Analysis of Laminate Thickness Influence on Compressibility Behavior in a Rift Process

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Abstract—RIFT (Resin Infusion under Flexible Tool) process modelling requires accurate material data like resin viscosity, reinforcement compressibility and reinforcement permeability. During the mould closing, the compression phase and the resin flow are important stages that strongly influence the quality of the obtained parts. In RIFT process the upper mould is a formable vacuum bag: its flexibility makes the pressure field change the local compaction state of the reinforcement and so it alters the permeability. Preform compaction depends on its compressibility, that is influenced by laminate thickness: the aim of this work is to analyse the relation between them. Moreover, this analysis is carried out observing preform deformation during process condition, in fact compression is applied by vacuum bag instead of compression testing machine.

Keyword-Liquid Resin Infusion, RIFT, compressibility behaviour, fabric compaction

I. Introduction

Nowadays LRI (Liquid Resin Infusion) processes are widely used for manufacturing of composite parts in different fields, from the aerospace to the aeronautical or the automotive, because of inexpensiveness of rough material and increasing quality of produced parts. In LRI process the dry reinforcement is laid on a rigid tool, then the upper mould is closed and finally the resin is introduced by an overpressure or by means of vacuum. During mould closing in LRI processes, compression phase and resin flow are important stages that strongly influence the quality of obtained parts [1], [6]. RIFT (Resin Infusion under Flexible Tool) is a particular LRI process in which there is a formable vacuum bag as upper mould: its flexibility makes the pressure field (that induces resin flow) change the local compaction state of the reinforcement and so it alter the permeability, because this last depends on compaction state [7].

RIFT process modelling requires accurate material data like resin viscosity, reinforcement compressibility and reinforcement permeability. In this work the attention is mainly focused on the compressibility of reinforcement, particularly on how it is influenced by preform thickness. In fact it has been observed that compressibility behaviour changes with preform thickness that, obviously, depends on the number of plies. Compressibility tests have been carried out on three different kind of preform, constituted by 5, 10 and 20 plies of plain weave glass fabric. A compressibility model has been found out from tests results and it has been verified by a 15 plies preform.

At present most compressibility experiment on fabric are conducted with a typical compression testing machine. The latter consists of a stainless steel cylindrical pot, within which a guided piston induces the exact amount of fibre compaction in the z direction (perpendicular to laminate plane), imposing mechanical loadings to fibrous preforms. Test samples of fibrous preforms are placed between two plates: during the test, the movement of the piston is controlled and so the applied force too. Compressibility curve can be obtained measuring reinforcement deformation and applied load. In this study, the analysis is carried out through a new methodology: preform deformation has been observed during vacuum application, while thickness and pressure changes have been measured in-situ. Therefore tests have been carried out under conditions similar to a conventional RIFT process, moreover no typical compression testing machine has been required to perform these experiments. In addition, because there is no test fluid, pressure sensors can be placed close to the specimen. The new methodology used for this work has been explained exhaustively in [8].

II. Background

During flow of resin in the reinforcements the total external pressure applied to the composite (that is the atmospheric one) is equal to the sum of the resin pressure and the pressure supported by the fibre network, i.e.

$$P_{ATM} = P_R + P_F \quad (1)$$

where P_R is the resin pressure and P_F is the fibre pressure (pressure supported by the preform). The fibre pressure is primarily a function of the preform fibre volume fraction v_f, but it is also strongly influenced by the presence of a wetting fluid. On the other hand the resin pressure is influenced by the boundary conditions applied at the flow front and at the resin supply. For a standard RIFT process, the resin pressure is maintained at 1 atm in the injection reservoir and 0 atm at the flow front (vacuum side) [9].

The compressibility of materials is a function of both fabric weave style and mechanical flexural properties on the micro and macro scale, moreover this relation changes with the number of layers and fibre orientation at the interface between the plies [10].

Few studies have been found in literature regarding compression behaviour of the reinforcement during RIFT, and both theoretical and experimental models have been proposed .

