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Experimental and numerical investigations of pressure-controlled resin transfer molding (PC-RTM)

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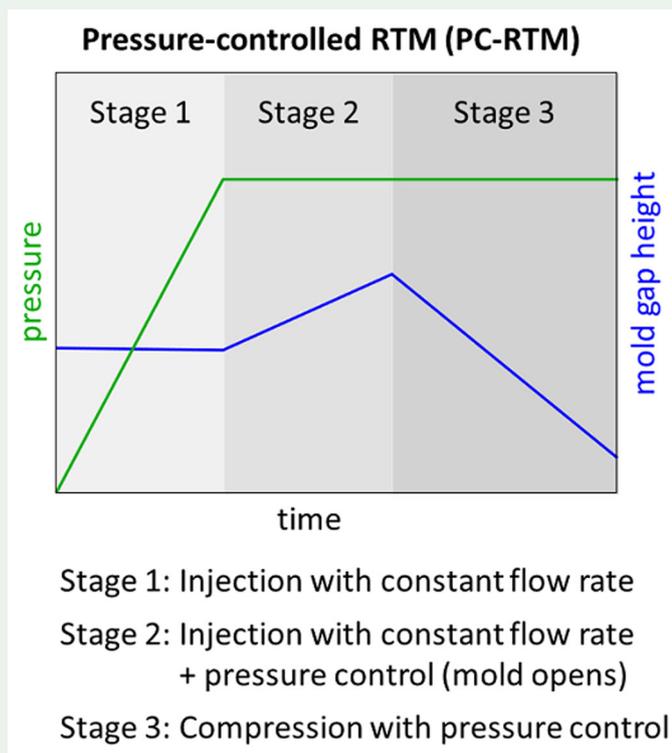
ABSTRACT

To increase the use of fiber reinforced lightweight structural components in the automotive industry, their manufacturing processes have to obtain demanding economic requirements. One possibility is to use Compression Resin Transfer Molding (CRTM), which is fast and can be highly automated. One disadvantage can be the very high cavity pressure during injection. To avoid this disadvantage, a pressure-controlled RTM (PC-RTM) process was developed. PC-RTM uses a variable mold gap height and an embedded pressure sensor to control the cavity pressure actively during mold filling. In this work, we investigate this process by experiments and simulations with varying initial mold gap and controlled cavity pressure. We show that PC-RTM is a viable manufacturing process with short cycle times and high robustness. Furthermore, the simulations are validated by comparison to the experiments and show the same process characteristics.

KEYWORDS

Resin transfer molding; process development; process simulation; mold filling

GRAPHICAL ABSTRACT



1. Introduction

Continuous fiber reinforced plastics have a huge potential to realize lightweight constructions in the

automotive industry. To increase their market share, more economic manufacturing processes have to be developed and especially aspects like short cycle time,

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process robustness and high automating degree have to be addressed. One example is Compression Resin Transfer Molding (CRTM), which is recently increasingly investigated because of its high automation potential for manufacturing structural car parts. In CRTM, a mold gap (in our work, we use the term mold gap height defined as the difference between final part thickness and current cavity thickness) increases the preform permeability and during the injection step the cavity pressure is much lower than in conventional High-Pressure Resin Transfer Molding (HP-RTM). After the injection, a subsequent compression step is needed to achieve the final part thickness, where very high cavity pressures are reached.

High pressure peaks can arise during injection in HP-RTM and during the compression step in CRTM. In contrary, the pressure-controlled RTM (PC-RTM) process prevents high pressure peaks during any step of the process [1,2]. This can be used to manufacture sandwich parts, where it is essential that the cavity pressure does not exceed a specific value to avoid defects like infiltration or crushing of the core material [3–6].

A small gap of the upper mold tool already leads to a significant increase of permeability while the resin infiltrates the preform. This fact is used to control the cavity pressure by adjusting the cavity height during the whole infiltration stage. Besides the expected improvement on the quality of embedded foam cores, this also decreases investment cost, as no high-pressure tools nor large hydraulic presses are necessary when manufacturing components using PC-RTM [7].

Mold filling simulations of RTM are already frequently used to analyze the infiltration behavior of complex parts. The modeling in commercial software is mainly based on finite-elements discretization based on work of Brusckke or Trochu [8,9], but recently also finite-volume schemes are being used [10,11].

