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Microwave Resin Preheating Integrated with AI-Based Flow Front Monitoring for Liquid Composite Molding Processes

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Abstract. The impregnation represents a crucial phase in liquid composite molding (LCM) processes. Researchers over the years have used various approaches for monitoring, based on smart weave, pressure sensors, dielectric. Among the LCM processes, the vacuum bag allows the use of visual systems for detecting the resin flow front. The integration of monitoring systems with controllers for automated management of process parameters leads to an improvement in the characteristics of the final manufactured component. In the present work, an AI-based system integrated with the control of a resin preheating system allows for improvement of the impregnation stage. A machine learning approach, based on the You Only Look Once (YOLO) algorithm, has been integrated with the visual monitoring system to detect and dynamically track the resin flow front in real time. The flow front position has been compared with the theoretical one, evaluated by using the Darcy's law and based on the mismatch the controller suggests a proper in-time regulation of microwave power. The implemented system is capable of processing images through an AI-based algorithm and extracting the kinematic data of the flow front and integrating the information from the thermocouples and the visual system to control the microwave power.

Introduction

In recent years, the use of composite materials for the manufacturing of components has been increasing, justified by their ability to significantly reduce weight; in line with recent findings, this trend is particularly evident in the automotive and EV sectors, where composites contribute not only to lightweight design but also to improved aerodynamic performance, enhanced mechanical strength, greater durability, and overall higher energy efficiency, thus meeting the growing demand for more efficient and sustainable vehicles[1]. Liquid Composite Molding processes have emerged as a versatile and cost-effective class of manufacturing technologies for composite structures, enabling the production of high-performance components through the impregnation of dry fiber preforms. In LCM [2], [3] the flow front position in porous media is controlled by the balance between viscous and capillary forces acting over distinct void scales. Viscosity influences displacement differently across scales, it strongly amplifies macroscopic viscous forces. Therefore, in liquid composite molding processes, the advancement of the flow front assumes great importance, both with regard to the time required to produce the part and the level of quality achieved in terms of defects, such as voids or dry spots. Different systems are used by researchers to evaluate the position of the flow front, some less invasive based on dielectric sensors [4] , visual systems[5], and others more invasive[6]. Yu Y. et al. in [7] used embedded fiber optic (FBG) sensors to locally detect resin arrival within different laminate layers, and their measurements, combined with piezoelectric data, enabled accurate real-time reconstruction of the three-dimensional resin flow front during the infusion process. Fernandez Leon et al. [8]present a digital twin for analyzing the resin transfer molding (RTM) process, aimed at detecting non-uniform resin flow and potential defects such as dry spots. The approach uses two deep learning surrogate models trained on synthetic simulation data to enable accurate, real-time monitoring of flow and pressure, achieving prediction errors below 1% and demonstrating good agreement with experimental results. Several authors have exploited the integration of flow front detection with control, with particular reference to the preheating of the resin. Therefore, by acting on the viscosity and preheating the resin, the infusion time can be reduced[9] [10]. In this work, a digital twin of the Seeman Composites Resin Infusion Molding Processes (SCRIMP), with a resin preheating system using a microwave, has been implemented. The purpose of this digital twin is to control the power to be delivered through the microwave. The system is composed by two environments: a physical one, from which it acquires temperature and visual data [5], and a digital one which evaluates the resin flow front position by means of a machine learning algorithm and compares it with the position obtained by modeling of the infusion phenomenon using Darcy's law. Finally, the system determines the variation in the power delivered by the microwave.

Materials and Methods

The vacuum bag is set up by stacking 8 sheets of glass fibers HexForce twill 2/2, with areal density of 390 g/ m^2 and a sheet of flow medium RDA130V150, with areal density of 130 g/ m^2, prelaminated with a ELA 20 film; the resin used is SX10EVO, premixed with the Epoxy based hardener in the mixing ratio of 100:26, with a viscosity of 0.8 Pas@25°C. A SCRIMP process was used to manufacture panels of 240 x 300 x 2.6 mm^3.

