CONTROL OF RESIN FLOW USING MULTIFUNCTIONAL INTERDIGITAL ELECTRODE ARRAY FILM

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Keywords: VaRTM, Flow Control, GFRP, Electrical property.

Abstract
Any slight differences in the wrinkle of the vacuum bag or misalignment of the fabric preform in VaRTM cause unexpected resin flow. We propose a flow control scheme using a multifunctional interdigital electrode array (MIEA) film to actuate the resin flow as well as monitoring resin flow and temperature. Capacitive interdigital electrodes were adopted as electrodes for dielectric heating utilizing resin permittivity. Increase in resin temperature decreases resin viscosity, thus the resin flow velocity at the heated area increases. Using the connecting grid, an arbitrary location can be heated by changing the wire connections. The validity of the proposed flow control scheme was investigated by manufacturing cored GFRP structures by VaRTM. As a result, the occurrence of dry spot was prevented with flow control, whereas dry spot occurred without flow control.

1. Introduction
To prevent dry spots occurring during the vacuum-assisted resin transfer molding (VaRTM) process, resin flow simulation to optimize resin inlet or outlet location is usually conducted. However, any slight differences in the wrinkle of the vacuum bag or misalignment of the fabric preform cause unexpected resin flow, even if the mold conditions such as temperature, preform type, and vacuum pressure are set to be the same. This unexpected resin flow causes dry spots including small voids, which significantly deteriorate the mechanical properties of the structure [1-3]. Consequently, monitoring dry spots and methods are essential, to prevent their occurrence in real time during the VaRTM process.

In our previous study [4], a capacitive area-sensor array was developed for full-field monitoring of resin flow during the VaRTM process, by improving the grid sensors for cure monitoring [5]. Each square sensor was aligned without any non-sensed space. Thus the film measured the full field flow monitoring area, and did not miss a dry spot that occurred anywhere on the film. Because of its thinness, (13 μm thick), the sensor film was very flexible and could easily be attached to complicated or curved molds. The flexible film sensor was successfully applied to a structure with radius of curvature R=60 mm for cure monitoring [5].

For highly complex structures, the sensor film may require some slits to avoid wrinkling, similar to the laying process of the fabric on the complex mold.

In the present study, we propose a flow control scheme using the same film to actuate the resin flow as well as monitoring resin flow and temperature. The film works multifunctionally as actuator and sensor for resin flow and temperature; thus the film is named a multifunctional interdigital electrode array (MIEA). Capacitive interdigital electrodes were adopted as electrodes for dielectric heating utilizing resin permittivity. Increase in resin temperature decreases resin viscosity, thus the resin flow velocity at the heated area increases. Using the connecting grid, an arbitrary location can be heated by changing the wire connections. The validity of the proposed flow control scheme was investigated by manufacturing cored GFRP structures by VaRTM.

2. Multifunctional interdigital electrode array (MIEA)

A pattern of electrodes and wiring of MIEA, made by photolithography, is shown in Fig. 1. The configuration of the film was 200×200×0.013 mm^3. Because of the thinness of the film the MIEA was very flexible, and could easily be attached to complicated or curved molds. Moreover, the film was stacked between the composite laminates and the mold. Flow interference and decreased strength may not occur in the cured composites. The sensor may be also used as an electrode for monitoring the health of the structure in the case of manufacturing CFRP after curing, and it remains attached to the structures during its service period. Of course it can be removed, if not required, by coating the film with a release agent.

Wiring was attached to the back of the film and connected to interdigital electrodes on the other side by through-hole connection. The electrodes were aligned in a matrix or grid, and the wiring of the electrodes was divided between rows and columns. Wires 1, 2, …, 5 were used to identify the longitudinal connections, and A, B, …, E identified the horizontal connections. Thus, there were a total of 25 sensors/actuators and 10 wires. The sensors/actuators had capacitive interdigital electrodes with input voltage V+ and ground. Each sensor/actuator had a square sensing/actuating area.