Mold filling simulations of CRTM were first established by Pham [12,13], who modeled one-dimensional and two-dimensional resin flow based on Darcy's law [14] using a finite-element method. Shojaei [15] developed a three-dimensional finite-element/control volume method to simulate the resin flow of CRTM in thick parts. By using a finite-volume formulation, mold filling of CRTM can also be simulated for small mold gap heights, where the preform is still in contact with the tool [16]. The method enables further developments in RTM mold filling simulations, for example the implementation of resin viscosity models [17] or of advanced process variants as we present in this work.

Besides the modeling of the preform permeability, it is also very important to model the

temperature-dependent resin viscosity accurately to correctly predict the fluid pressure inside the cavity. Various models were published to describe the curing and viscosity behavior of thermoset resins, as for example by Kamal [18], Grindling [19], Bernath [20] or by Castro and Macosko [21].

In this work, the open-source toolbox OpenFOAM is used, where the full Navier-Stokes-equations are numerically solved by a finite-volume method [22]. For the PC-RTM mold filling simulation we implement a time- and solution-dependent boundary type to control the compression velocity during the whole mold filling stage.

The main aims of this work are to show the successful implementation as well as the advantages of the process and to validate the mold filling simulations of PC-RTM by comparison to the experimental investigations.

2. The PC-RTM process

PC-RTM continues the experimental investigations made in the ultra-RTM process variant, which was developed as a CRTM process with addition of a pressure control during the compression step [5].

Figure 1 shows the eight process steps of PC-RTM. Firstly, the layup is stacked of several fibrous layers. Secondly, the preform is put inside the open mold. Afterwards (3.) the mold is closed to an initial mold gap. In step four, the injection starts while the mold gap height is held constant. The fifth step starts, when the predefined pressure control value is reached. The mold gap is actively increased, whereby the mold opening velocity is controlled by the hydraulic press. The mold opening velocity depends on the cavity pressure that is measured by an integrated sensor, which is normally located close to the inlet, where the highest pressure arises. In principal any other point inside the cavity, e.g. close to a foam core, could be used to control the process pressure. Injection flow rate is kept at a constant value during the whole injection. When the desired amount of resin is injected, the inlet gate is closed and step six starts, where the part is compressed to its final thickness while keeping the pressure constant. Subsequently the part is cured (7.) inside the mold and finally it is demolded (8.).

The whole mold thus acts like a “breathing” tool which opens during injection and closes during compression.

In this work, we focus on the mold filling steps of the process that means steps four to six. The schematic devolution of pressure and mold gap height in these steps are shown in Figure 2. Further on, the three steps of Figure 2 are referred to as Stage 1, 2 and 3. When realizing PC-RTM, besides the process temperature and the injection flow rate,

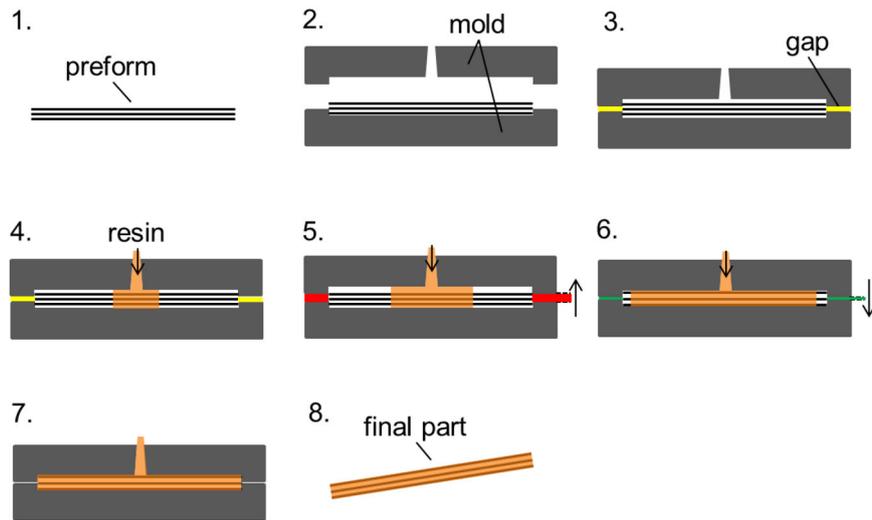


Figure 1. PC-RTM with 8 process steps; 1: Stacking of the preform, 2: Transfer to open mold, 3: Closing mold to initial gap height (and applying vacuum), 4: Injection with constant mold gap height; 5: Injection with opening mold and constant cavity pressure; 6: Compression with constant cavity pressure, 7: Curing, 8: Demolding.

