# On-line Monitoring of Resin Flow Using Capacitive Sensor Array During VaRTM Production Process

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**Abstract:** Advanced composite products with high fibre volume often suffer from dry spots formation during VaRTM production process. In order to facilitate mould design and process control, numerical simulations are usually used. Commonly used simulations of the resin transfer moulding process relies on a set of permeability coefficients. It is necessary to calibrate the permeability coefficients for each individual laminate stacking sequence and mould geometry separately. This paper describes the development of an on-line monitoring system for calibration of the permeability coefficients. Moreover, it can monitor a cure state of the composite. Monitoring system functionality is demonstrated on a transparent mould and is also compared with the simulation.

**Keywords:** vacuum-assisted resin transfer moulding; monitoring system; permeability coefficient; synchronous demodulation, fringing electric field; capacitive sensor.

## 1 Introduction

The vacuum-assisted resin transfer moulding (VaRTM) production process is widely used production method in the segment of advanced fiber-reinforced plastic composite materials. The VaRTM production method utilises a pressure gradient between inlets and outlets for resin matrix transportation in the mould. A fabric weaving style and its laminate stacking sequence strongly affect the fabric permeability. Increased attention is focused on the permeability because this parameter directly affects the occurrence of so-called dry spots (see Fig. 1). Those uneven or insufficiently saturated places may occur especially in the case of products featuring more complex forms. To avoid the dry spots, numerical simulations of filling process are widely used for process design or control. The permeability coefficients are one of the most critical entries into the simulation.

Fig. 1: An example of a typical dry spot;

Methods for determining the permeability coefficients are based on Darcy's law. The principal information is resin flow position during permeability measurement. Various methods have been used already. One of the first and well-known method is the SMARTweave™ (Sensor Mounted as Roving Threads) [1] that utilises a grid of conductors embedded into the fabric and employed for measuring of direct current conductivity at the grid node. The main disadvantage of the SMARTweave is invasiveness by wires incorporated into a final product or mounted on the mould wall still in touch with the product. Moreover, it is demanding on a plenty of wires. A similar method with lower demands on wires developed by Luthy et al. [2] utilises wires in a lineal configuration for direct current conductivity measurement. Flow position is thus continuous. Another method with similar invasiveness has been developed by Dominauskas et al. [3]. The method is based on a time-domain reflectometry, which measures the time delay between sending a high-speed electrical pulse and its echo reflected from impedance discontinuities. The main advantage is an ability to detect multiple flow fronts (dry spots). An interesting approach has chosen Lekakou et al. [4], who embedded an optical fibre core at the surface of the moulding. The flow front position and curing of an epoxy resin is measured by a loss of light. Another possibility for flow front measurement utilises pressure sensors wich was performed by Wei et al. [5]. The pressure beside the flow front is a critical parameter for permeability measurement, so their approach leads to reliable results.

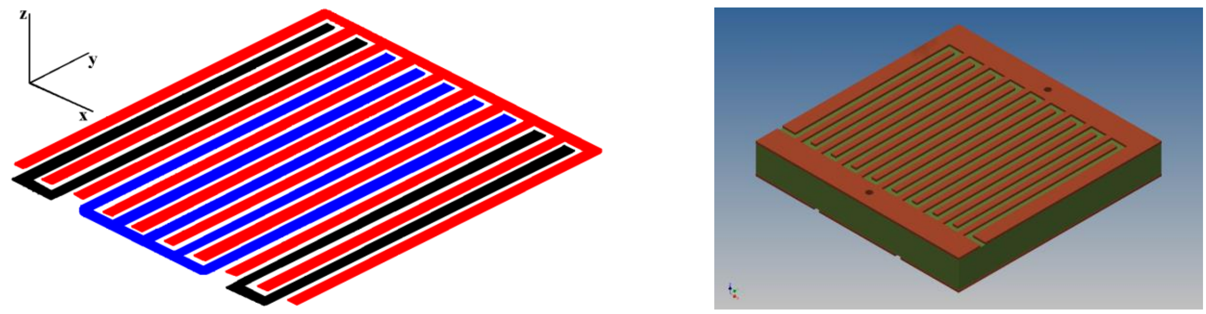
Work described in this paper falls into an area of capacitive sensors. One of the interesting work has been done by Yenilmez et al. [6], who embedded a grid of opposite electrodes into the mould wall. Due to a precise implementation of the electrodes, their solution is non-invasive. The invasiveness is one of the most focused features indisputably; nevertheless, this solution has high demands on production and so costs, especially for moulds with complex geometry. This disadvantage has partially overcome by Kobayashi et al. [7], who proposed a patch-type flexible matrix capacitive sensor. Their work was probably inspired by Hegg et al. [8]. The work, most related with our, was proposed by Matsuzaki et al. [9] thanks to employing of fringing electric field capacitive sensors with interdigital electrodes. Theirs sensor configuration enables full-field flow monitoring.