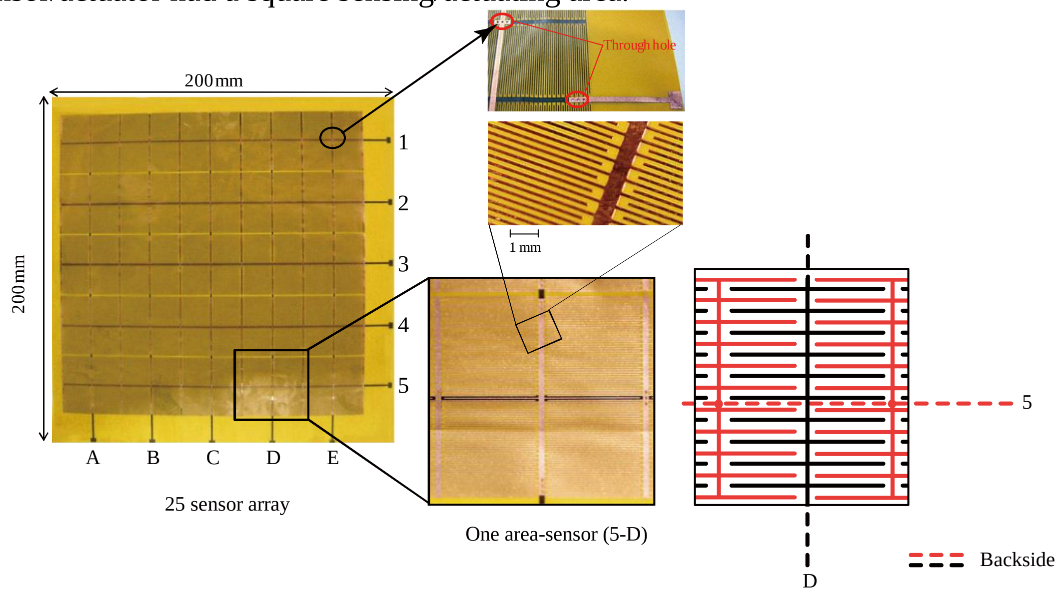


Fig. 1 Multifunctional interdigital electrode array (MIEA) film.

3. Flow control using dielectric heating

The flow velocity of resin inside the mold through the fiber preform during the VaRTM process can be assumed to follow Darcy's law

$$\mathbf{U} = -\frac{\mathbf{K}}{\phi\mu}\nabla P \tag{1}$$

where **U** is flow velocity vector, **K** is preform permeability tensor, ϕ is porosity, μ is resin viscosity, and ∇P is gradient of pressure. We focus on flow velocity control by viscosity change of the resin based on Eq. (1), by raising the resin temperature. The relationship between viscosity and the temperature until cure starts is [6, 7]

$$\mu = \mu_\infty \exp\left(\frac{U}{RT}\right) \tag{2}$$

where μ_∞ is the viscosity at infinite temperature, U is activation energy, R is the universal gas constant, and T is absolute temperature.

To investigate how the viscosity changes when the temperature rises, we conducted measurements of the viscosity of resin developed for RTM, low viscosity epoxy (Kokusai Chemical, Z-2), and two types of unsaturated polyester (UP) resin (Japan U-Pica, U-pica 4007A and DH material, Sundhoma PC-184-C). The resin viscosity was measured using a viscometer (Toki Sangyo, TVC-5) while the resin was heated on a hot plate (Thermolyne Cimarec). The temperature was measured using a type K thermocouple and recorded on a PC by a data logger (Keyence, NR-250).

Figure 2 shows the relationship between the viscosity and temperature of the three resins. The viscosity of all of the resins decreased exponentially with increasing temperature and agreed well with Eq. (2). The viscosity of Sundhoma PC-184-C resin, which had the lowest viscosity of the three resins, decreased approximately by half for a 10°C temperature increase, implying that the flow velocity doubled, which is a sufficiently large increase for resin flow control.