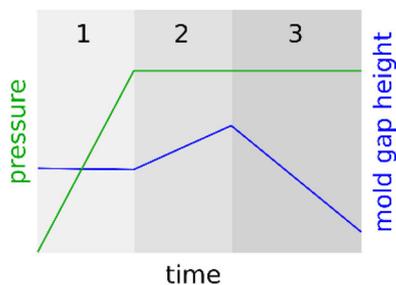


Figure 2. Schematic representation of cavity pressure and gap height of the three mold filling stages of PC-RTM (cf. steps 4 to 6 in Figure 1).

only two important process parameters have to be set: the pressure control value and the initial mold gap height. The pressure control value determines the maximum mold gap height, the mold filling time and the clamping force needed. By changing the initial gap height, the pressure increase rate during injection step can be adjusted.

3. Experimental setup and simulation model

The objectives of the experimental investigations are to ensure the feasibility of PC-RTM, to evaluate the reproducibility and to validate the simulation method. The important PC-RTM process parameters are summarized in Table 1. The table shows the parameters that are held constant in all investigated configurations and the parameters that are changed in each configuration.

3.1. Experimental setup

A mold with a plate geometry is used having an injection runner in the middle of the plate (cf. Figure 5). This ensures a nearly one-dimensional mold filling

Table 1. PC-RTM parameters for experimental investigations and validation of the simulation method.

Parameter	Value	Unit
Injection flow rate	100	g/s
Injected resin volume	660	g
Resin density	1120	kg/m ³
Mold temperature	393	K
Initial mold gap height	0.1, 0.3, 0.7	mm
Pressure limit	1,52,030	bar

behavior and therefore ensures a good comparability to the simulation model. Experimental investigations are performed at the Fraunhofer ICT (Pfinztal, Germany) using a three-component high-pressure RTM injection machine (KraussMaffei, type RTM 8/3.2 K) and a hydraulic press (Dieffenbacher Compress Plus DCP-G 3600/3200 AS) that includes an active parallel holding system to prevent an inclination of the upper mold part. Four capacitive distance sensors are installed at the mold corners (capaNCDDT 6230 controller and sensor type CS5 with a dynamic resolution of 0.1 μm by Micro-Epsilon). The mold gap is tracked during the whole process and is measured as the mean value of the four distance sensors. This value is also used during the start of the injection, when the gap height is controlled to a constant value.

With a distance of 25 mm to the inlet gate, a pressure sensor (6167 A by Kistler Instrumente AG) is embedded into the mold which is connected to the press control unit. The sensor is leveled with the mold surface to not influence the filling behavior.

To realize the pressure control, a control system is used with the pressure at the embedded sensor as the process variable and the press force as the controller output. During the start of the injection, the press force is adjusted to hold a constant gap height. The moment, the pressure at the sensor reaches the set control value,

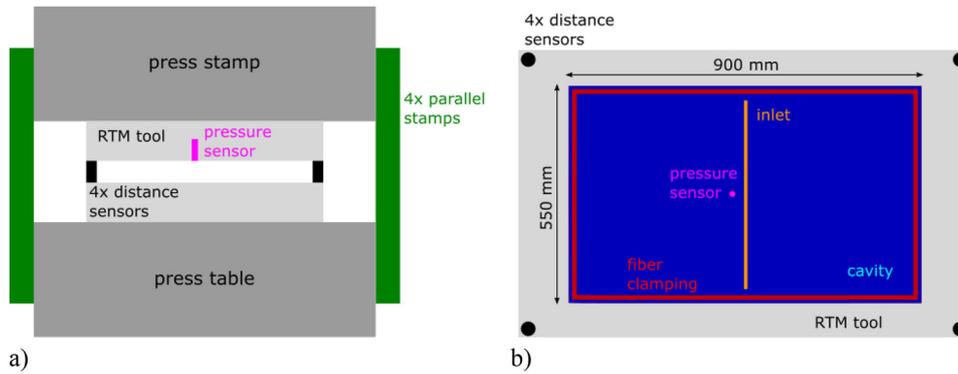


Figure 3. Schematic representation of the experimental setup including mold geometry, fiber clamping, distance sensors and pressure sensor; side view of a) the press setup and b) top view of the lower RTM tool.