Next chapter describes the development and demonstration of a monitoring system based on point fringing electric field (FEF) capacitive sensors with interdigital electrodes. The main demands on the monitoring system are the non-invasive, non-intrusive, low-cost and easy installation of sensors, and wireless. An intended usage of the monitoring system is for either permeability estimation purposes in arbitrary mould section or as a verification tool during process design. Demonstration of the monitoring system is performed on a transparent mould and is also compared with the simulation.

# 2 Methodology and implementation

## 2.1 Online monitoring system

The monitoring system is based on capacitive sensors with a fringing electric field. Capacitance changes of sensor depend on changes of dielectric property of material penetrated by sensor electric field. The sensitivity of FEF sensor decreases exponentially with the distance between the sensor surface and dielectric changes [10]. The sensor consists of several comb-shaped coplanar electrodes. An example of the electrodes arrangement is shown in Fig. 2a.




a) An arrangement of FEF sensor coplanar electrodes;

b) An example of used FEF sensor;

Fig. 2: A demonstration of sensor with coplanar electrodes;

The driving electrode (red) is connected to the harmonic voltage supply. The sensing electrode (blue) is connected to the signal processing circuit. The sensor can also be equipped with a guard electrode (in the figure marked in black) which shields, to a certain extent, the surrounding field that might cause interference. The guard electrodes also ensure that the measurement area is not affected by a deformed electric field at the sensor edges. Developed monitoring system has the side guard electrodes excluded for simplicity. Nevertheless, used sensors have included backplane guard shield. An example of used FEF sensor and their model is depicted in Fig. 2b. It is evident that FEF sensors are intended solely for non-metallic moulds. To satisfy main requirements on the monitoring system it is necessary to instal the sensors into the mould wall as close as possible to the mould surface, but still below the surface as is depicted in Fig. 3. An electrical field intensity lines in Fig. 3 (marked by 6) has a pattern typical for interdigital electrodes. As it is indicated by attenuated field line thickness, sensed area is penetrated by the field lines with lower intensity, and so sensor features lower sensitivity. Moreover, due to low cost and easy sensor installation, the sensitivity may differ rapidly among sensors. The development of the monitoring system was commenced by author's previous work [11], which via pioneering experiments helped to find main requirements on the final system. Pioneering experiments confirmed FEF sensor sensitivity, as it became a crucial factor for next analogue circuit design.

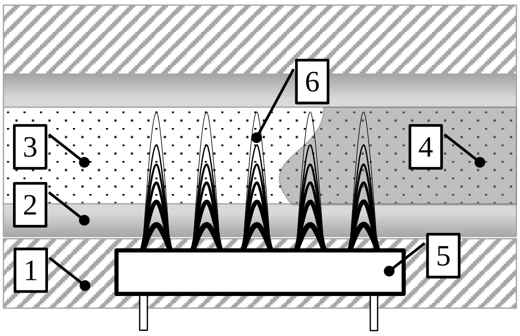



Fig. 3: Side view of FEF sensor installed in the mould wall.
(1-mould, 2-gelcoat, 3-fabric, 4-fabric&resin, 5-sensor, 6-FEF);

