NEW APPROACH IN PROCESS MONITORING OF VACUUM ASSISTED RESIN INFUSION PROCESS (VARI)

Feiler M.[1], Chatzigeorgiou L.[1], Aoki R.[1], Dudenhausen W.[1] and Drechsler K.[2]

[1] Institute of Structures and Design, German Aerospace Centre, Pfaffenwaldring 38-40, Stuttgart, 70569, Germany

[2] Institute of Aircraft Design, University of Stuttgart, Pfaffenwaldring 31, Stuttgart, 70569, Germany

ABSTRACT

Non destructive quality assurance of CFRP parts is a very important item when producing structural aircraft components for military or civil application. Nevertheless, manufacturing and inspection costs have to be reduced on account of economical reasons. Therefore, Liquid Resin Infusion processes for infiltration of dry textile performs are going to be established in the commercial aircraft industry as an alternative to prepreg processes. Besides cost effectiveness due to its physical accessibility the infusion process offers new opportunities for on-line quality assurance, – hence, all critical process parameter are known.

A new and innovative approach for on-line monitoring of vacuum assisted resin infusion (VARI) processes using optical LockIn thermography is lined out. Fundamental investigations on monitoring of resin flow front are carried out. Several experiments demonstrated that optical LockIn thermography is suitable for characterising the unsteady infusion process. Furthermore, resin front propagation and velocity are determined by analysing the temperature pattern monitored during the infusion process.

1. INTRODUCTION

Since decades carbon fibre reinforced plastic (CFRP) has been used for highly loaded, lightweight parts in military or civil aircraft, e.g., empennage of Airbus commercial aircraft or Eurofighter fuselage. State-of-the-art technology used for production of these sophisticated structures is prepreg technology. In order to meet increasing economical demands as well as technological requirements new manufacturing methods are needed.

In terms of reducing manufacturing cost of CFRP parts for aerospace applications Liquid Resin Infusion (LRI) processes combined with new approaches in textile preforming proved their high potential for enhancing production efficiency. The best known LRI process, the Resin Transfer Moulding (RTM) uses high injection pressure in order to impregnate dry preforms, which are placed in a closed mould [1], [2]. Accurate geometry of complex shaped parts as well as high fibre volume fractions are assured by this process. However, limited part size due to high cost of complex moulds makes RTM suitable only for smaller parts. Therefore, the Institute of Structures and Design of the German Aerospace Centre (DLR) in Stuttgart developed a Vacuum Assisted Resin Infusion process (VARI) [3], [4], [5], and demonstrated with various test parts impressively its potential for a cost effective, reliable, robust, and reproducible high quality manufacturing process.

Furthermore, physical accessibility of process monitoring systems during the infusion process is given. Especially non-contact quality control procedures, known from non destructive testing of CFRP parts, could potentially be used for process monitoring. The on-line monitoring of the whole manufacturing process in correlation with the knowledge of effects of manufacturing failures, could in future lead to a significant reduction of NDT inspection in CFRP production.

The new and innovative approach for on-line monitoring of the VARI process discussed in this paper is the usage of LockIn thermography. Results obtained with this method demonstrate the capability for characterisation of the process and enables to improve the understanding of the infusion process. Monitoring of the flow front shape or detecting air leakage in the setup, both having a relevant impact on the quality of fibre reinforced parts, are the goals to be achieved by this method.