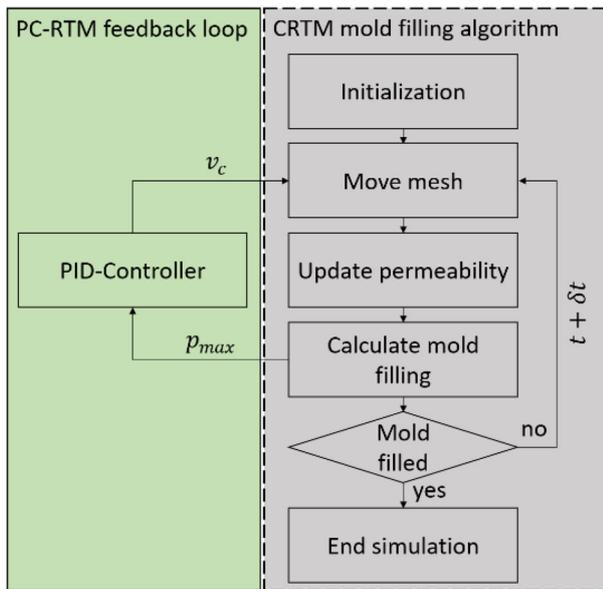


Figure 4. Simulation algorithm for simulating mold filling of PC-RTM. A PID-controller sets the compression velocity.

the controller is changed from mold gap to pressure. It now adjusts the press force, so that the pressure inside the cavity is controlled to a constant value.

Additionally, a fiber clamping based on an adjustable polymer gasket is used to avoid race tracking effects. Two vacuum ports are mounted to apply vacuum in the mold cavity before resin injection. The experimental setup is shown in Figure 3.

We use an epoxy resin system (Voraforce 5300 by DOW) with a pre-heating of the resin to 90°C. The fabric used is a non-crimp unidirectional glass fiber fabric by SAERTEX GmbH & Co. KG (layup: [0°/90°/0°]). The measured area weight is 1200.5 g/m² with a mean deviation of 6.51 g (0.54%). Measurement was done according to DIN EN 12127:1997.

Each experimental configuration is repeated at least four times.

3.2. Simulation model

To simulate mold filling of PC-RTM, the method for simulating CRTM as published in [16] is used.

It is a full three-dimensional simulation based on the finite volume discretization of the Navier-Stokes-Equations with an additional porous drag term in the momentum equation based on Darcy's law:

$$\nabla p = -\mu \cdot \mathbf{K}^{-1} \cdot \tilde{\mathbf{v}}, \quad (1)$$

where $\tilde{\mathbf{v}} = (1 - \varphi) \cdot \mathbf{v}$ is the volume averaged velocity with the fiber volume fraction φ and the resin velocity \mathbf{v} . ∇p is the pressure gradient in the cavity, the parameter μ is the dynamic resin viscosity and the symmetric second-order tensor \mathbf{K} defines the anisotropic permeability of the fibrous preform. To realize the pressure control to a fixed value, we add a control system to the CRTM simulation algorithm using a virtual proportional-integral-derivative (PID)-controller to set the compression velocity.

Figure 4 shows the simulation algorithm used for simulating PC-RTM with the embedded PID-controller. The controller gets the information of the fluid pressure p_{max} at a previously defined point in the simulation model as process value. Subsequently, the controller output sets the upper mold velocity according to the desired pressure control value. In the next step, the simulation mesh is moved with the defined mold velocity v_c , which also changes the fiber volume fraction. This leads to a change in the permeability, which is updated at each time step before the mold filling is calculated. The simulation model is shown in Figure 5. The symmetry of the plate is used to model only half of the cavity. The mesh consists of uniform hexahedral elements with a grid size of 5 mm in both in-plane directions. The cavity pressure to control the mold velocity is evaluated at the point in the simulation model, which is at the same location as the pressure sensor used in the experiments. The boundary conditions of the simulation model are summarized in Table 2. The inlet boundary is set to a constant flow rate during injection (Stage 1 and 2) and set to a wall boundary condition during compression (Stage 3). At the sidewalls outside of the fiber

clamping, the resin is allowed to flow out of the simulation domain like the experimental mold geometry that also allows resin leakage at these edges. As the simulation is non-isothermal, the temperatures of the inlet (363 K) and of the mold wall (393 K) are set according to the experiments. The reference height of the cavity without mold gap is 2.3 mm ($\varphi_{\text{ref, global}} = 0.6162$), whereas in the fiber clamping it is designed to be 1.6 mm. To allow a small amount of resin flow through the fiber clamping, we locally adjust the fiber volume fraction and its permeability according to the designed geometry.