Developed monitoring system, depicted in block diagram in Fig. 4, is intended to instal onto the mould for better manipulation during the production process. Wireless communication is provided by radio frequency module XBee ® by Digi International. The pair of modules works in a transparent operation regime when act as a serial line replacement. Both communication directions are used. The wireless module at the mould part is connected with a microcontroller hardware serial interface. The microcontroller controls a multiplexer ADG1406 to channel selection according to preprogrammed measuring cycle in a range up to 48 channels. Sensing electrodes are connected directly to multiplexer inputs. The multiplexer output leads measured signal into analogue circuits which are the heart of the monitoring system because it converts the measured electrical capacitance of the sensor to an electrical voltage. The analogue circuits will be described in the next paragraph in detail. The measured analogue signal is digitised by 24-bit analogue-to-digital converter AD7710, which is controlled by the microcontroller via a serial peripheral interface. Because the mould part of the monitoring system is powered by a battery, the analog-to-digital converter is also used for monitoring battery condition. The microcontroller periodically reads the set of channels and send data frame into a personal computer.

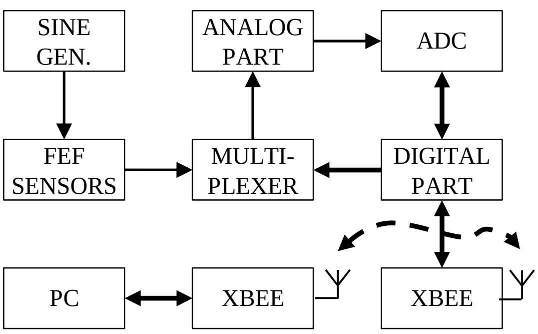



Fig. 4: Schematic diagram of main components of the monitoring system;

A user application for data processing was created by LabVIEW development system. The user application is among others able to visualise data by the help of a 3D graphic CAD model loaded in STL format.

The analogue circuits design is closely related with satisfying the main demands on the monitoring system. Above mentioned problems with sensor sensitivity leads to analogue circuits, which are able to handle with low signal-to-noise ratio. Synchronous demodulation is a well-known method for recovering these signals. Synchronous demodulation is based on multiplying the measured signal by reference signal and subsequent filtering off every harmonic component except DC component of the signal. As is depicted in the block diagram of the analogue part (Fig. 5), the synchronous demodulation is used for conditioning of both measuring and reference (harmonic voltage supply on the driving electrode) signals. These signals are consequently processed proportionally. The ratio A/B ensures a suppression of reference signal drift. Both synchronous detector and ratio implementation are part of AD698, which is here used untraditionally because it is signal conditioning subsystem for a linear variable differential transformer. One of the most important parts is the capacitance converter, which is based on AD823 wired in current-to-voltage configuration. Harmonic voltage supply with frequency 15 kHz is generated by low distortion sine generator, which is also part of the AD698.

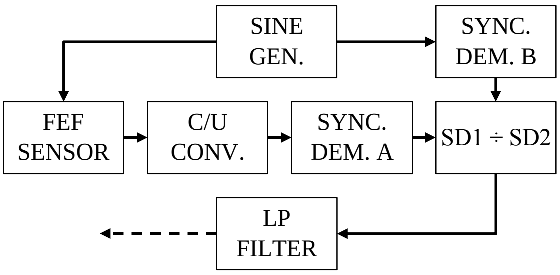



Fig. 5: Schematic diagram of analogue circuits;

## 2.2 Permeability estimation

The resin flows through a porous medium such as fibrous reinforcement according to Darcy's Law, which states that the flow rate of resin per unit area is proportional to the pressure gradient and inversely proportional to the viscosity of the resin. Darcy's Law is given as follows

$$V = \frac{K}{\mu}\nabla P \,, \tag{1}$$

where $V$ is Darcy's velocity, $K$ is permeability tensor, $\nabla P$ is a pressure gradient, and $\mu$ is a viscosity of the resin. In order to in-plane permeability measurement or estimate respectively, the thru-thickness permeability is neglected. In case of thin shell structures with isotropic fabric is possible to express in-plane permeability as follows:

$$K = \mu L^2 \frac{\varphi}{2T\Delta P} \,, \tag{2}$$

where $\mu$ is the fluid viscosity, $\varphi$ is the preform porosity, and L is the distance between pressure difference $\Delta P$. For accurate permeability measurement is necessary to measure the pressures in the place of FEF sensors. Nevertheless, hereafter system demonstration uses pressure gradients estimated from the numerical simulation.