Among theoretical ones, some researchers proposed a 3D model of the unit cell and then they established analytical expressions for relations among the fibre volume fraction, the applied compressive force and the preform thickness reduction on the basis of this model and beam theory in the mechanics of materials [12], [14]. The same researchers then developed a micromechanical model to investigate elastic compression behaviour during compaction of both single-layer and multi-layer of woven fabric preforms, evaluating the effects of the meso-architecture on their compaction behaviour, and they found it much more complicated in a multi-layer woven fabric preform than in a single layer one. Other researcher presented another theoretical model based on two approaches: i) micromechanical; ii) rheological [15]. In the first one, based on the equation of continuity, Darcy's law and Terzaghi model, the total stress in the mould was equal to a viscous stress due to the fluid flow and to an elastic stress due to the fibres response. The second approach was a rheological one where the models of Zener, Burger and Maxwell were used. Another researcher investigated analytically the effect of preform compressibility on the fibre volume fraction and pressure distribution in resin saturated region [16]. Totally different fibre volume fraction and pressure fields during the resin infusion process were obtained, which also yielded the different permeability distribution and flow front advancement.

As regards experimental models, the compaction of fibres can be described through an empirical power law (2), which relates compaction pressure and v_f [17], [18]:

$$v_f = v_{f0} * P_{COMP}^B \tag{2}$$

where P_{COMP} is the difference between the fluid and the atmospheric pressures, v_f is the fibre volume fraction and v_{f0} is the initial fibre volume fraction. Moreover the reorganization of the fibre network and the effect of friction were studied. In fact, dry and wet compaction behaviours are different, because of lubricating action of liquid matrix. The results of sequences of successive compaction cycles applied to dry preforms and to preforms saturated with distilled water and silicon oil were presented. Another equation used to model compaction can be found in [19], and it is capable of modelling compaction effects of woven preforms on a phenomenological basis. It can be expressed as:

$$\sigma_{zz} = A_S \frac{\left(\sqrt{\frac{v_f}{v_0}} - 1\right)}{\left(\sqrt{\frac{v_a}{v_f}} - 1\right)^4} \tag{3}$$

where σ_{zz} is the preform stress, A_S is the empirical spring constant, v_f is the fibre volume fraction, v_a is the maximum possible fibre volume fraction and v_o is the unloaded fibre volume fraction, that refers to the volume fraction of fibres when no stress is applied.

Other researchers set an experimental device to impose hydro-mechanical loadings to fibrous preforms [20], [22]. The compaction phase as described through Toll and Manson's model, based on a power law formulation, is defined according to Equation (4) as:

$$v_f = A * P^B \tag{4}$$

where A and B are the empirical coefficients of the power law, while P is the pressure supported by the preform.

In this work, Equation (4) is chosen to do data regression on experimental results.

III. Experimental Equipment for Compressibility Evaluation

Compaction experiments were conducted in the “Laboratory of Technologies and Manufacturing Systems” of the “University of Cassino and Southern Lazio” in order to determine the relation between compressibility behaviour and preform thickness, that depends on the number of plies.

The preform studied in this work was a glass woven fabric 0°-90°, with a plain weave architecture. Compressibility tests have been carried out on three different kind of preform, constituted by 5, 10 and 20 plies of fabric. Plies of 10 cm x 10 cm fabric were carefully cut and placed on the tool. To measure thickness variation during the vacuum by a laser displacement, a rigid plate was placed upon the laminate, so that the measured point was representative of the entire surface of the specimen, under the hypothesis that the sample was compressed uniformly. Similar conditions to a conventional RIFT process were reproduced: outlet tubing was connected to the vacuum pump, a distribution network was placed in this pipe and around the inlet side of the specimen to better uniform the vacuum among the layers. The inlet resin tubing was not present in the test equipment, as there was no resin infusion. The entire test equipment consisted of:

- a vacuum pump (Edwards RV5);
- a flat metal plate as tool;
- a system suitable to regulate the level of vacuum;
- pressure sensors (an analogue vacuum gauge and a pressure transducer Druck PMP 1061), the latter with a precision of 0.25 kPa;
- a laser displacement sensor (LDE High Speed), with a precision of 10μm.