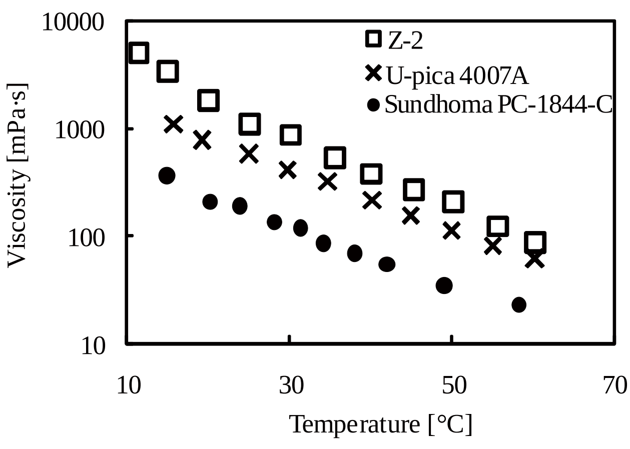


Fig. 2 The relationships between viscosity and temperature of epoxy resin (Z-2) and UP resins (U-pica and Sundhoma).

4. VaRTM flow control experiments

4.1 Experimental procedures

Flow monitoring and actuating using MIEA was conducted to investigate the feasibility of flow control to prevent dry spots. Figure 3 shows the experimental setup; the MIEA was placed on the acrylic plate and eight layers of 1K glass cloth (Molymer SSP, YEM1801) were stacked on the film. The urethane foam core was inserted between the fourth and fifth layer. This model structure simulates the keel structures of marine vessels.

The waveform generator output 800 Hz and 2 V_{pp} waves, and the digitizer measured impedance by switching the selected sensor on the MIEA using a relay, for estimating resin impregnation. After that, the wave generator output 800, 1200 and 1600 Hz waves, and the temperature distribution was estimated by measuring the frequency dependence of the resin permittivity. The impregnated areas were then calculated with temperature compensation. If possible location of a dry spot was identified, dielectric heating was applied at the selected electrode for 15 s. The temperature/flow monitoring and dielectric heating were repeated in sequence.

To prevent the occurrence of dry spot, we use detection of the sharpness of the resin flow front. This is because the sharp flow front easily causes the dry spot by touching another sharp flow front. Since the detection of sharp flow front is straightforward, it can be easily installed in the controller system and performed automatically in real-time. The electrode selected for dielectric heating was judged as follows.

(i) Identifying un-impregnated electrodes that were located at the lower and upper of the impregnated electrodes.
(ii) Heating impregnated electrodes in the left of the electrodes.

This flow control scheme aims to alleviate the sharp rapid flow which may result in dry spots in the future. For a more efficient selection scheme, a complex optimization problem has to be solved which requires further detailed research and is now under investigation.

Heating was applied when the selection criteria were satisfied. Since the viscosity of the resin decreases exponentially with increasing temperature, a 10 °C temperature increase doubles the flow rate, which changes the flow pattern sufficiently. Although a larger temperature increase is favorable for increasing flow rate, excessive heating may shorten the gel-time. Since we confirmed that a temperature increase up to 20 °C does not greatly affect the cure process, the temperature should be increased up to 20 °C.