# 3 System demonstration

## 3.1 Experimental setup

The transparent mould in the form of a fan blade with dimensions 75 x 33 cm was provided with 20 sensors monitoring system. Square sensors of 1 $cm^2$ area were installed into the mould wall approximately 0.5 to 1 mm below the mould surface. Whole experimental setup is depicted in Figure 6. Laminate stacking sequence of thin shell product was composed of 3 layers of glass multimat (fabric 0/90, mat, 900 g/m2) with epoxy resin Havel LH288. Moreover, the laminate was provided by flow mesh Compoflex RF 150 for increasing permeability. Two inlets and one outlet gates were equipped by runners where of 1.5 mm diameter. The resin at the inlet was freely sucked into the mould by a pressure gradient between atmospheric pressure and pressure of vacuum pump, which kept absolute pressure 15 kPa. Based on fibre volume fraction measurement, the porosity of laminate was 65 %. Resin viscosity was measured during the filling process for both, more accurate permeability estimation and numerical simulation. The filling process was recorded by a camera from the top view so that monitoring system outputs could be easily compared with reality.

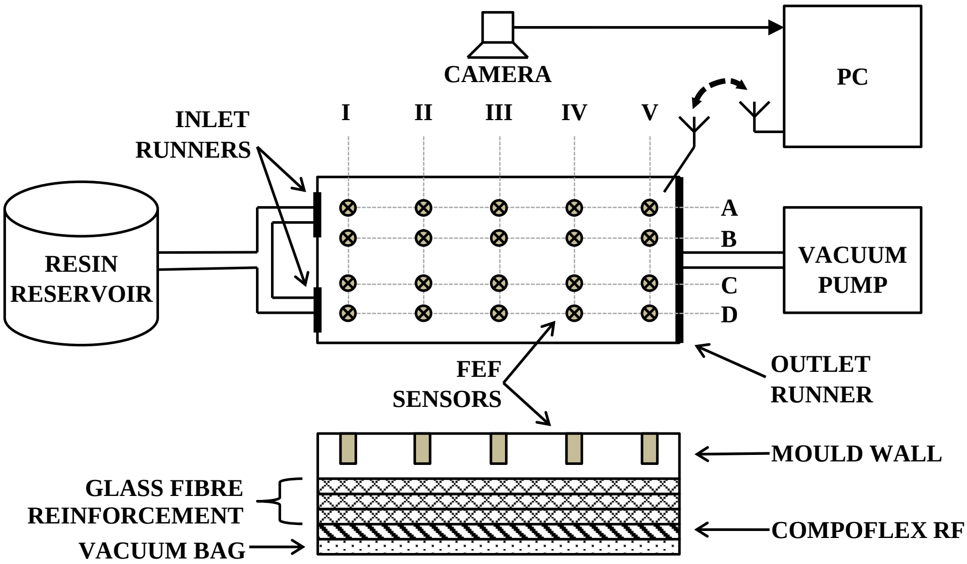



Fig. 6: Schematic setup of the experimental demonstration;

Numerical simulation was performed with the help of PAM-RTM software. Based on the above-mentioned experimental setup, the filling process was modelled as two-dimensional by neglecting the resin flow in the thickness direction. Among others, the pressure gradient was obtained from the numerical simulation for permeability estimation purpose.

## 3.2 Result and discussion

Based on the experiment mentioned above, permeabilities in five sections of the mould was estimated with the help of equation 2. The permeabilities and relevant parameters are summarised in Table 1.

Tab. 1: Estimated permeabilities and relevant parameters;

| section | time (s) | length (m) | pressure (Pa) | viscosity (Pa·s) | permeability ($m^2$) |
|---|---|---|---|---|---|
| I-II | 101 | 0.17 | 50549 | 0.24 | 4.4E-10 |
| II-III | 167 | 0.17 | 32463 | 0.21 | 3.6E-10 |
| III-IV | 230 | 0.17 | 24777 | 0.20 | 3.3E-10 |
| IV-V | 321 | 0.17 | 18814 | 0.19 | 2.9E-10 |
| entire mould | 959 | 0.75 | 85000 | 0.21 | 4.7E-10 |

As is mentioned in Table 1, the permeability estimation was performed in the sections I-II, II-III, III-IV, IV-V, and within the whole mould. The filing times of the sections were evaluated from relative changes in the capacitance (see Fig. 7) measured and stored by the monitoring system. Relevant pressures gradients in the sections were estimated from the numerical simulation, whereas pressure gradient in the entire mould was given by the vacuum pump and atmospheric pressure.

