we use is very high [3]. For edge injection, RTM-Worx gives results that are exact, because the pressure gradient is linear in that case and the flow front position is a quadratic function of time, which is also solved exactly by our numerical integration scheme.

The worst case for the model presented in this paper is point injection, because the pressure gradient is a logarithmic function of the radius in that case, a function that is difficult to capture with the piecewise linear FEM approximation. This case is presented in figure 4, and the conclusion is that the error due to numerical approximation in the implementation of this model in our RTM-Worx software is less than one per cent for only a few hundred elements!



E[-]	t_N [s]	Error [%]
80	5.22	1.9
152	5.28	0.8
482	5.34	0.4
2114	5.33	< 0.2

Exact fill time from analytical solution for filling of this particular quarter disk: 5.32 seconds.

E = number of elements
t_N = calculated filling time

Figure 4: Test case to determine numerical error: filling of a quarter disk. The grey bands show the flow front at equal time intervals. At the right, the table shows the calculated filling time and relative error for different meshes, from course to very fine.

Note that linear elements and first order time integration alone are not sufficient to guarantee this high accuracy. What is very important is that (1) the algorithms are mass conservative and (2) flow front propagation algorithm and pressure calculation are identical. The model presented in this paper meets both requirements.

In practice, typical models have at least a couple of thousand elements to capture the geometry and reinforcement layup of a part with sufficient detail. This means that numerical accuracy is never a problem and the difference between prediction and reality is only governed by the accuracy of the material parameters

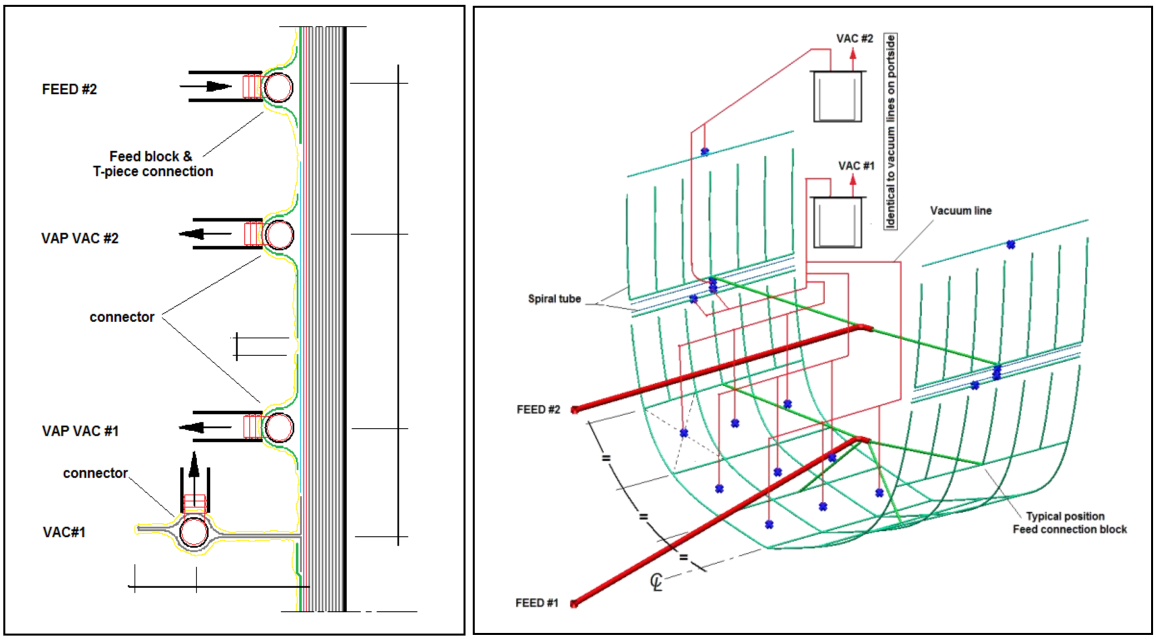


Figure 5: Principle of the 2-step continuous bag & reinforcement method. Layout of membrane material, vacuum connections and resin inlets shown at the left. At the right, the setup for a full scale infusion trial is shown.

