SPECIAL PROBLEMS DUE TO VACUUM INJECTION OF LARGE SHIP STRUCTURES

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ABSTRACT

The most common production system for large composite structures in shipbuilding industry is still hand lay up. In order to improve and to reproduce quality of the products, attempts are undertaken to produce large structures by means of vacuum injection techniques. This and the new restrictions, ordered by the Dutch legislation on the amount of styrene evaporation is a major reason to explore and exploit the possibilities of this technique. The size and the complex 3-D shape of the (hull) structures and stacking sequence of the laminates to be injected are major obstacles. However, removable bulkheads may be rather flat structures and only the size problems remains. Therefore, such bulkheads are chosen for first attempts, described in this paper.
To overcome part of these problems several tests are undertaken to get a proper insight in the time needed for injection. Based on data obtained from injection tests of small flat panels the time needed for injection of larger laminates will be predicted based on the models of Darcy. Problems during injection are described and solutions are given.

INTRODUCTION

The use of Fibre Reinforced Plastics (FRP) has shown to be a major success in shipbuilding industry in the last decades. The most important constituents of FRP are glass fibres as reinforcement and a polyester resin as a matrix. FRP has a number of advantages above steel, wood and aluminium. The economical benefit is especially large in the production of small vessels with relatively many double curved panels and large production volumes.
Larger structures of FRP are also common in the marine industry. Vessels up to a length of 70 metres are produced, nowadays. The production volume of these is often limited to < 10 products. These vessels are produced either on a positive or in a negative mould.
From the early days the most convenient production process seemed to be hand lay up. It is a cheap method, well controllable, a lot of experience is available and a certain quality is assured. Polyester resin contains styrene as a reactive solvent (co-monomer). However the disadvantage of styrene vaporisation and labour intensity and the need for higher quality are becoming more and more important. Dutch legislation restricts the styrene content in the air to 25 ppm. This implies the need for a closed mould technique. Developments of vacuum injection techniques of large marine structures already date from the late seventies. Le Comte (Holland) experimented with the injection of boat hulls in the eighties up to a length of 15 – 20 metres and maximum laminate thickness of 20mm. [1]
Recently some hulls for leisure craft are finished in experimental set ups (see fig 1)
Other large structures are blades for wind turbines, they are shown below. (fig. 2)

But still the most common production system for large composite structures is hand lay up. In order to improve and to reproduce quality of the products attempts are undertaken to inject large structures by means of vacuum injection techniques. [ref. 2, 3, 4]
Still one of the main problems industry fears is the appearance of leaks in the foils, rims and seams and the accompanying risk of product damage. Covering large laminate surfaces sheets have to be glued together implying an extra risk. To avoid this risk, a large sheet of FRP can be made. Accompanying disadvantage is that the FRP sheet is less transparent than the plastic sheet is and the process is harder to follow and possible leaks are harder to detect.

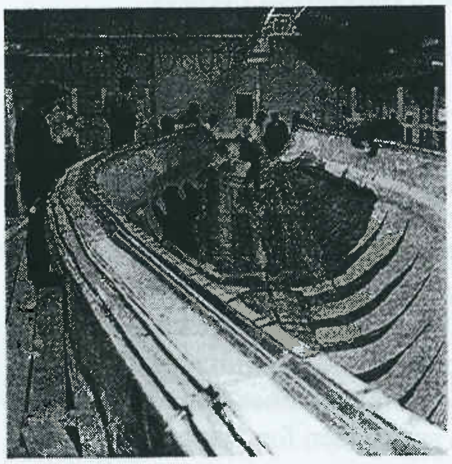

figure 1: injection of 17 m boat hull
(photo: TNO - CLC, Holland)

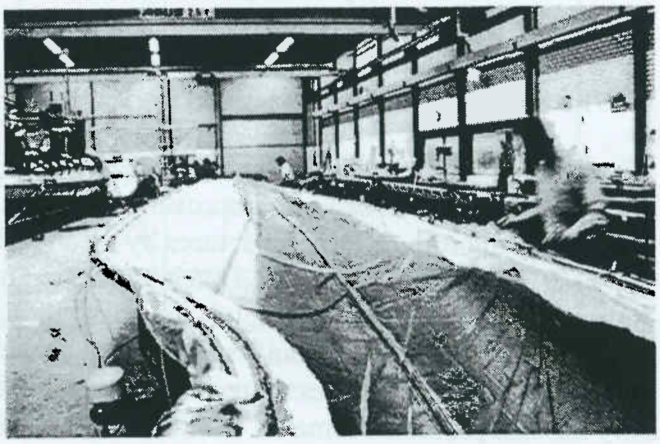

figure 2: injection of wind turbine blades
(photo, TNO-CLC, Holland).