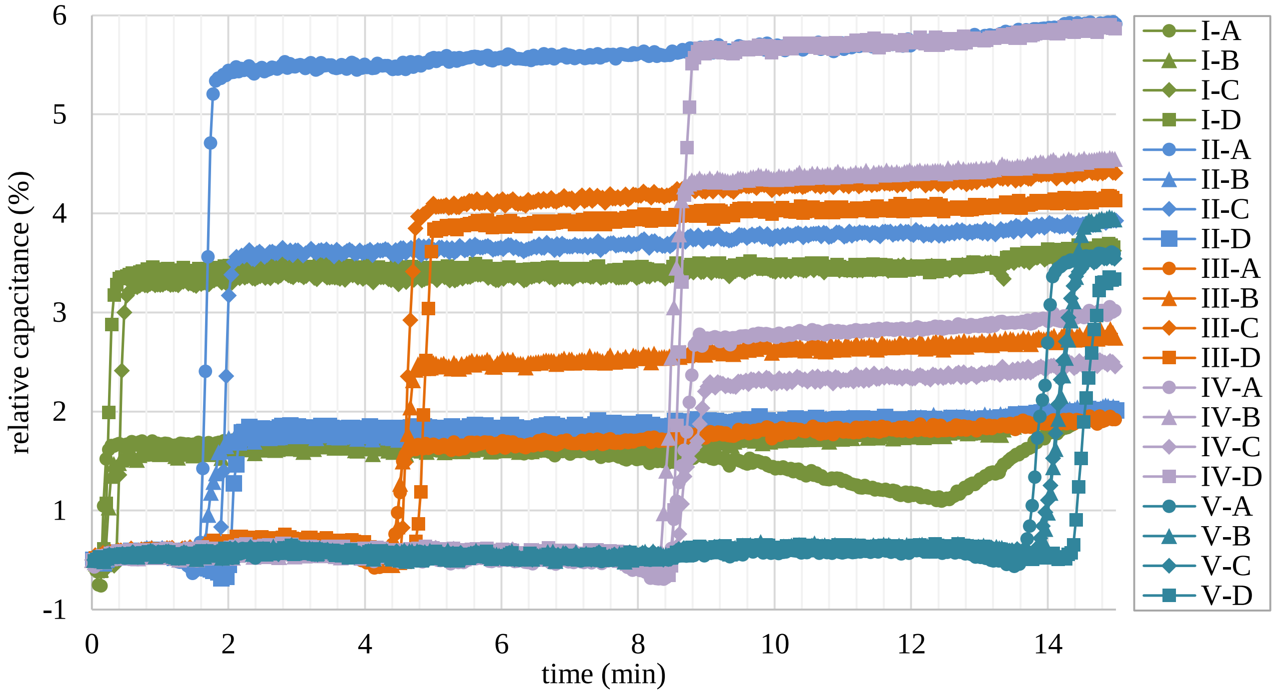


Fig. 7: The sensor relative capacitance changes during filling process;

The permeability was also estimated by best fitting the simulated and measured filling times in the relevant sections. Thus founded permeability was 4.75E-10 $m^2$, and it was used for numerical simulation in the next comparison. In Table 2 it is possible to see the comparison between real filling process from a camera, the graphical output from the monitoring system, and numerical simulation. It is clearly seen that simulation matches real filling process very well. Only a little difference can be found at the beginning of the filling process. The permeability founded by best time fitting is in good accordance with the permeability estimated from the entire mould filling time. Other permeability estimates are affected probably by pressure gradients, whose value was roughly estimated from the numerical simulation.