CONTINUOUS REINFORCEMENT, SINGLE BAG METHOD

For the infusion of a 62 meter long minesweeper, a project done in cooperation with SNSZ shipyard in Saint Petersburg, reinforcement had to be continuous. Because of the height of 8.5 meter, infusion had to be done in two steps. Basically, this can be done with a partial infusion, filling only the first 5 meters in height, followed by a second infusion after the resin from the first shot has cured. However, the flow front typically contains a lot of voids and is not necessarily completely porous. This would lead to a weld line with a very high void content, which is definitely not acceptable. Our conclusion was that the issue to solve in this particular case can be formulated as: ‘how can we create a sharp transition between wetted out and dry fibres’. This would be sufficient to do two injections and create a perfect weld in between.

Membrane material

To get rid of unwanted voids, the solution is to use membrane material. This Gore-Tex like material is permeable for gas (e.g. air) and impermeable for resins and commercially available. The behaviour of the membrane is not difficult to understand: once it is fully wetted out, it closes. Consequence of this behaviour is that we could theoretically succeed in creating a sharp transition between dry and wet fibres with very low void content, but that at 100% fill of the first stage, the vacuum would be closed off and we would not be able to compensate for the hydrostatic pressure due to the weight of the resin. We solved this by adding a second vacuum line, which is separated from the laminate by a strip of glass NCF that takes long enough to fill to allow the membrane to do its job.

For the second stage, we obviously need a resin feed above the membrane. However, in order to control exactly where the first infusion stops, and to be able to ensure complete fill at the weld line, we need to fill a short section from top to bottom. Another strip of membrane material will guarantee a perfect fill. The final layout at the transition line with membrane, vacuum connections and feeding line is shown in figure 5, together with the basic design of an injection strategy to fill the entire part.

Degassing and Injection equipment

The first stage requires an injection of about 14 tonnes of resin in a single shot. With such a large quantity of resin, manual mixing is not an option, mixing and degassing in batches (of 200 kg) like we did in other projects (like the hulls for the Oyster 100' and 125') does not scale: it would require involving too many people and the number of operations leave too much room for error. In addition, the resin feeding lines have a length of up to 30 meter long and even with a diameter of 1.5", the pressure loss is considerable. Finally, for the second shot of 6 tonnes of resin, in order to eliminate unwanted hydrostatic pressure we would need to position the resin containers on a platform at a height of 6 meters. This is clearly not feasible in practice.