NEW PRODUCTS OF FRP

Although FRP has become an important material in marine structures, its success is mainly limited to leisure craft and navy and fishing vessels. The introduction of FRP material in structures of conventional ships is difficult. A structure of FRP is thought to have more disadvantages. Cost will be too high and the reliability in operation is thought to be less.
In 1997 the project Composites in Ship Structures started at the Ship Structures Laboratory and the Laboratory of Engineering Mechanics and Fibre Reinforced Plastics. The project contains a feasibility study of large load bearing secondary ship structures made of FRP, like a removable bulkhead and hatch covers. In order to be considered feasible for conventional ships, the following criteria are set. The composite structure compared to a steel structure has:

- to be 50 % less in weight
- to fulfil the same performance requirements
- to be of the same cost level

The structures are designed as relatively simple; large flat panels in a sandwich construction, because a sandwich construction is ideal regarding weight and bending stiffness. Bending is the dominant loading system on such a bulkhead. The required combination of low weight and low cost level implies that a cheap but very good production technique has to be chosen, cheaper and higher quality than for conventional hand lay up processes is required. Vacuum injection can provide a solution in both a high stiffness and a cheap production.
However, the possibilities of vacuum injection technique for panels of the required size of 8,50 x 11,1 metre were insufficiently known or at least insecure. No references could be

found for such large structures on the influence of the stacking sequence, influence of thickness, influence of flow direction relative to the flow direction, calculable impregnation etc. therefore, some experiments are performed

In the first part of the research project a number of different type of sandwich beams were tested. These beams are 2 meters long and 10 cm wide. In order to get a good comparison between the beams, a repetitive quality of the laminate is necessary. Considering the number and the quality of the beams, the exploration of vacuum injection technique as a production technique was desirable. This technique is investigated in this stage of the project.

CONCEPT OF VACUUM ASSISTED INJECTION MOULDING TECHNIQUE

The dry laminate is draped In the mould (in this case the table). It is covered by a plastic (PE) sheet. The rims are made airtight by taping. An inlet pump is connected to the mould at one side and on the other side an outlet pump is connected. (see fig. 3) The pressure at inlet side will be substantially higher than at the outlet side but lower than or equal to atmospheric pressure.
On both sides a container filled with liquid nitrogen is connected between mould and pump to prevent styrene vapour coming in the pump. Due to cooling the vapour will condense in this container. On both pumps extra digital pressure sensors are mounted. The container with matrix material is placed at the inlet side of the mould, between the nitrogen (styrene trap) container and the mould.
Pumps, containers and mould are connected by flexible, transparent, reinforced tubes.
The pressure difference accomplished by both pumps is the driving force for flow of the resin through the laminate. The velocity of the resin can be influenced by the magnitude of the difference. However, the atmospheric pressure is the maximum value for this pressure difference. The pressure difference between the inner side of the mould and the atmospheric pressure at the outside of the mould compresses the laminate. The fibre fraction in the laminate will be influenced by this pressure difference.
Only the product surface, facing the mould is smooth. The smoothness of the other surface depends largely on the type of the top layer in the laminate. Rovings will effect in general a smoother result than CSM. To achieve a smoother result it is also possible to remove the top layer.