Furthermore, simulations of standard HP-RTM processes with constant injection flow rate and constant injection pressure of 15 bar, 20 bar and 30 bar were carried out as a reference for comparison to the PC-RTM Simulations.

3.2.1. Permeability

An exact measurement of the permeability depending on fiber volume fraction is crucial for a realistic simulation of the PC-RTM mold filling.

The permeability of the fibrous material that is used in the experiments is measured at different fiber volume fractions calculated with the measured area weight in a linear permeability test setup [23]. The preform is placed in a rectangular mold and resin is injected through a linear inlet at constant pressure using a test fluid with constant viscosity. Several pressure sensors are integrated in flow direction into the mold to track the flow front progression. The fiber volume fraction can be changed by increasing or decreasing the cavity height with

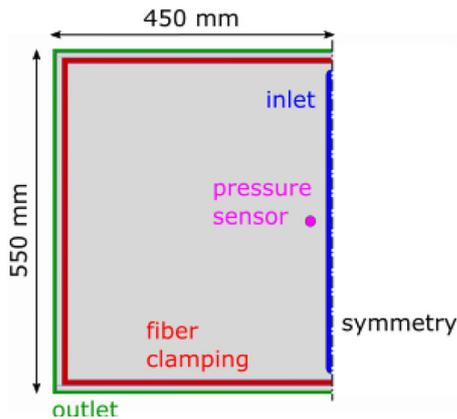


Figure 5. Simulation model with inlet, outlet, fiber clamping, pressure sensor and symmetry boundary condition.

spacer plates. The method is, therefore, conducted similarly to the PC-RTM experiments.

The resulting graph in Figure 6 shows the measured permeabilities and their standard deviations. As can be noticed, the standard deviations are very low except for the measurement of the lowest fiber volume fraction, which can be explained by an increased race tracking and thus a heterogeneous flow front in the experiments. In the simulations, the permeability is interpolated with an exponential fit between the measured points.

3.2.2. Viscosity

Like the permeability, also the dynamic resin viscosity μ of the thermoset resin influences the cavity pressure significantly. To describe the cure- and temperature-dependent viscosity, the Castro-Macosko rheology model [21] is used in the simulations:

$$\mu = \mu_0 \cdot \left[\frac{\alpha_g}{\alpha_g - \alpha} \right]^{C_1 + C_2 \cdot \alpha}, \quad (2)$$

$$\mu_0 = B \cdot e^{\frac{T_b}{T}}, \quad (3)$$

with the cure degree α and the temperature T as well as the cure degree at the point of gelation α_g and the model parameters B , C_1 , C_2 and T_b . The model parameters are identified by performing rheology measurements at different isothermal temperatures, which is described in detail in [20]. To model the devolution of the cure degree depending on temperature and time, we use the Grindling kinetic model [19] that includes vitrification dependent diffusion. The model, measurements and the param-

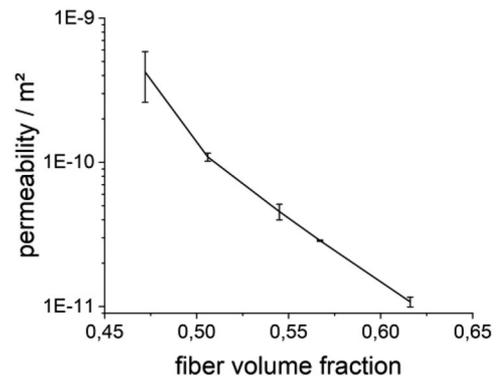


Figure 6. Measured permeabilities and standard deviations of the non-crimp glass fiber preform with a layup of $[0^\circ/90^\circ/0^\circ]$ in flow direction for different fiber volume fractions.

Table 2. Boundary conditions of the validation model.

Boundary	Velocity	Pressure	Temperature
Inlet (Stage 1 and 2)	fixed flow rate: 50 g/s	zero gradient	fixed value: 363 K
Inlet (Stage 3)	slip velocity	zero gradient	fixed value: 363 K
outlet	zero gradient	fixed value: 1 bar	zero gradient
lower mold wall	slip velocity	zero gradient	fixed value: 363 K
upper mold wall	PID wall velocity	zero gradient	fixed value: 363 K

Table 3. Parameters of the Castro-Macosko rheology model and the Grindling kinetic model, as defined in [20].