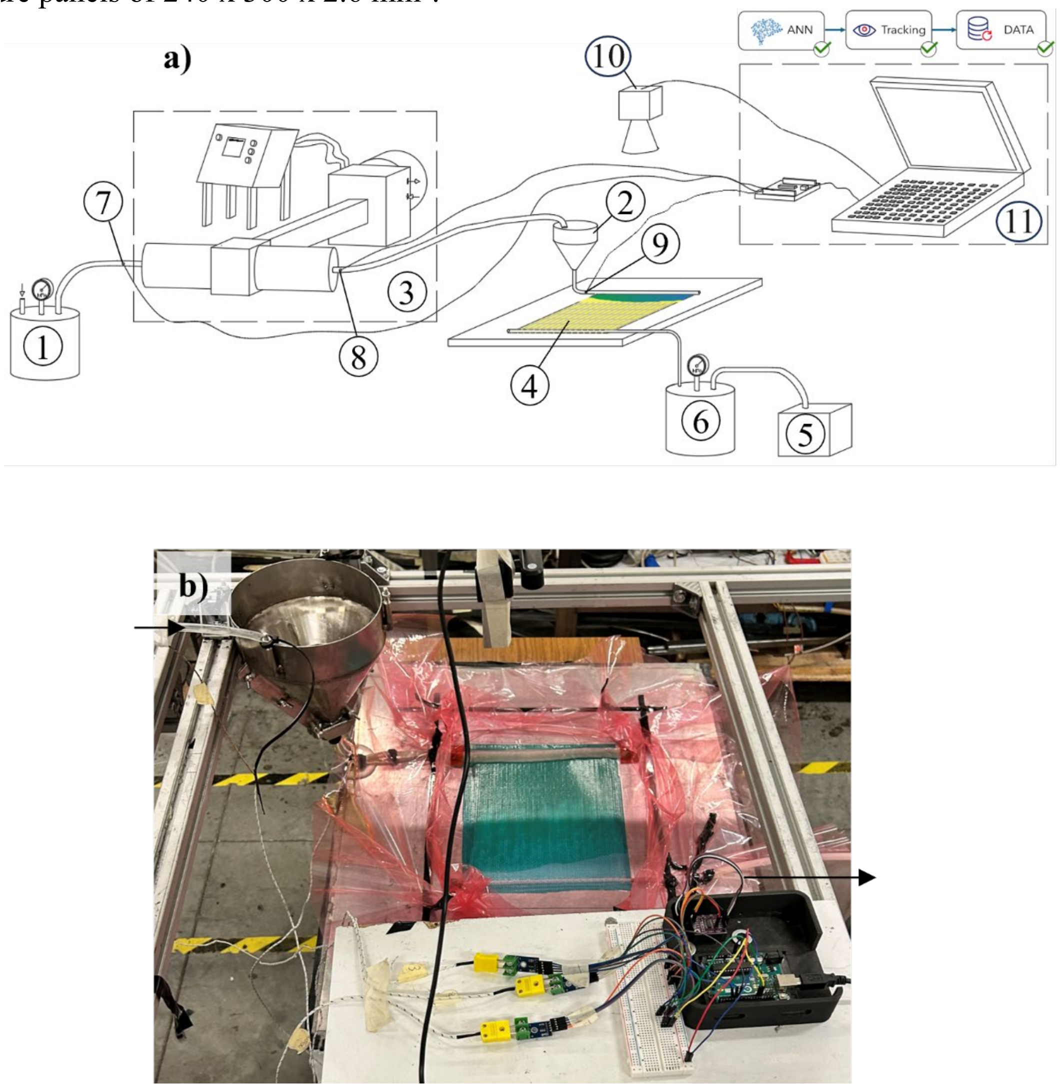

Fig.1 Laboratory-scale SCRIMP setup: (a) schematic of the process, showing the microwave resin preheating system, mold, and data acquisition setup; (b) photograph of the mold, highlighting the preheated resin inlet (top-left arrow) and the resin outlet toward the vacuum pump (bottom-right arrow).