Fig. 1 shows the entire set-up described above, while Fig. 2 illustrates vacuum bag details.

Vacuum bag was initially at atmospheric pressure to set at zero the laser displacement sensor, which was placed above vacuum bagged preform held up by a rigid support. Then, vacuum was gradually drained, thanks to the regulating system of resin trap that allows to control the vacuum level and to carry out various measurements. The displacement was recorded at different levels of pressure from the atmospheric one to the maximum vacuum achievable, after allowing displacement to reach steady state at each of these levels. The outputs of pressure transducer and of laser displacement sensor were recorded by a PC-based data acquisition system and were analysed. The experimental set up is shown in Fig. 3a, b.

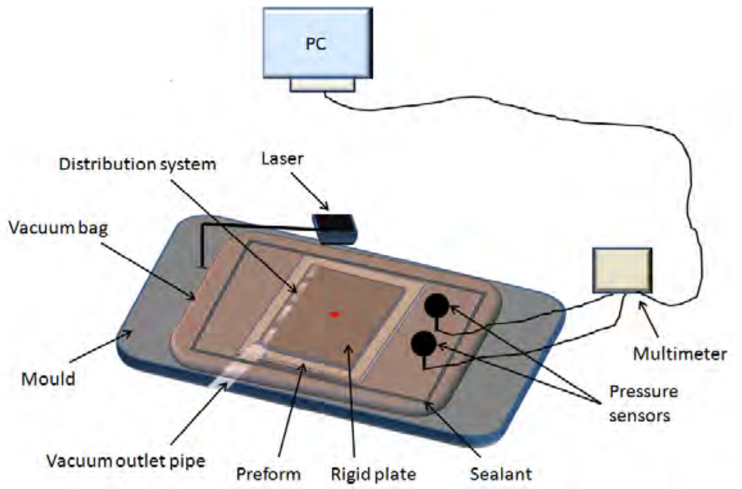

Fig. 1. Compressibility test equipment.

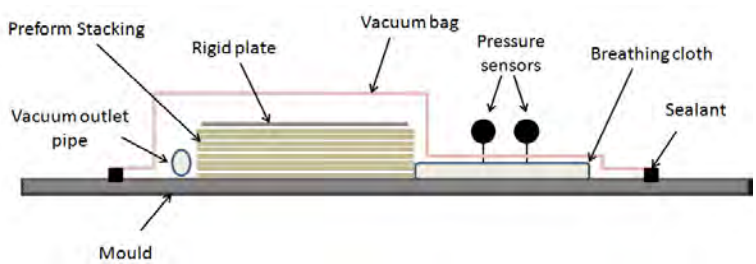

Fig. 2. Vacuum bag scheme.

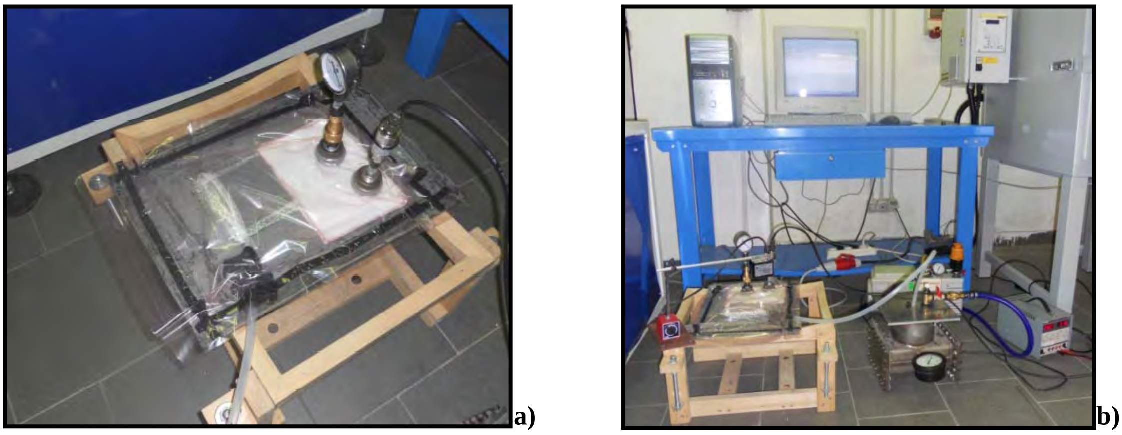

Fig. 3. Laboratory equipment used for the experimental test.