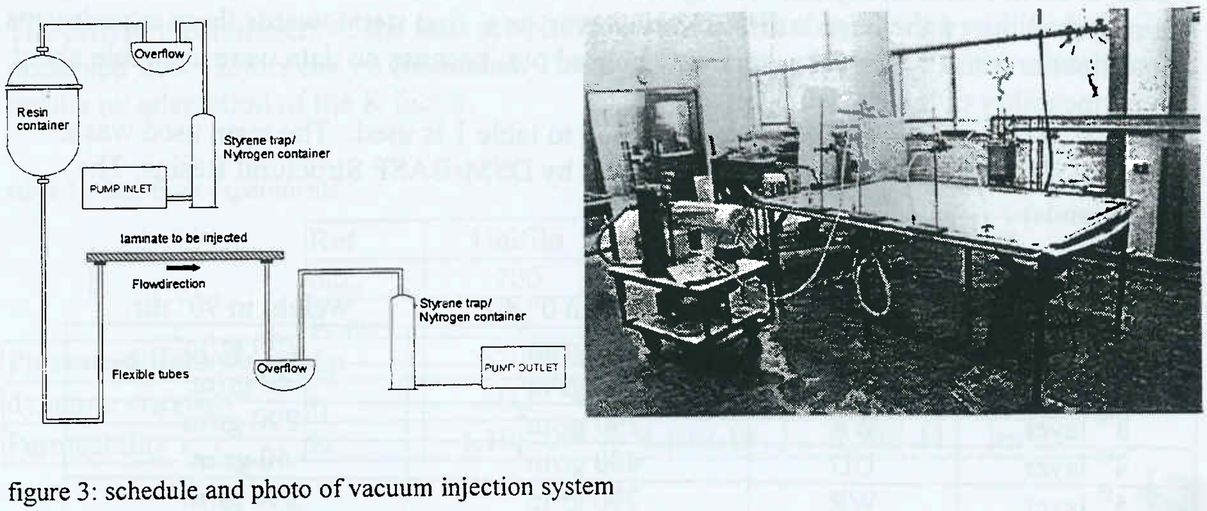

figure 3: schedule and photo of vacuum injection system

THEORY OF FILLING A POROUS VOLUME

The time needed for impregnation can be calculated with the aid of the empirical Law of Darcy [5], This is explained in an accessible way by Harten and Nijhof [6].

$$q = -\frac{k}{\eta}\frac{dp}{dx} \qquad (1)$$

This can be transformed to:

$$t = \frac{\eta x_F^2}{2K\Delta p} \qquad (2)$$

Equation 2 represents the filling process along a line, where:

q	=	specific volume	[m/s]
η	=	dynamic viscosity of filling medium	[Pa.s]
k	=	average permeability of the fibre package	[m^2]
K	=	k/ψ = flow factor	[m^2]
ψ	=	porosity of the fibre package	[-]
dp/dx	=	pressure gradient	[Pa/m]
Δp	=	pressure difference between inlet and outlet	[Pa]
x_F	=	injected distance	[m]
t	=	injection time	[s]

K will be determined experimentally. In [4] it is stated that this factor can only be estimated well by experiments. As can be seen from formula 2 a low dynamic viscosity will contribute to a quick injection.

A higher permeability can be achieved by the addition of highly permeable transport layers. The resin will flow easily and quickly through these layers over the laminate to be injected. Additionally the resin will impregnate the fibres of the other layers.

PERMEABILITY TESTS

Plates of 2,1m^2, with an asymmetric injection are taken as a simulation experiment for the filling behaviour of the large bulkheads. However, as a first step towards these experiments, some smaller tests (0,15x1,00meter) were carried out, because no data were available about the permeability of the chosen laminate.

For most of the samples the laminate according to table 1 is used. The resin used was a polyester resin: Synolite 0592 – N – 2. (offered by DSM•BASF Structural Resins, The Netherlands)

table 1: layer sequence

no. of layer	type of layer	weight in 0° dir.	weight in 90° dir.
1st layer	WR	290 gr/m^2	290 gr/m^2
2nd layer	UD	480 gr/m^2	40 gr/m^2
3rd layer	WR	290 gr/m^2	290 gr/m^2
4th layer	UD	480 gr/m^2	40 gr/m^2
5th layer	WR	290 gr/m^2	290 gr/m^2

The fibres in the UD layers lay perpendicular to the resin flow during impregnation. This is thought to be an unfavourable orientation for the resin flow. However, this orientation is necessary, because a preferred fibre orientation in the length direction of a bulkhead necessary to withstand the in service loads on the bulkhead. Injection in the main fibre direction would imply that the even larger disadvantage of larger injection length is accepted. Obviously, some additional transport layers are needed for a proper resin flow.
The following transport layers are considered and are placed on top of the bare laminate

1. Injectex (Roving, 295 gr/m^2)
2. Unifilo (CSM, 450 gr/m^2)

TEST RESULTS SMALL SCALE

Fig 4 indicates that a transport layer is required indeed, to inject more than 45 cm of the laminate. The resin starts curing after 2 hours and 15 minutes and further impregnation is impossible.
A laminate with a Unifilo (CSM) layer shows the fastest impregnation results. The laminate in combination with injectex shows a smoother result than in combination with Unifilo. The quality seems to be a bit better in case injectex is used (visual inspection). The quality is checked on void content (visually), thickness and weight fractions. No test samples are taken out for mechanical testing.