Fig. 1a illustrates the laboratory-scale setup of the SCRIMP process, integrated with a microwave system for resin preheating. A positive pressure applied to the resin catch pot (1) drives the catalyzed resin, at a flow rate of 0.19 L/min, into the resin vessel (2), passing through the microwave (MW) preheating system (3). The resin then flows through the porous medium (4), guided by a vacuum generated by the vacuum pump (5), which is connected to the vacuum bag via a resin trap (6). The fluid is conveyed through PTFE pipes with an inner diameter of 10 mm. The developed digital twin system consists of a virtual replica based on Darcy's law, integrated with the physical environment via three thermocouples: the first (7) positioned before the MW system; the second (8) measuring the temperature at the exit of the MW system, to prevent it from exceeding 39 °C and causing premature polymerization; and the third (9) placed at the mold inlet to monitor the resin temperature for viscosity evaluation. A camera (10) records the process, enabling flow front monitoring through a machine learning approach based on the You Only Look Once (YOLO) algorithm, with data acquisition and processing carried out on a laptop (11). A more detailed description can be found in [5]. A picture of lab scale system is depicted in Fig. 1b.

Fig. 2 shows a scheme of the digital twin, the physical environment is composed by a camera and three thermocouples to acquire information on the resin flow together with a MW system to preheat the resin; the digital environment is made by an Arduino board to read the thermocouples signals, and a python code implemented on a laptop. The frames captured by the camera are first processed using a YOLO algorithm to detect the resin flow front, see Fig. 3. Then, the system evaluates and compares the real flow front position obtained from YOLO with the theoretical position predicted by a Darcy's law model. Moreover, this comparison is used to manage the MW.