Being able to derive thicknesses during the test, the values corresponding to fibre volume fractions were obtained from the thickness through the relation shown below:

$$v_f = \frac{n * A_f}{h * \rho} \qquad (5)$$

where v_f is the fibre content, n the number of layers, A_f the fabric surface density, h the thickness and ρ fibre density.

IV. Compressibility Models

A series of 5 tests for each kind of laminate were carried out, so 15 specimen were accurately prepared and tested. The results of this tests are reported in Fig. 4-6, as mean value of v_f for each different pressure level, and a data fit is added. The function used for this data fit is a power one, according to Equation (4), and the coefficient values are reported in Table I. The result are also compared between them, as visible in Fig. 7: it can be seen that the thinner the preform is, the higher the fibre volume fraction is.

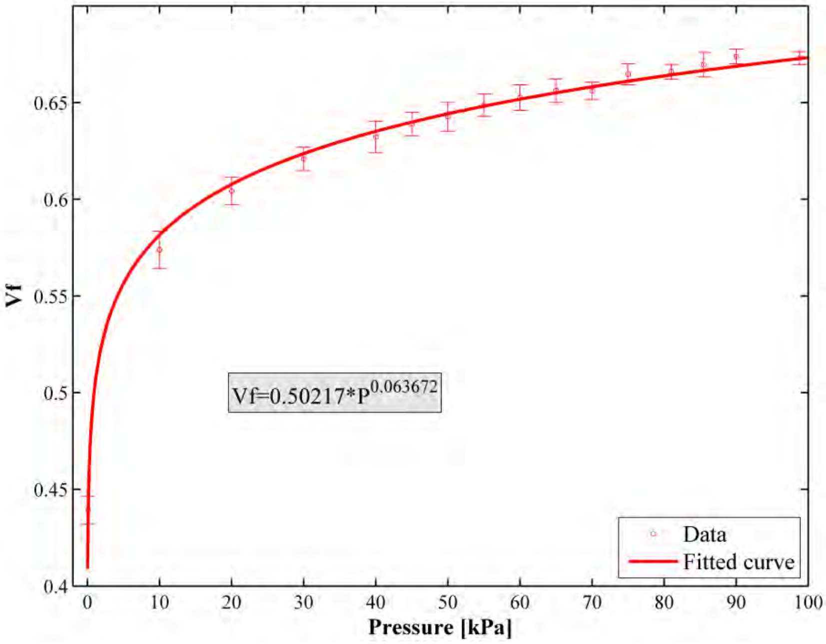

Fig. 4. Experimental data and regression for 5 plies preform.