2. VARI PROCESS

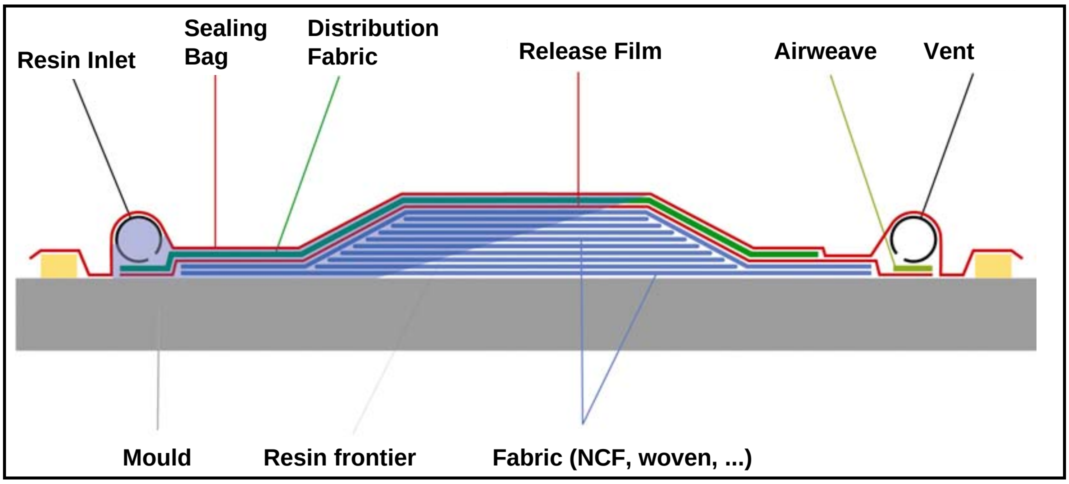
The goal in development of the VARI process was to provide a low cost process which enables the industry to manufacture high performance composite aircraft structures having fibre volume fractions up to 60 %. Therefore, low tooling and labour cost had to be achieved. Additionally, expensive process equipment like autoclave or heated press should be avoided. This leads to a vacuum assisted process. The usage of dry fabrics and liquid resins in an infusion process also reduces the material cost compared to prepreg materials. The mentioned demand on a vacuum assisted resin infusion process can be met for various resin systems and fabrics using the VARI process. For understanding the goal of the process development, a closer look at the resin flow behaviour in a one dimensional direction is appropriate. The resin flow through dry fabric can be described by Darcy's law, for a Newton fluid streaming through a porous medium [6]. The resin front velocity can be calculated by

$$v = \frac{K \cdot \Delta p}{\eta(1-\varphi) \cdot s} \tag{1}$$

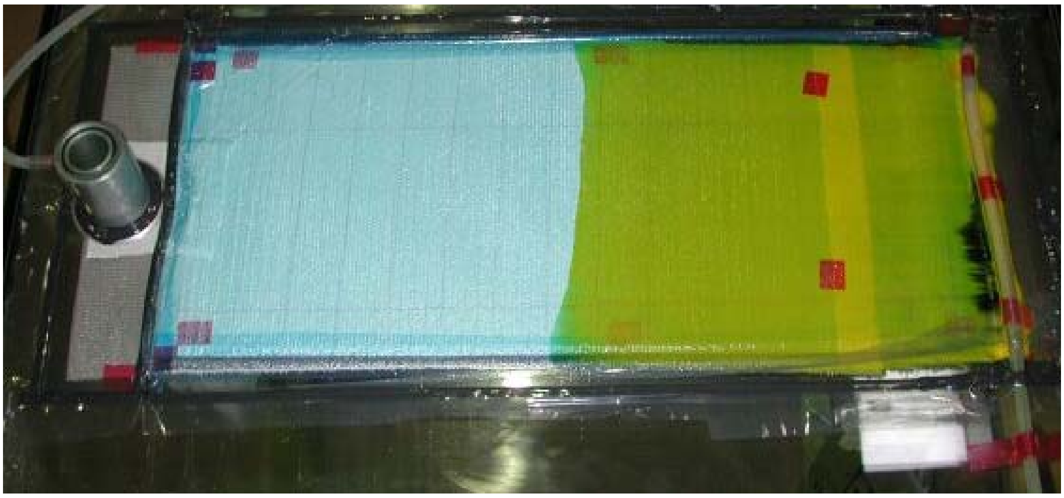
depending on the permeability of the dry fabric (K), the differential pressure between resin inlet and front (Δp), the dynamic resin viscosity (η), the fibre volume fraction (φ) and the distance between resin inlet and front (s). The integration (having v replaced by ds/dt) leads to

$$\int_0^{x_f} s\,ds = \int_0^{t_f} \frac{K \cdot \Delta p}{\eta(1-\varphi)}\,dt \rightarrow \frac{1}{2}x_f^2 = \frac{K \cdot \Delta p}{\eta(1-\varphi)}\,t_f \tag{2}$$