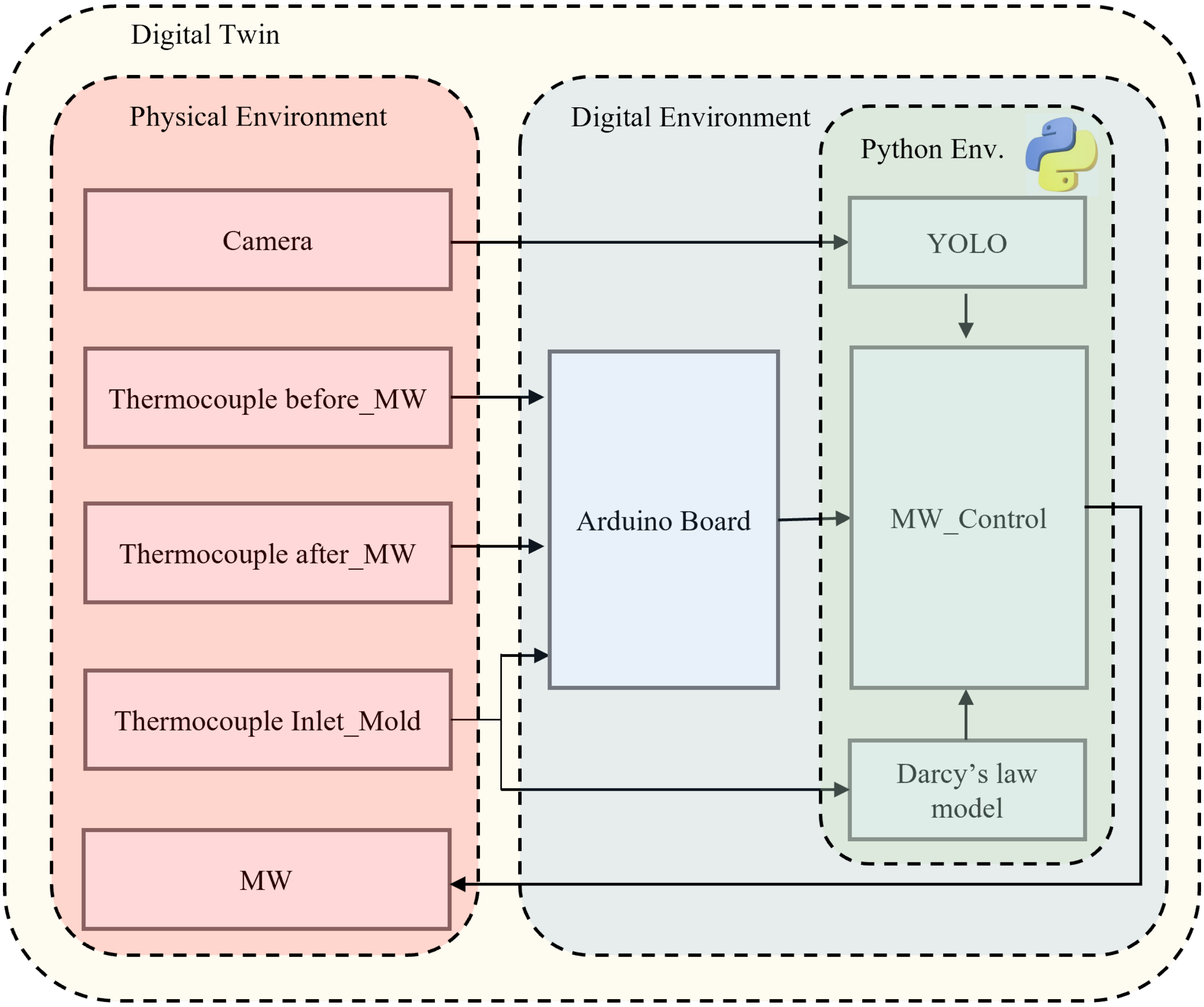

Fig.2 Digital twin scheme.

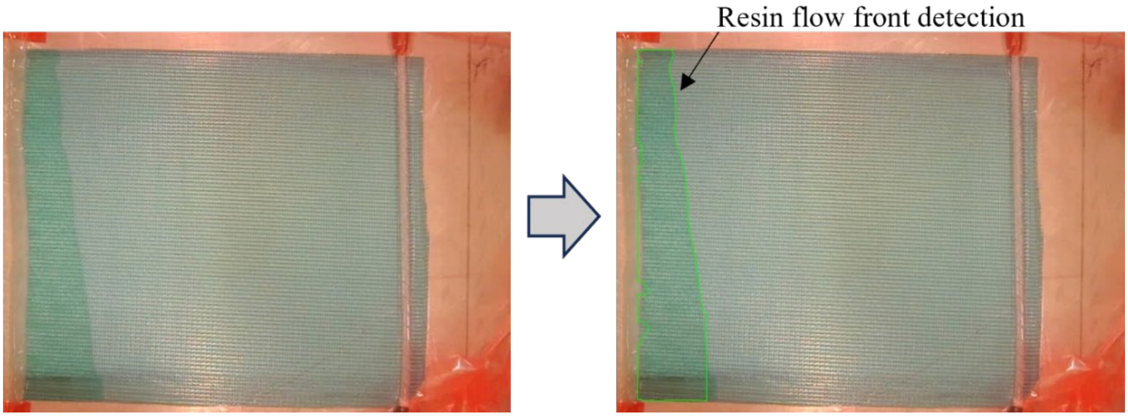

Fig.3 Flow front obtained from YOLO elaboration.

For each frame, the coordinates of the resin flow front are determined. The values corresponding to the mold's centerline (see Fig. 4) are extracted and plotted as the acquired position in Fig. 5. The temperature measured by the thermocouple at the mold inlet is used to estimate the resin viscosity, which is then applied in the Darcy model to predict the flow front, shown as the estimated position in Fig. 5.