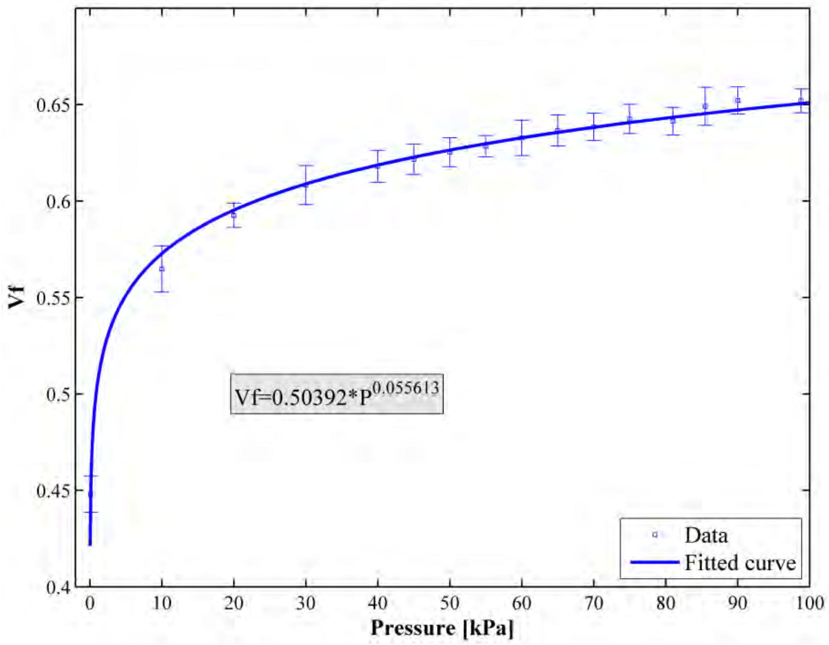

Fig. 5. Experimental data and regression for 10 plies preform.

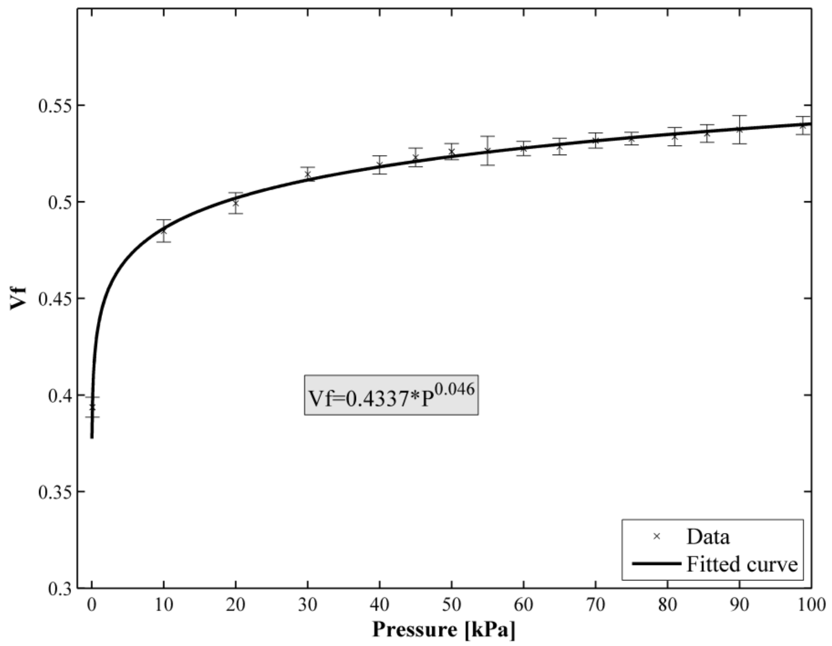

Fig. 6. Experimental data and regression for 20 plies preform.

TABLE I
Regression Coefficient from Experimental Test

N. of Plies	Coeff. A	Coeff. B
5	0.50217	0.063672
10	0.50392	0.055613
20	0.43370	0.046000

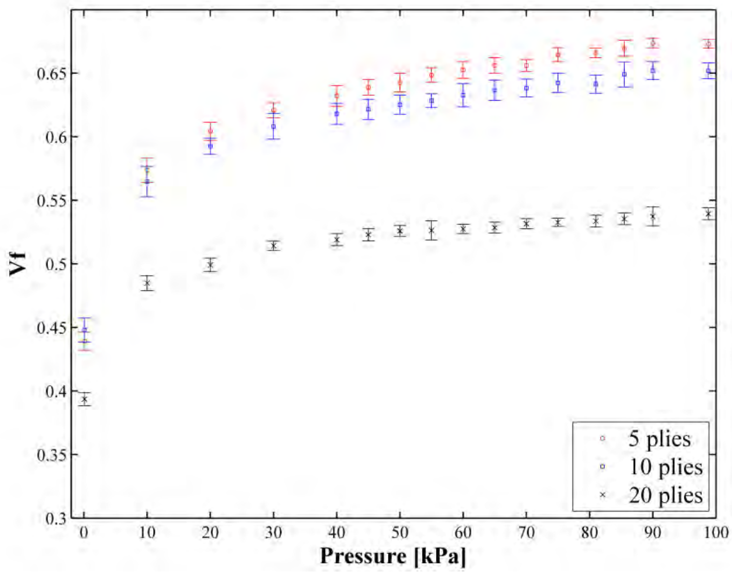

Fig. 7. Results comparison.