It can be easily seen, that the maximum achievable distance has a square dependence to the infusion time. By given permeability of the fabric, pot life time and viscosity of the resin and the maximum atmospherically pressure difference of 1000 hPa, the achievable distance is not sufficient for infusion of large parts. Usually, large aircraft structures are shells with a very small thickness to area ratio. Therefore, the preferred resin flow direction for a vacuum assisted process is in thickness direction of the fabric, which is one of the basic principle of the VARI process. The impregnation of the fabric along thickness direction is realized by a particular resin distribution fabric dispensing the resin on the lay-up surface. The principle of a distribution fabric is known since the 1970's, nevertheless, the best known usage is at the Seeman Composite Resin Infusion Moulding (SCRIMP) process [7]. Another very important principle is the manipulation of the process parameters, pressure and temperature. The fibre volume fraction as well as the porosity of the structural parts is controlled by varying pressure and temperature, i.e., the resin viscosity. Furthermore, excellent part quality could only be achieved by correct adjustment of the mentioned parameters and knowledge of the resin front movement within the lay-up. Figure 1 shows the principal lay-up for the VARI-process. The lay-up is almost similar to a conventional vacuum bagging, except the resin distributing fabric. Between the carbon and the distribution fabric a release film has to be placed to allow the separation of these layers after curing. The most important item is to ensure the proper impermeability of the lay-up to prevent voids in the part caused by any setup leakage. After evacuating the setup, the resin will be distributed across the lay-up surface in order to impregnate the carbon fibres in thickness direction, which is demonstrated in a section drawing, Fig. 1, by the wedge shaped resin front. The setup of a flat test plate with a resin infusion line is shown in Fig. 2, where also the resin front in the distribution fabric is

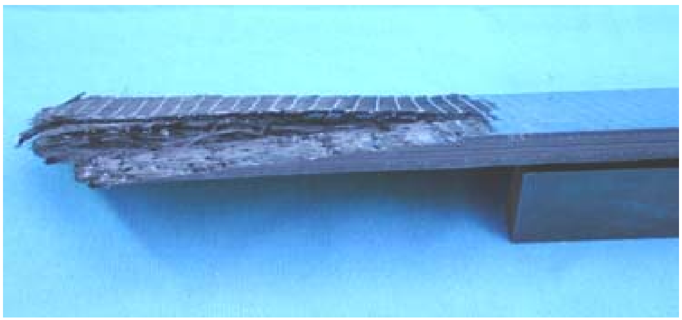


"**Fig. 1.** Schematic VARI lay-up."


"**Fig. 2.** Set-up of a flat plate."

visible. The infusion process is finished by resin pouring into the resin trap at the vents and followed by the curing process.