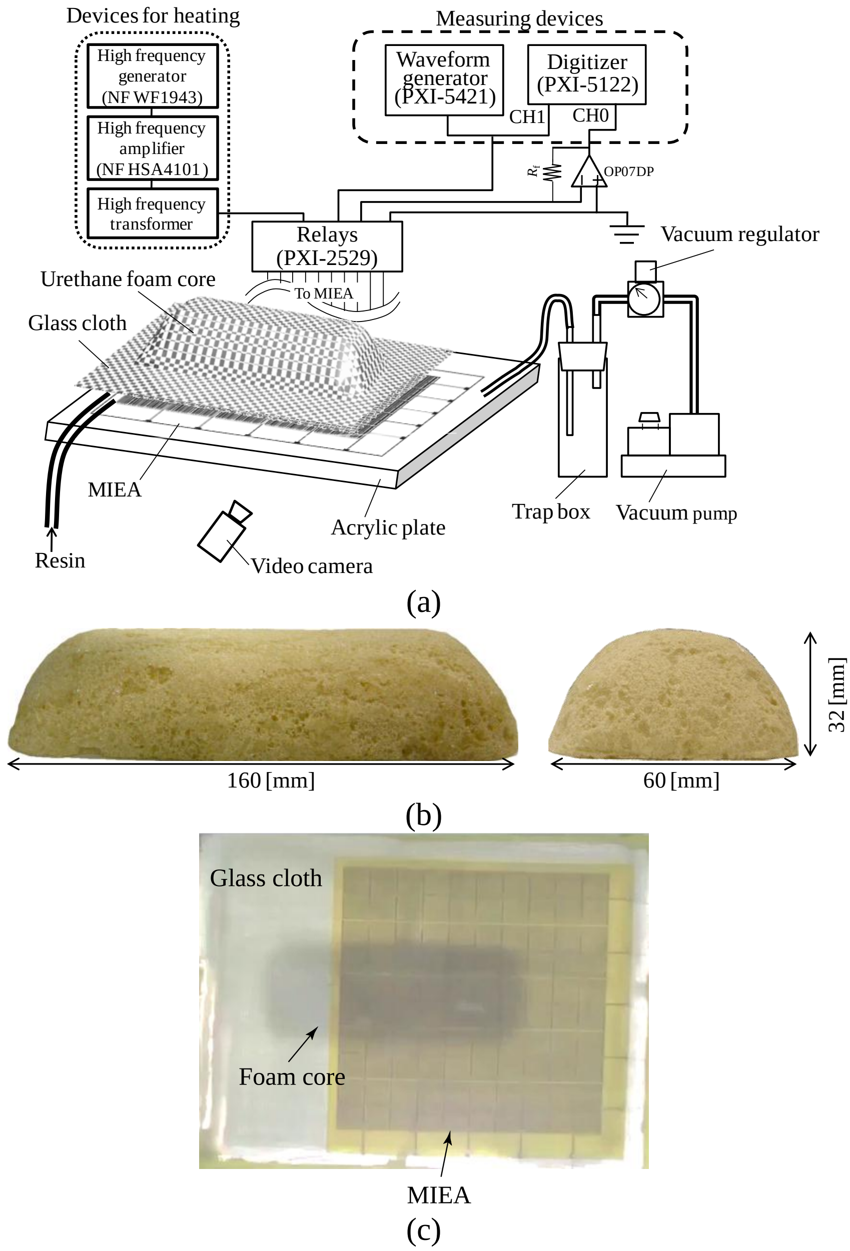
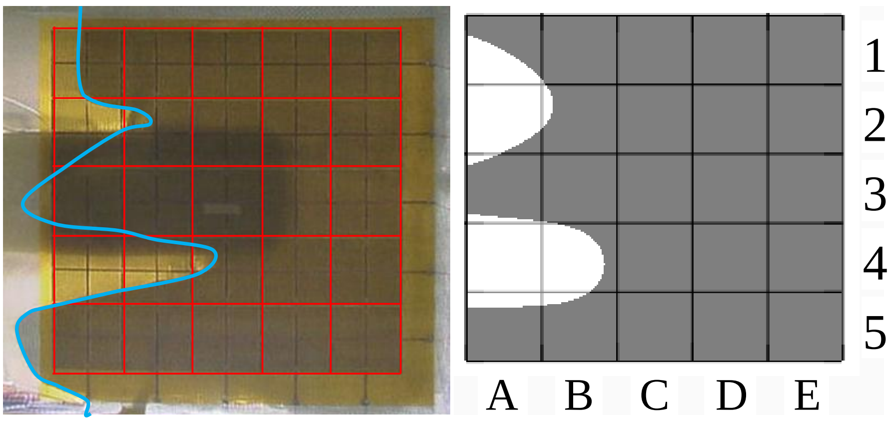


Fig. 3 Experimental setup for smart flow to prevent dry spot. (a) overview, (b) configuration of foam core material, and (c) alignment of foam core, glass cloth and MIEA (seen from bottom side through the acrylic plate).