As aforementioned, the number of plies in the preform affect the behaviour to the pressure action, but in Equation (4) this influence is not taken in account. Therefore a new equation is proposed, in order to considerer the effect of laminate thickness on preform compressibility:

$$v_f = A * n_p^2 + B * P^C \quad (6)$$

in which n_p is the number of plies, while *A*, *B* and *C* are regression coefficients. The result of this new data fit is represented in Fig. 8, in which is present also the values of regression coefficients. R^2 for this data fit is 0.9793, while the coefficient A, B and C are respectively -3.1642 10^{-4}, 0.53714 and 0.050109. The developed equation well describes the relation between the number of plies, the compaction pressure and the volumetric percentage of fibre, in fact, as it can be visible from Fig. 9-11, the curves of data fit well reflect the experimental ones, even if for few points they are not included in data deviation.

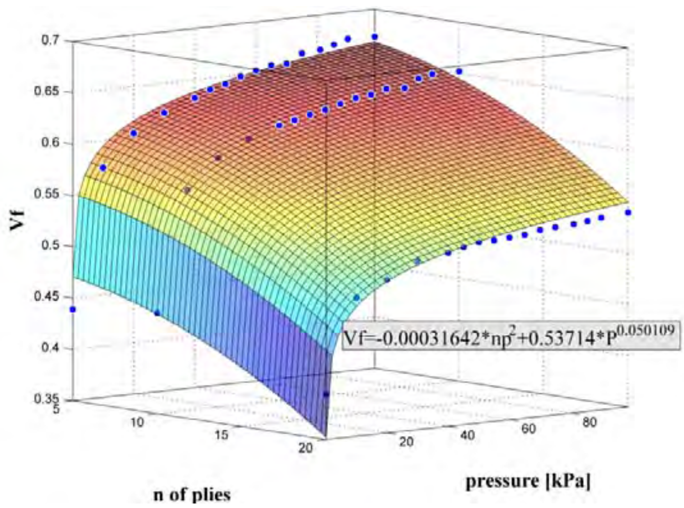

Fig. 8. Relation between number of plies and pressure for compressibility.

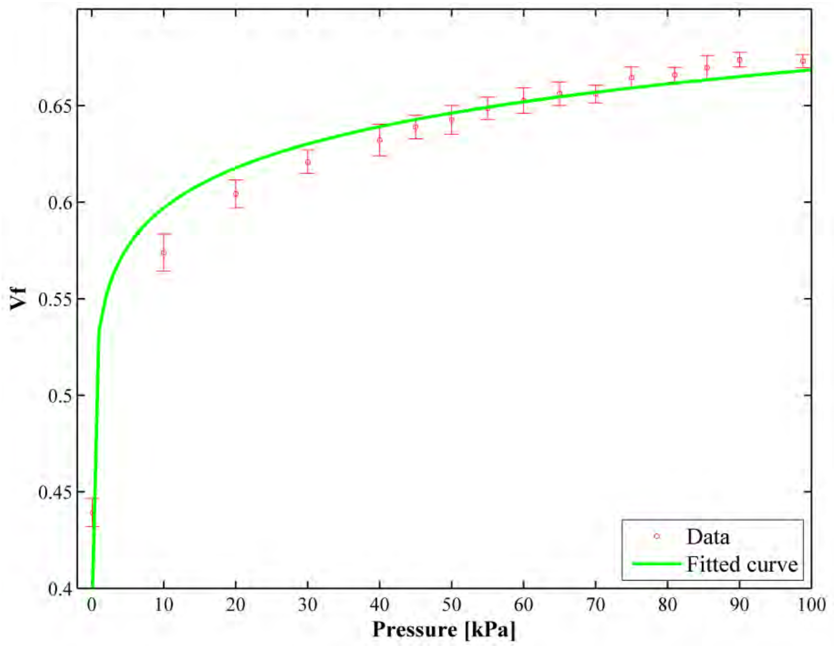

Fig. 9. Experimental data and new regression comparison for 5 plies preform.