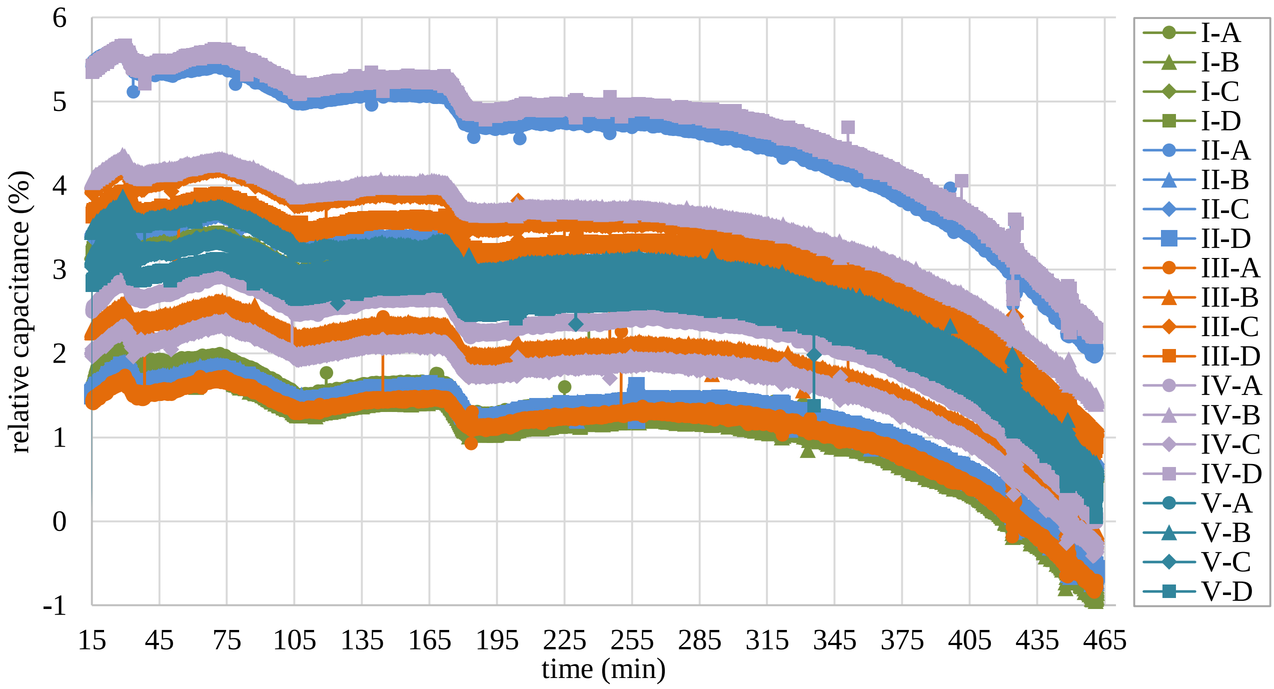
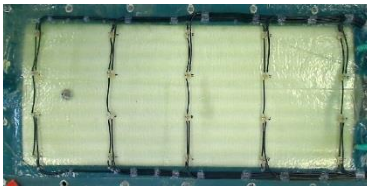
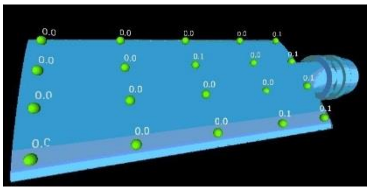
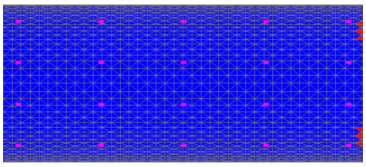
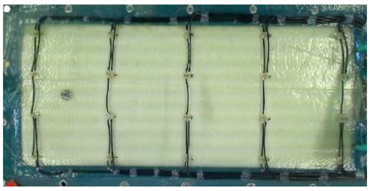
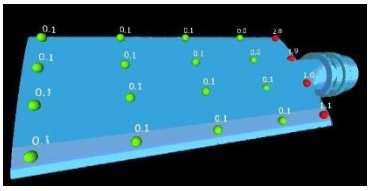
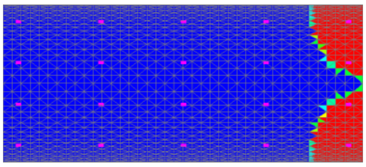
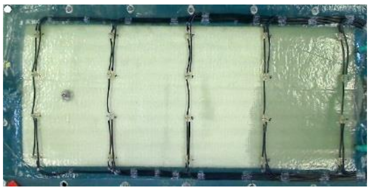
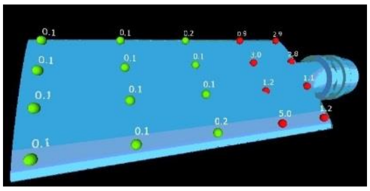
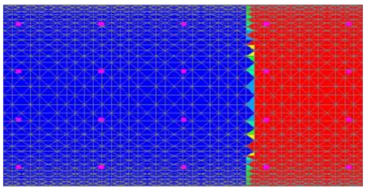
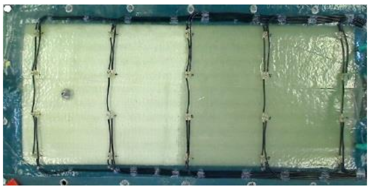
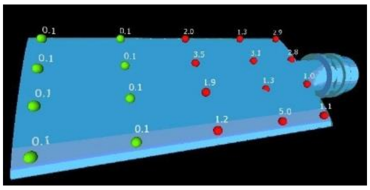
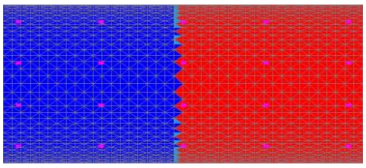
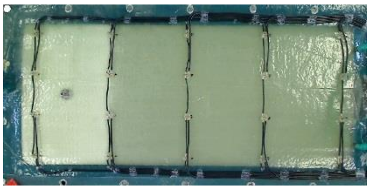
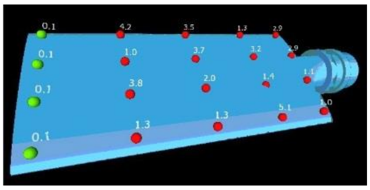
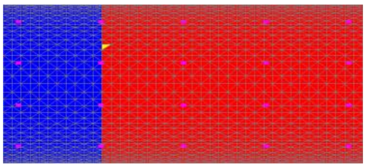
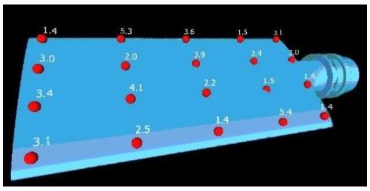
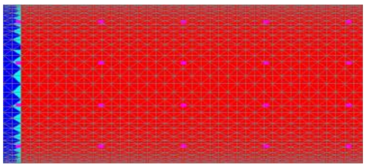