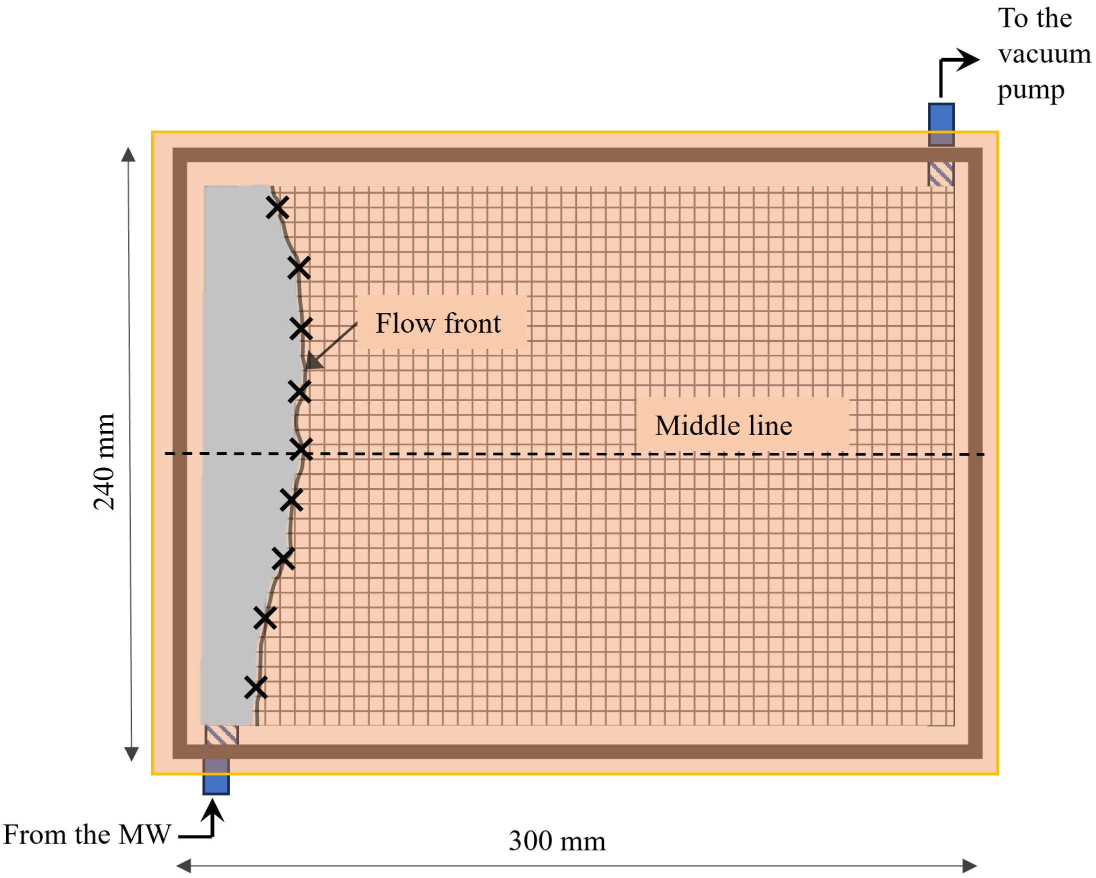

Fig.4 Flow front position.

The MW Control block of the digital twin monitors, for each frame, both the acquired position obtained via the YOLO algorithm, and the estimated position predicted by the Darcy model. As shown in magnification (a) of Fig. 5, if the acquired flow front lags behind the estimated one, the MW power is increased; otherwise, it is decreased. In the former case, highlighted in (a), a check on the maximum temperature after the MW system is performed to prevent premature polymerization.

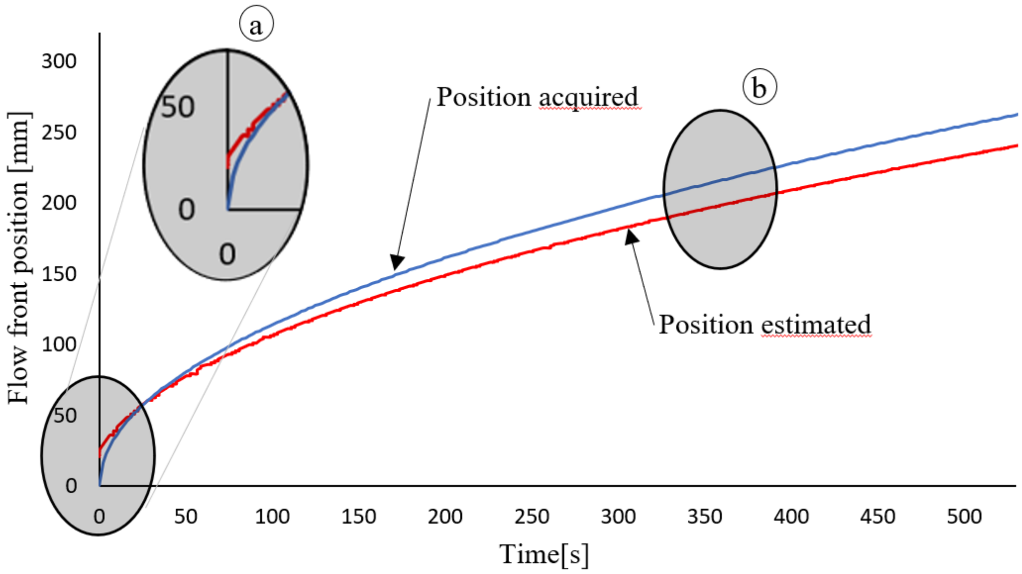

Fig. 5. Control logic: resin flow front positions—acquired by YOLO and estimated by the Darcy model. (a) Estimated exceeds acquired; (b) acquired exceeds estimated.