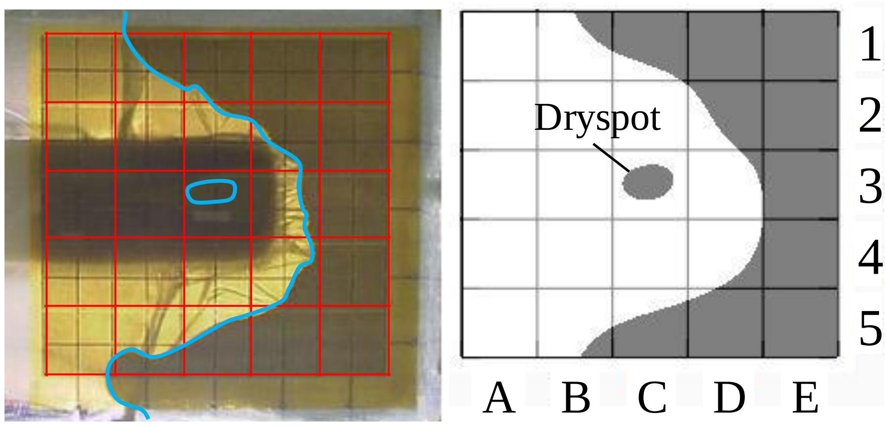
4.2 Results and discussion

Figure 4 shows resin impregnation without flow control, taken by video camera through the bottom acrylic plate on the left, and the flow front monitored using MIEA on the right. The red grid is the electrode location on the MIEA, and the blue line is the flow front. Detailed discussion regarding the flow front monitoring of this experiment can be found in [4]. Figure 4 shows the impregnation at (a) t=¼ T and (b) t=½ T, where full impregnation was set at t=T. From the recorded image in Fig. 4(a) for t=¼ T, it was observed that the resin flow under the urethane foam core was delayed compared with the side areas. The two flows on both sides of the foam core impregnated faster than the central flow around the core region, and the two side flows touched before the center area was impregnated with resin. Consequently, a dry spot occurred at (b) t=½ T around the core region.