Fig. 8: The sensor relative capacitance changes during curing process;

The curing process was also monitored. Epoxy resin contains considerable polar groups that lead to the intense capacitive response [12]. The concentration of the polar groups changes by the epoxy resin crosslinking during its curing. The curing is possible to see in Figure 8. Because used capacitive sensors are sensitive not only to resin but also to fabric and its stacking sequence, it is necessary to verify more rigorously the relation between capacitive response and curing process before utilisation the monitoring system for cure monitoring at this sensor setup.

Tab. 2: Comparison of flow front progress;

| time [s] | camera | monitoring system | simulation |
|---|---|---|---|
| 0 |  |  |  |
| 28 |  |  |  |
| 129 |  |  |  |
| 296 |  |  |  |
| 526 |  |  |  |
| 847 |  |  |  |

# 4 Conclusion

The on-line monitoring system was developed and experimentally demonstrated on the permittivity estimation. Thanks to the signal conditioning with synchronous demodulation has accessed the utilisation of capacitive sensors with the fringing electric field. The sensor configuration allows non-invasive and non-intrusive measuring the presence of the resin. Due to non-invasiveness and non-intrusion of the monitoring system, the permeability can be estimated directly in the full-scale production mould with no affect to moulding quality. Nevertheless, future work will be focused on enriching of monitoring system by pressure measurement for permittivity estimation improvement. As was shown, the graphical output from the on-line monitoring system can be easily used as the tool for verification of the process design, whereas possibility to store capacitance data can be used for permeability estimation during post-processing.

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