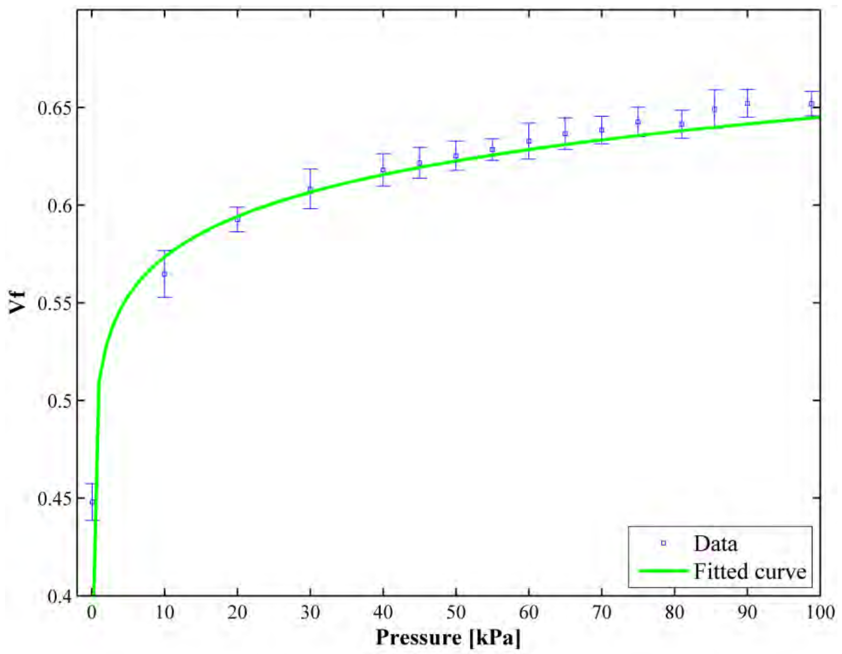

Fig. 10. Experimental data and new regression comparison for 10 plies preform.

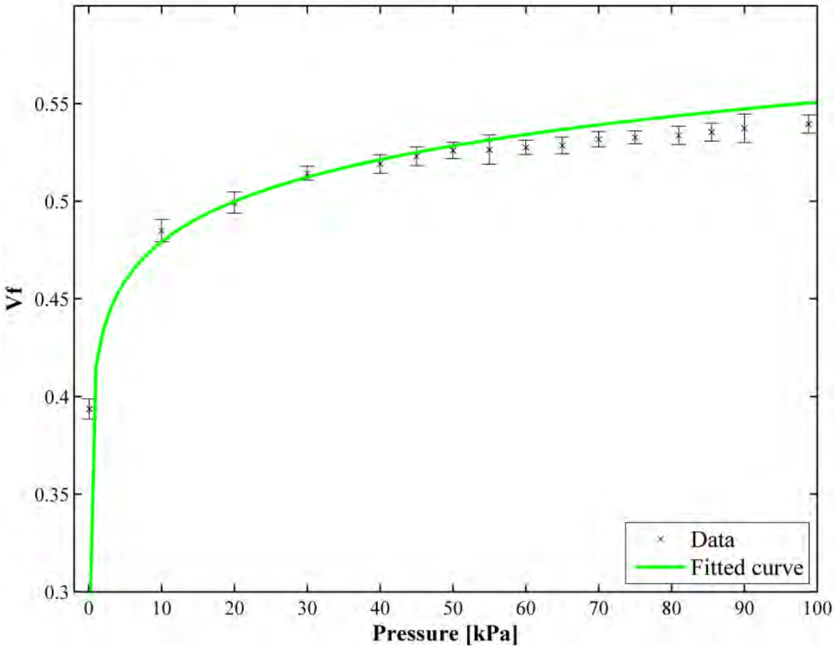

Fig. 11. Experimental data and new regression comparison for 20 plies preform.