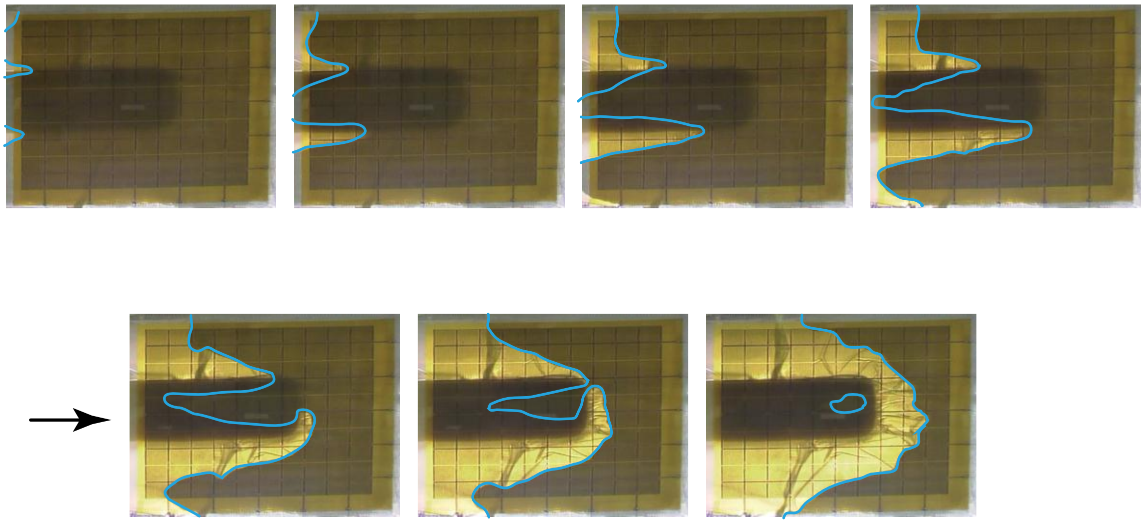
Figure 5 shows the results of flow monitoring and controlling by dielectric heating. The estimated temperature distribution using the frequency dependence of the resin permittivity is also shown. Although it is difficult to install a thermocouple and obtain a precise temperature, the actual temperature at the heated area during VaRTM was supposed to be 35-40 °C from the IR camera in our experimental setup. This value corresponds to a 10-15°C temperature increase, implying doubled flow rate. From the flow monitoring, the side flow around the edge of the core was faster than in the core center region, similar to Fig. 4. The faster side flow was caused because the core bottom was not flat, and the presence of a small gap accelerated the flow velocity. Based on the selection scheme of heating locations, electrodes 3-A and 5-A were chosen to heat. The estimated temperature also showed the temperature rising at electrodes 3-A and 5-A, thus dielectric heating was successfully performed. By comparing the time history of resin impregnation with/without flow control, due to the dielectric heating, the flow velocity increased at the core center region, the flow delay at the central region was alleviated, and occurrence of the dry spot was prevented. By dielectric heating, the gel time of the heated resin may be faster than in other areas, which will induce adverse residual stress. Observed from the temperature distribution at (b) *t*=½ *T*, the heated resin moved to the outlet from 3-A to 3-C. Thus the heated resin is always at the flow front, and the residual stress problem can be solved by continuing vacuuming until the heated resin is evacuated. At the present stage of development, it is difficult to sense or control the flow that travels above the foam insert. Inserting multiple layers of MIEA in the composites may solve this problem though a feasibility study has not yet been conducted.



(a)

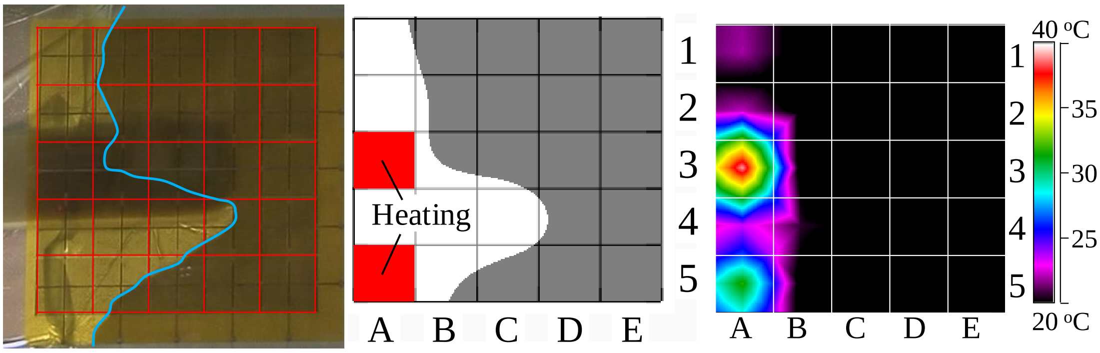


(b)