Results and Discussion

Fig. 6 shows the results of the laboratory test, specifically in Fig. 6a the acquired positions, evaluated using YOLO, and the estimated positions, using the model based on Darcy's law, are reported.

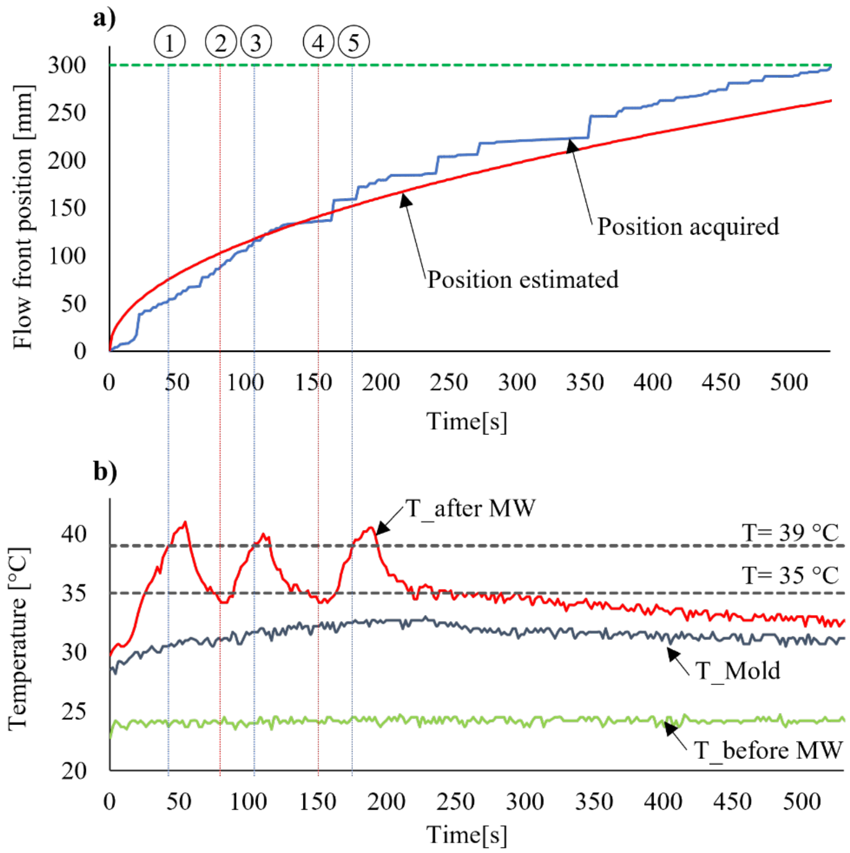

Fig.6 Results: a) resin flow front positions acquired and estimated; b) temperatures acquired.

In Fig. 6b, instead, the temperatures before MW, after MW, and at the mold entrance are shown. Furthermore, in the first one, the value 300 mm is reported, which represents the length of the mold; in the second, there are the two limits in terms of temperature: 39°C, which represents the maximum value that can occur at the MW outlet, beyond this value premature polymerization may occur and 35°C which is used to manage power control. Points 1 to 5 shown at the top of Fig. 6b highlight the operation of the DT. In the time between the starting and point 1, the acquired position of the resin flow front is lower than estimated, and therefore the power is increased. At point 1, although this condition is still met, the temperature has reached the 39 °C limit, which must not be exceeded to prevent premature polymerization. Therefore, the MW power is reduced, resulting in a decrease in T_after MW. Once the temperature reaches 35 °C, the estimated position of the flow front is still ahead of the acquired one. This corresponds to point 2, where the power is then increased. The same discussion applies to points 3 to 5. The test ends at about 530 s. From Fig. 6b it can be seen that the resin temperature before the MW is about 24 °C and the temperature at the mold inlet varies between a minimum value of 28 °C and a maximum of 33 °C, with an average value of 31 °C.

Conclusions

A feedback control system for microwave power has been implemented, based on resin flow front position values evaluated through an AI-based approach, specifically using You Only Look Once (YOLO) algorithm. It is capable of assessing the instantaneous position of the flow front and comparing it with that estimated via a flow model based on Darcy's law. The system monitors the resin flow front positions and the maximum temperature the resin can withstand before premature polymerization occurs.

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