After verifying the actual validity of the model, a further validation was performed: a compression test on a laminate of 15 plies was carried out and its results were compared with those from numerical model. As denoted in Fig. 12, the trend obtained according to the Equation (6) is within the range of experimentally measured values, so the introduced model can be considered reliable.

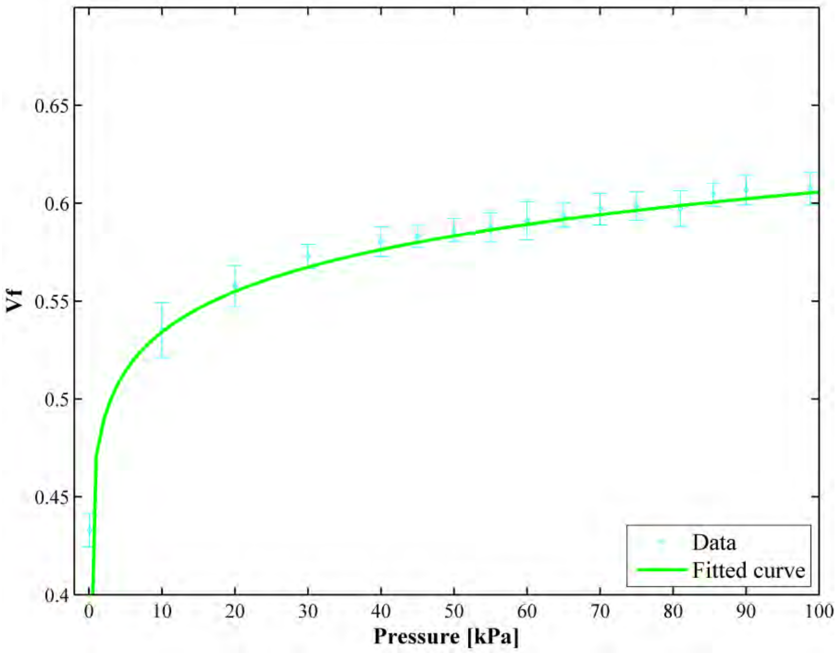

Fig. 12. Experimental data and new regression comparison for 15 plies preform.

The model proposed above can also be used for other types of reinforcement, not only for the glass woven fabric used in this work. It is obviously necessary to determine the constants of the model, and this can be accomplished by performing compression tests on the dry fabric: three tests (changing the number of layers) are sufficient to determine uniquely the constants required, in order to know in more details the compression behavior of material and to be able to perform simulations of RIFT processes on variable thickness laminates, in fact it is possible to define compressibility of all the areas of the component with only one relation. Moreover it is possible to carry out experimental tests on preform of a certain thickness and then to perform simulations on laminates with thickness different from that of experimental tests.

V. Conclusion

In the present work the preform thickness influence on its compressibility is investigated through a new experimental device. Thickness and pressure variations are measured so an experimental curve of compressibility is obtained, and it can be implemented in a software dedicated to numerical simulations of RIFT process. The characteristic of used equipment is that the compressibility curve is calculated under typical conditions of a RIFT process. Both thickness variation and pressure gradient during the vacuum were measured by means of a laser displacement sensor and a pressure transducer respectively.

Three different kind of preform were tested: 5, 10 and 20 plies, and regression curves for each kind of preform were obtained according to a power law function. From these data it can be seen that the laminate thickness, that is directly proportional to the number of plies, influences compressibility comportment of the preform, in fact the thinner the preform is, the higher the fibre volume fraction is. So a new equation was introduced, that takes in account four plies number, and a second data fit was carried out according to this. The new relation between volumetric fibre percentage, compacting pressure and number of plies was compared with experimental data and they are consistent, moreover a compression test on a laminate of 15 plies was carried out and its results were compared with those from numerical model, and a good agreement between both trend was found.

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