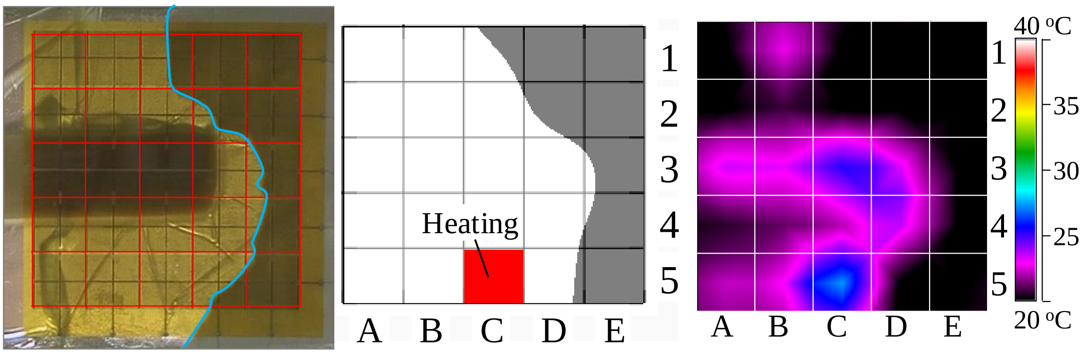


(c)

Fig. 4 Impregnation view and impregnated area estimated using MIEA without flow control. Resin flowed from left to right at (a) *t*=¼ *T*, (b) *t*=½ *T*, and (c) time history of resin impregnation.



(a)



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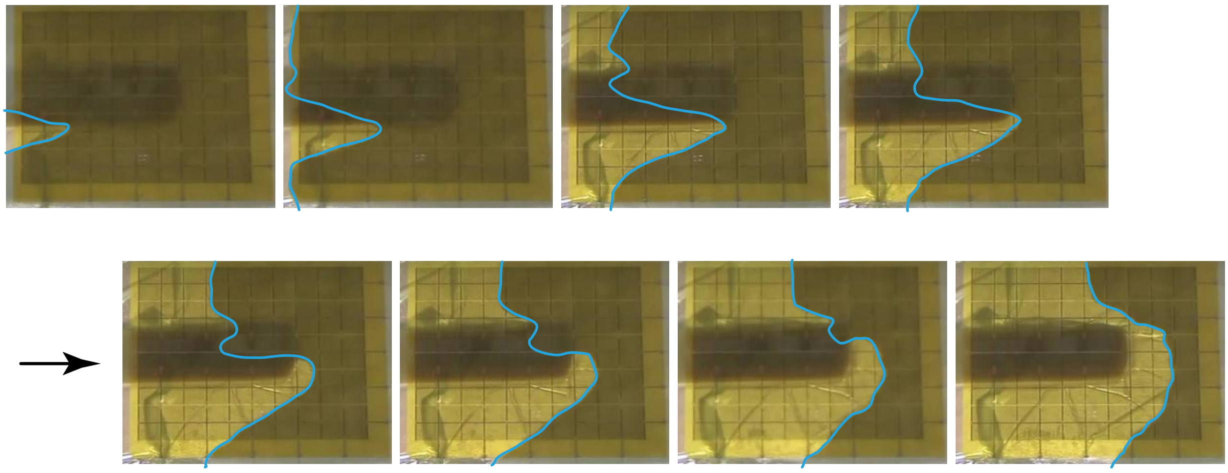

(c)

Fig. 5 Impregnation view, impregnated area and temperature distribution estimated using MIEA with flow control at (a) *t*=¼ *T*, (b) *t*=½ *T*. and (c) time history of resin impregnation.

5. Conclusions

The present study proposes a flow control scheme by monitoring and actuating resin flow/temperature using thin MIEA film during a VaRTM process. The capacitive interdigital electrodes on the MIEA were adopted as the sensor for monitoring resin flow front. The method increases the resin velocity by increasing the resin temperature at the appropriate locations to prevent dry spots. Foam cored GFRP structures were manufactured in VaRTM, and the effectiveness of flow control was investigated by comparing with and without flow control. As a result, the occurrence of dry spot was prevented with flow control, whereas dry spot occurred without flow control.

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