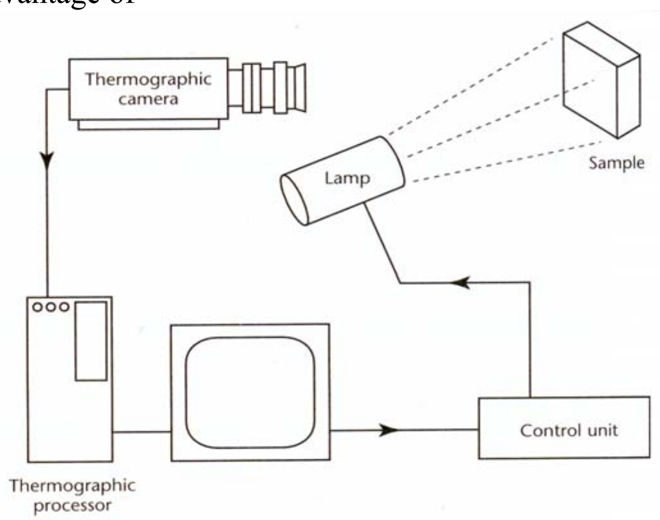
For characterisation of the infusion process, the visibility of the resin front in the distribution fabric is only one essential item. Due to the resin flowing off into the fibre preform (in its thickness direction) the typical wedge shaped resin front occurs. This resin front shape depends on the permeability of the distribution fabric in flow direction and the permeability of the dry textile lay-up in its thickness direction. To verify this shape, a section cut through a partially impregnated laminate is given in Figure 3 (upside down). Considering variation of permeability in thickness direction, i.e., different permeabilities of each ply, the resin front shape is different from the wedge shape.


"**Fig. 3.** Wedge shaped resin front."

As mentioned, the quality of the infusion process is influenced by many parameters. Adjustable parameters of the infusion process are infusion pressure and temperature. Increasing temperature will reduce the resin viscosity and therefore improve the wetting process. However, when producing large parts the reduction of pot life must be considered. The infusion pressure, i.e., the pressure remaining in the evacuated lay-up, controls the obtainable infusion distance. To prevent boiling of the resin or components of the resin the infusion pressure must not fall below the resin boiling pressure. Otherwise gas bubbles will occur which can not be removed by increasing pressure. Besides the correct infusion pressure the most important item for production of high quality parts is the proper impermeability of the whole infusion setup. Set-up leakage generates dry spots in the laminate by entrapped air.
The fourth determinant parameter is the wetting process itself. The resin front shape in-plane and in thickness direction depends on numbers and positions of the vents and resin-inlets, the set-up of the distribution fabric on the parts' surface and the permeability of the dry textile preform. In order to characterise the wetting process a visualization of the resin front in-plane and in thickness direction should be achieved by a remote and non destructive testing method.
The LockIn thermography, well known as suitable for non destructive testing of CFRP parts, can contribute to this goal.

3. LOCKIN THERMOGRAPHY

The LockIn thermography is a photothermal non destructive testing technique, which allows to deposit energy in a remote way (absorption of intensity modulated light) and analyse the resulting temperature pattern remotely by usage of infrared radiometry. Especially the evaluation of CFRP parts has been successfully carried out with LockIn thermography.
In case of optical LockIn thermography the investigated part is exited by intensity modulated light using halogen lamps, see Figure 4. The sinus modulated heat flux propagates in the part as a heavily damped thermal wave. Reflecting at thermal barriers and drawn back to the surface the propagated thermal wave interferes with the applied thermal wave [8], [9], [10]. The temperature pattern of the investigated sample is recorded by an IR camera. After processing the signals of each pixel by a Fourier transformation, either amplitude change or phases shift of the temperature pattern referred to the applied thermal wave, are obtained. Amplitude and phase signals are pictured whereas each pixel is colour-coded. Unlike the amplitude, the phase signal is not affected by inhomogeneity of light exposure, the infrared or optical emission ratio of the sample. Furthermore, the depth range for imaging of hidden features is twice the value of the amplitude signal [11]. For non destructive testing of CFRP parts this gives the advantage of



“**Fig. 4.** Setup principle of optical LockIn thermography.”

detecting thermal barriers selectively. Additionally, due to the dependence of the phase shift to the propagation length of the thermal wave, information on defect depth can be obtained. Furthermore, the thermal diffusion length depends on thermal conductivity, density and specific heat of the investigated part and the modulation frequency of the intensity modulated light. Therefore, the achievable sensing range is limited by the thermal behaviour of the sample, i.e., thermal diffusivity.