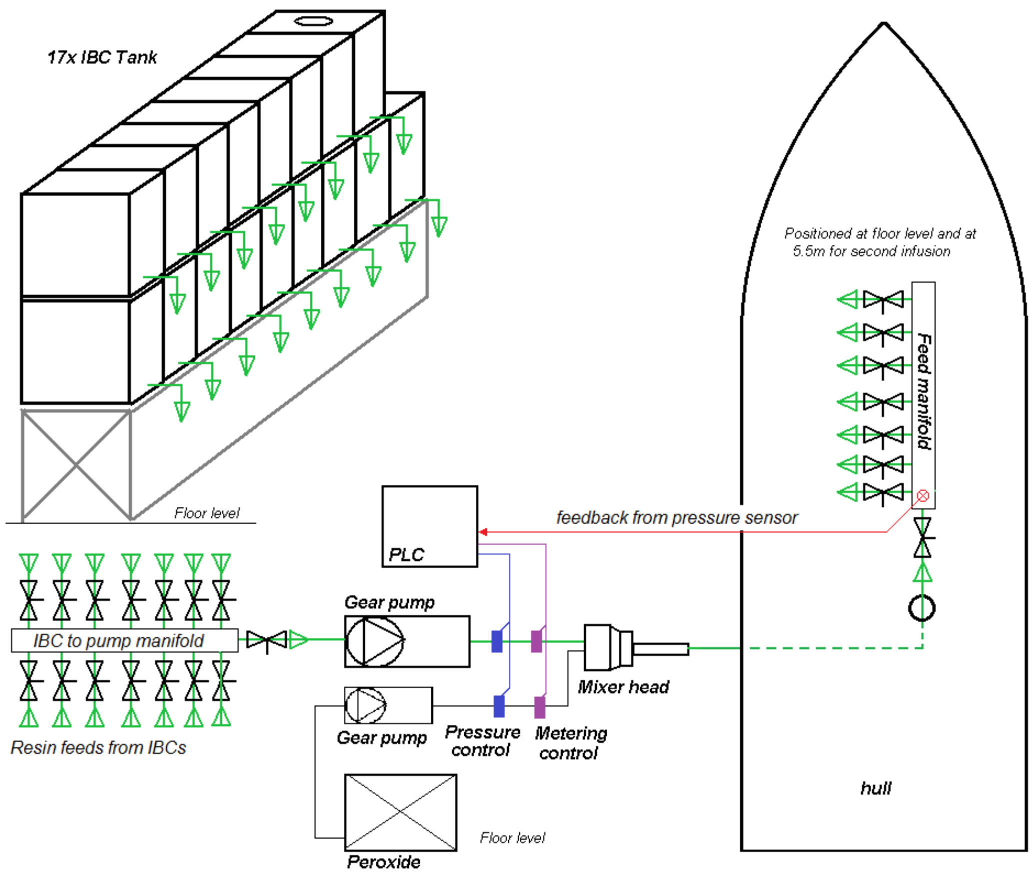


Figure 6: Schematic overview of the 2KM degassing and mixing equipment. Degassing was done prior to injection in a separate step. During injection, the mixing pump output was controlled by a pressure sensor located on the feed manifold, close to the bag to compensate for pressure losses in the long (30 meter) feeding tubes while guarding the vacuum level under the bag.

In order to reduce the risk to a manageable level, equipment was designed to degas and mix the resin. This equipment (supplied by 2KM) is show schematically in figure 6. With a pressure sensor in the feed manifold to guard the pressure level and control the pressure at and output of the mixing pump, the pressure losses in the feeding tubes can be compensated while the vacuum under the bag is guaranteed. With this system, only one single feeding tube from mixing pump to manifold is necessary. For the second stage, the hydrostatic pressure difference because of the 6 meter height difference is no longer an issue, the feedback control with the pressure sensor at the manifolds (now positioned at 5.5 meter height) automatically takes care of it.

Infusion

The two infusions to inject the 62m minesweeper hull were successfully carried out by SNSZ on June 30 and July 1, 2011. The first shot of 14865 kg vinyl ester resin took 172 minutes; the second shot of 6065 kg resin took 151 minutes.

CONCLUSION

While there is no theoretical limit to the size of infusions, and smaller infusions can be done quite easily, large infusions require use of robust technology to reduce the risks to a manageable level. Flow analysis technology makes it possible to engineer the injection process up front, to analyse the bottlenecks and design an injection strategy that has a low sensitivity for the variations that occur in practice. In combination with mixing and degassing equipment, this makes it possible to infuse large quantities of resin in a single shot.

One of the major issues that limited infusion of large parts was the maximum height that can be done in a single shot due to the hydrostatic pressure resulting from gravity. The technology we developed, which involves the use of membrane material and mixing pumps controlled by a pressure sensor close to the bag eliminates the height limit: continuous reinforcement can be laminated under a single bag with infusion. The only limit that still exists is the maximum height that can be done in a single shot. But the extra time this requires is not really an issue for the parts we are dealing with in this context: the time required for the infusions is only a small fraction of the preparation time.

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