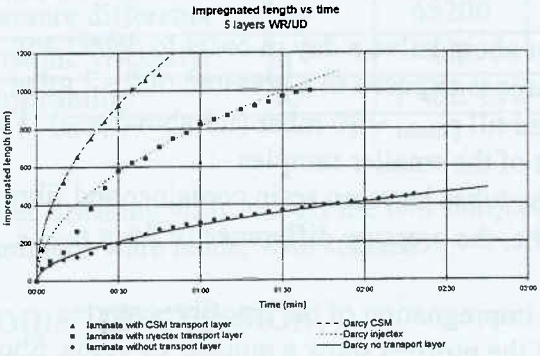

figure 4 : results test of samples (0.15 x 1.00m)

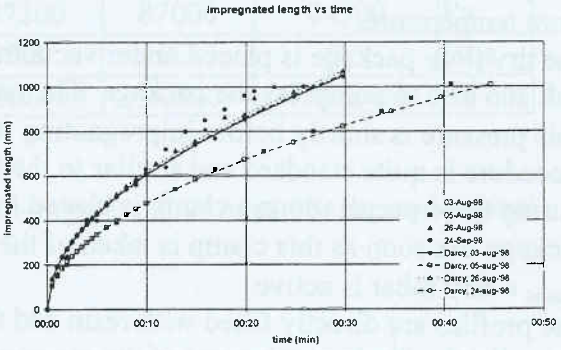

figure 5 : flow results of laminates (1.0 x 2.1m)

The different parameters of the tests are plotted in table 2. In combination with formula 2 the presented flow factors can be calculated. The equation of Darcy is fitted to the experimental results by adaptation of the K factor.

table 2 : data from experiments

	Ref	Unifilo	Injectex	no transport layer	
	p_{inlet}	700	700	700	mbar
	p_{outlet}	50	28	50	mbar
Pressure difference	Δp	65000	67200	65000	Pa
dynamic viscosity	η	0.3	0.3	0.3	Pa.s
Permeability	K	1.10E-09	4.10E-10	5.50E-11	m^2

TEST RESULTS LARGE SCALE

After finishing with success on small samples discussed above larger panels of 1,00 by 2,10 metre are prepared for injection. Unifilo is chosen as a transport layer on top of the laminate described in table 1. The reason for this choice is that permeability is the dominant parameter over surface smoothness for the large removable bulkheads.

During the injection process of the first large panel (reference 03-aug-98) a substantial number of voids appeared in the laminate. The laminate can't be used for the sandwich structures and other mechanical testing. The voids appeared although the laminates were produced under the same conditions (temperature, material and pressures are kept the same) as for the smaller samples. The only difference in production system was the application of a profile at inlet- and outlet side. This profile establishes a parallel resin front due to the several inlet openings along the profile. (compared to one inlet opening establishing a circular resin front) But this should benefit the injection process.

On forehand the resin in the resin container is boiled for 30 minutes under very low pressure (p_{inlet} < 6 mbar) to free the resin from air. After boiling the resin the pressure is raised till $p_{inlet} \approx$ 680 mbar. Air enclosed in the resin can be removed well by boiling the styrene in the resin. The pressure has to be decreased beneath the boiling pressure of styrene (p_{boil} = 12 mbar) at room temperature.
The dry fibre package is placed under vacuum for about halve a day in order to detect any leak and also to compress the package. The package is exposed to a pressure of 0 - 2 mbar. This pressure is shortly before impregnating raised till $p_{outlet} \approx$ 30 mbar (far above p_{boil}). This procedure is quite standard and similar to the test of the smaller samples.
During these preparations a clamp is placed on the tubes between resin container and fibre package. As soon as this clamp is taken of the tube, the pressure difference of $\Delta p = p_{inlet} - p_{outlet} \approx$ 650 mbar is active.
The profiles are directly filled with resin and the impregnation of the dry fibres starts immediately. Resin coming out of the grooves of the profiles show a number of voids. Shortly after impregnation starts. These voids disappear and a continues flow of pure resin comes out of the profile. In the tube no voids can be seen. During the injection process the voids keep on appearing in the laminate. The voids move faster in the forward direction of the resin front than the resin does. This was explained in [6], by the pressure gradient in the resin, along the product. However new voids keep appearing and some of them stay behind and seem to have 'stuck' in the fibres.
Because the problems where recognised during the process several attempts where undertaken, without success, to remove the voids by chancing p_{outlet} for a few seconds.
After the in- and outlet ports are closed the pressure in the mould has to equalise. Voids close to the outlet side shrink and some vanish due to local pressure increase. However closer to the inlet side the voids are bigger and the intensity is much higher due to local pressure decrease.