The LockIn thermography already demonstrated its capability for non destructive testing of cured CFRP parts. A variety of imperfections, e.g., porosity, embedded contaminations or delamination, can be located with this technology [12]. Nevertheless, the question to be answered in this paper is, whether optical LockIn thermography is suitable for on-line monitoring of the vacuum infusion process. Literature study showed, that LockIn thermography was not yet established for investigations of unsteady processes like the infusion process. However, this innovative application of the contact-free technique could enable an on-line quality assurance during manufacturing of CFRP parts using the VARI process.

Combining LockIn thermography and the vacuum infusion process a new approach has to be made. Instead of measuring thermal diffusivity in order to determine material properties, the resin front velocity should be determined by amplitude and phase images.

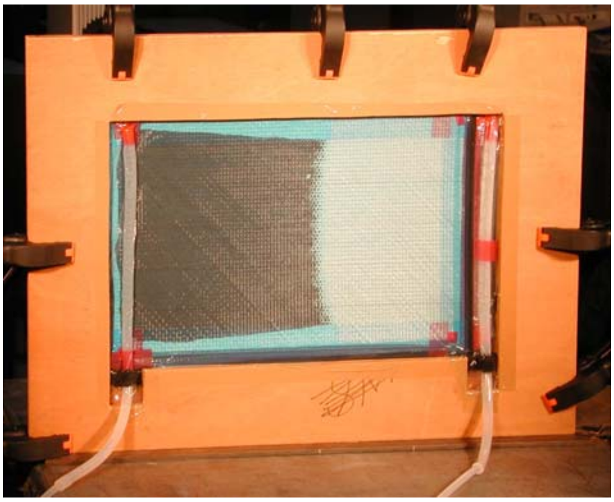
The correlation between resin front velocity and exication of the sample can be done by the modulation frequency of the lighting of the sample and the infusion process. According to the modulation frequency and the number of modulation periods the propagation of the resin front in the part can be calculated. Using the algorithms for steady state investigations, the phase or amplitude images of each modulation period are consolidated in one phase or amplitude image representing all modulation periods. Taking into account that at steady state investigations the temperature pattern of the part at all periods is the same, hissing of the signal can be minimized. Compared to the steady state temperature pattern, different temperature patterns occur caused by the variation of thermal diffusivity by wetting the fibres during unsteady infusion process. Although, averaging the results, the change in thermal diffusivity should be significant for being displayed in the image. To verify this assumption several experiments have been carried out.

4. EXPERIMENTAL ARRANGEMENT

The experimental setup for LockIn thermography measurements during the infusion of a flat CFRP plate is illustrated in Figure 5.

“**Fig. 5.** Experimental arrangement.”

Usually the VARI lay-up is placed on a rigid mould made of steel or CFRP in order to assure the parts geometry accuracy. However, the fundamental investigations are carried out without a rigid mould because of accessibility of the infusion setup from both sides. Herewith, the opportunity for measurements in reflection and transmission arrangement are given. A VARI setup during infusion viewed from the top, i.e., the distribution fabric side, can be seen in Figure 6. In reflection mode this side is illuminated by the intensity modulated halogen lamps. The vent and inlet line, as well as the resin front and the wetted part area can be seen in this Figure.

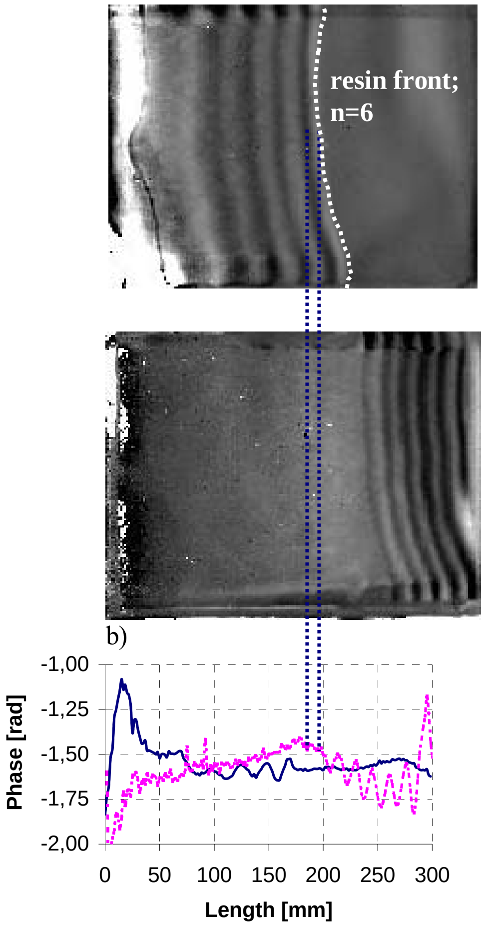


"**Fig. 6.** VARI setup during experiment."

The sample size was 400 x 300 x 4 mm which is large enough to establish a homogeneous infusion process with little edge effects. The thickness of 4 mm was chosen following typically used shell thicknesses of aerospace structures. Several experiments have been made with different VARI process parameters in order to vary infusion times.

5. RESULTS & DISCUSSION

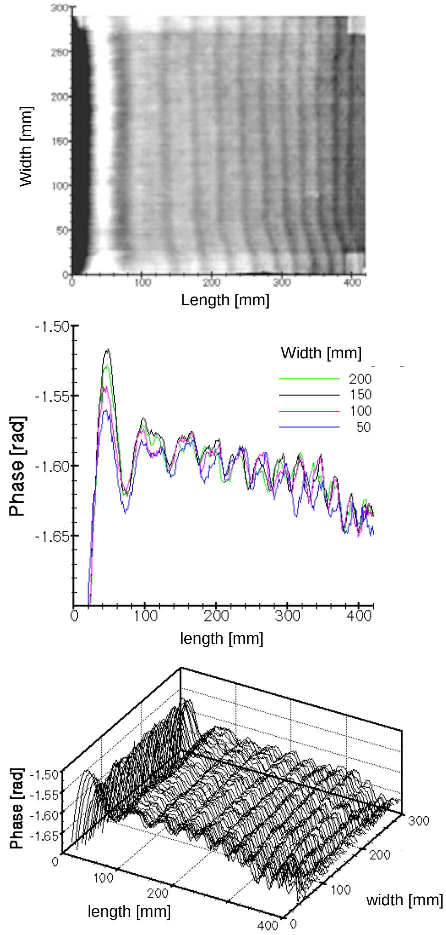
The obtained results are exemplarily described at samples of two 4 mm thick CFRP plates manufactured of room temperature curing resin and biaxial non crimp fabric.
The phase image of the plate, resulting from 6 measuring modulation periods (n=6) is illustrated in Figure 7a). Typical line structures with a certain width can be seen in this figure. Due to the resin front propagation and therefore the change of diffusivity during the measuring periods, these lines are identified as the thermal texture of the resin front. At the position of the first line it can be seen, that measuring started after the resin infusion began. Hence, the number of line structures correlate with the measuring periods. It seems to be evident that each line displays the resin front position at this certain time. To evaluate this behaviour, optical measurements were carried out and demonstrated, that the beginning of each line structure represents the propagation of the resin front at this measuring period. Furthermore, this allocation is proved by comparing the last line structure visible in the phase image with the resin front position at the end of the experiment (see blue lines in Figure 7).
Since the measurement time of the 6 modulation periods was significantly less than the time for infusion a second measurement with identical parameters was started. The phase image of the second measurement is illustrated in figure 7b). As expected the correlation of the line structures and their arithmetical congruence with the measuring periods is excellent.
The evaluation of phase shift during the unsteady infusion process in a cross section in the middle of the plate is illustrated in Figure 7c).



a)

b)

c)



"**Fig. 7.** Phase image 0,06 Hz, n=6."