Directly after the test a new laminate is prepared (reference 05-aug-98) following the same procedure. It is suggested in [6] that due too the high velocity of the resin the voids are trapped. In order to decrease the velocity the inlet pressure is decreased from 680 to 500 mbar.
Also this laminate shows a tremendous number of voids.

In new laminates (reference 26-aug-98 and 24-sept-98) the absolute pressure at in and outlet sides are raised. Also the pressure difference Δp is higher. These laminates show satisfying results with few voids only. Preparation (apart from the pressure changes mentioned above) is the same in all of these tests.

Results of all the larger scale tests are plotted in figure 5. The different parameters of the tests are plotted in table 3. The presented flow factors can be calculated from the experimental data, using (2). The equation of Darcy is fitted to the experimental results by adaptation of the K factor.
The flow factor, K, of laminate 03-08-98 is slightly higher than experimental data show in table 2. The lower flow factor of laminate 05-08-98 can be explained by a higher pressure difference between inner and outer side of the mould and the resulting higher fibre content. The lower permeability of laminate 26-aug-98 and 24-sept.-98 contradicts this explanation again. However Δp is in this case significantly higher.

table 3 : exp. data

	ref.	03-aug-'98	05-aug-'98	26-aug-'98	24-sept-'98	
	p_{inlet}	680	500	990	960	mbar
	p_{outlet}	28	28	120	117	mbar
Pressure difference	Δp	65200	47200	87000	84300	Pa
dynamic viscosity	η	0.3	0.3	0.3	0.3	Pa.s
Permeability	K	1.40E-09	1.20E-09	1.10E-09	1.10E-09	m^2

After finishing with success the two samples (26-aug-98 and 24-sept-98) Four additional laminates were made, with success.

VOIDS - DISCUSSSION

Air enclosures

Air can be enclosed in fibres and in the crossings between the fibres. Even with very low pressures down to near vacuum it is hardly impossible to vanish all the air from and between the dry fibres. Under normal circumstances air is pushed forward by the resin front. Also trapped air voids can overhaul the resin front because of the pressure gradient in the resin. This "swimming upward" towards the location with lower pressure is well explained in [6]. However, some voids may be trapped in "fibre pockets" and not move at all. Trapping of air becomes more probable for the "turbulent" resin flow at large injection speeds using Unifilo transport layers.
The hypothesis of entrapped air by the resin is supported by the fact that no voids are enclosed by the laminates where injectex or no transport layer at all is used (where resin velocity is much lower).
However this theory doesn't explain the occurrence of voids in the resin coming directly out of the profiles because there are no fibres. Also under similar circumstances in smaller samples these voids do not occur.

Styrene vapour

After carrying out some additional tests (not described) the problems are solved with raising absolute pressures. Because the problems are solved by applying higher pressures it looks like the voids are filled with styrene vapour. Although p_{outlet} = 30 mbar is much higher than p_{boil} of styrene. Possible is that local pressure drops (sudden volume changes in a 'turbulent' flow) generate a lower pressure than the vaporisation pressure of styrene (= 6 mbar). This mechanism might occur when resin is coming out of the profile at the start of the injection procedure.

Contradicting this theory is that even if there are local instabilities of the pressure, the pressure close to inlet port is near 680 mbar and still voids are present. Polyester at this pressure is expected to have a quite sufficient solving capability for the styrene.

CONCLUSIONS

After carrying out additional tests it turns out that higher absolute pressures and increase of the pressure difference Δp from 650 to 860 mbar solve the problems of voids appearing in large laminates. Consequently, it is concluded that large products, with an unfavourable fibre orientation regarding the resin flow direction, like removable bulkheads can be produced. Still unexplained is the difference in appearance of voids in larger (2.1m^2) laminates and smaller laminates (0.15m^2).

A large laminate with Injectex is not yet investigated because the Unifilo material was preferable in the project Composites in Ship Structures. Unifilo was preferable because of higher resin flow velocity.

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