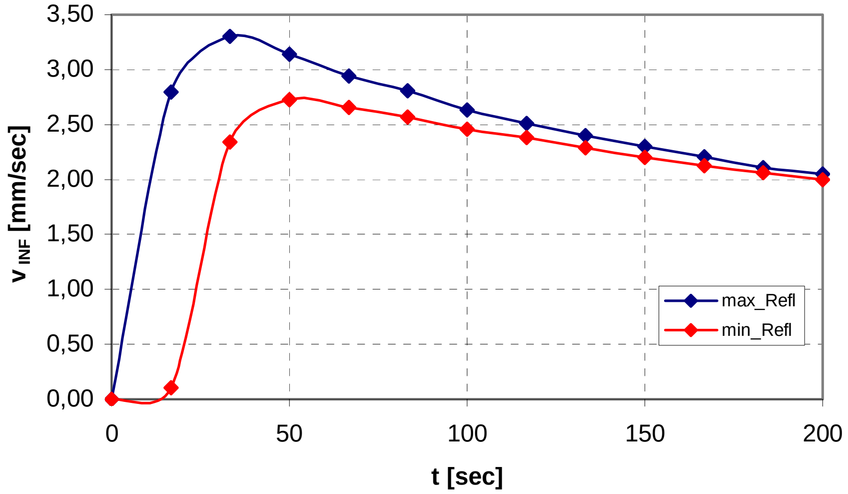
a) Experiment 1
b) Experiment 2
c) Phase profile

"**Fig. 8.** Phase image 0,06 Hz, n=12."

a) Phase Image
b) Phase profile 2-D
c) Phase profile 3-D.

In order to demonstrate the reproducibility of the LockIn thermography measurements several experiments with similar plate geometry and infusion parameters have been carried out. As an example the 3-D and 2-D characteristics of the phase shift are lined out in Figure 8a) and 8b). Due to experience the measuring periods were set to 12, in order to monitor the whole infusion process in one cycle. As expected, the line structures are congruent with that of the modulated periods. Although the applied algorithm calculates an average of all 12 frames of the measuring time the significant thermal texture of the resin front for each period can be well recognized in the phase images.

Using these results, the resin front velocity in plane of the distribution fabric can be determined from the modulation frequency and the number of measuring periods. Figure 9 shows the resin front velocity according to the length of the plate. Whereas the blue line illustrates the velocity distribution of the peak values in the phase shift diagram, see Figure7c), the red line represents the lower values. Although the resin front velocity can be measured by optical cameras in case of transparent vacuum foils, the infrared radiometry has the capability to monitor the resin front also at non transparent lay-up, assuming infrared permeability of the materials.



"**Fig.9.** Resin front velocity distribution."

6. CONCLUSIONS

Until now, LockIn thermography was only used as a remote and non destructive evaluation technique for structural parts with steady state material properties. It demonstrated its capability for inspection of CFRP parts with the advantage of an imaging process. The approach of on-line process monitoring of vacuum assisted infusion processes (VARI) is proposed here as a new innovative application of optical LockIn thermography.

Fundamental investigations have been carried out. The obtained results demonstrate the potential of LockIn thermography for characterising unsteady infusion processes with varying material properties. Beyond monitoring the resin front propagation, which is important to identify improper infusion processes, the velocity of the resin front was determined of the modulation frequency and periods.
Moreover, due to physics of thermal wave propagation, a depth information can be gained by analysing phase shifts. In future, this may give the opportunity for 3-dimensional characterisation of resin fronts. Also, impermeability of the infusion setup could be seen by changes of the thermal material properties due to entrapped air.

Suitable for process monitoring of vacuum infusion processes, the optical LockIn thermography has the capability of an economical online quality assurance of large CFRP parts during manufacturing.

ACKNOWLEDGEMENTS
The authors are grateful to the Institute of Polymer Testing and Polymer Science, University of Stuttgart - Department of Non Destructive Testing and the company e/de/vis GmbH, Stuttgart, for improvement of the LockIn thermography system and their support for the experiments.

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