Castro-Macosko viscosity model		
Parameter	Value	Unit
C_1	0.2492	–
C_2	6.4335	–
B	$7.8597 \cdot 10^{-3}$	Pa s
T_b	$1.0000 \cdot 10^{-3}$	K
a_g	0.7990	–
Grindling kinetic model		
Parameter	Value	Unit
R	8.3145	J/mol/K
A_1	$3.2088 \cdot 10^6$	1/s
A_2	$8.3155 \cdot 10^5$	1/s
E_1	$6.1458 \cdot 10^4$	J/mol
E_2	$5.3438 \cdot 10^4$	J/mol
n_1	4.24525	–
n_2	1.72672	–
m	1.1431	–
$K_{2, diff}^{T=T_g}$	19.2722	1/s
c_1	$3.5369 \cdot 10^3$	–
c_2	$5.9439 \cdot 10^3$	K
ΔT_g	$9.9837 \cdot 10^1$	K

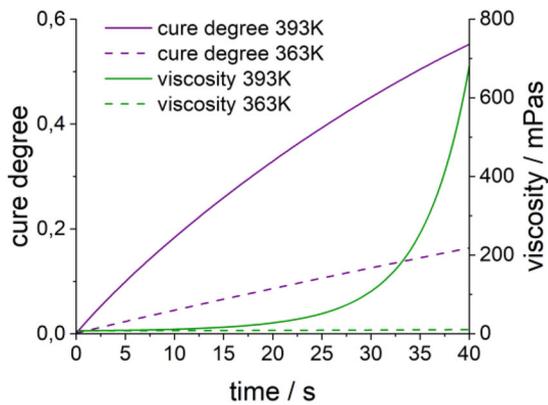


Figure 7. Modeled viscosity of the thermoset resin for two isothermal temperatures.

etrization are described extensively in [20]. The model parameters are summarized in Table 3 and the resulting cure degree and viscosity for two isothermal temperatures of 363 K and 393 K are shown in Figure 7.

4. Results

The experiments and simulations are evaluated in terms of the maximum mold gap height, pressure at the pressure sensor and mold gap height devolution during the mold filling.

Figure 8 shows the experimental results containing standard deviation error bars and, furthermore, the simulation results. The cavity pressures are shown as blue colored lines and the mold gap heights are shown in green color. The mold filling time is defined as the time when the final part thickness is reached and, therefore, the mold gap height reaches 0 mm.

The first row in Figure 8 shows the results with an initial mold gap height of 0.1 mm and a pressure control value of 15 bar (left), 20 bar (middle) and 30 bar (right). In Stage 1, the pressure increases while maintaining a constant mold gap height until the pressure control value is reached. At this point, Stage 2 starts: the mold opens and the pressure is kept at a constant value with injection still ongoing. After 6.6 s the set amount of resin is injected, so the injection stops and the compression with constant cavity pressure starts (Stage 3).

The second row in Figure 8 shows the results for the three configurations with an initial mold gap of 0.3 mm. The graph on the left again shows the three PC-RTM mold filling stages. In the graphs in the middle and on the right, the pressure limit is reached only in Stage 3. In the right graph this leads to a sudden increase in pressure after the injection to reach the desired control value in the compression phase.

In the third row in Figure 8, the results for the three configurations with an initial mold gap of 0.7 mm are shown. In neither of the simulations nor the experiments, the pressure limit is reached during injection. The configuration of initial mold gap of 0.7 mm and a pressure control value of 30 bar is not investigated here. The very high sudden pressure increase that is necessary after the injection in this case could not be realized in the experiments and therefore a comparison to the simulation is not possible.

The simulations show a very accurate controlling of the pressure with only a slight overshoot at the beginning of the controlling. The change of the boundary conditions from injection to compression, results in a drop in the simulated pressure for a couple of simulated timesteps until the control value is reached again.

In Figure 9, the maximum mold gap heights for the investigated process parameters for experiments and simulations are shown. It is clearly visible that the values show the same decreasing trend from high initial mold gap heights and low control pressures to low initial mold gap heights and high control pressures.

To visualize the results of the mold filling simulations, Figure 10 shows the simulated fields of filling degree, pressure, temperature and viscosity for one exemplary PC-RTM simulation. The pressure increases in the filled part of the mold from the flow front to the inlet. The temperature rises from the injection temperature close to the inlet to the mold temperature. The viscosity rises from the inlet to the flow front but stays at a very low value (< 10 mPas).

In the HP-RTM simulation with constant resin mass flow rate, the maximum pressure at the sensor is

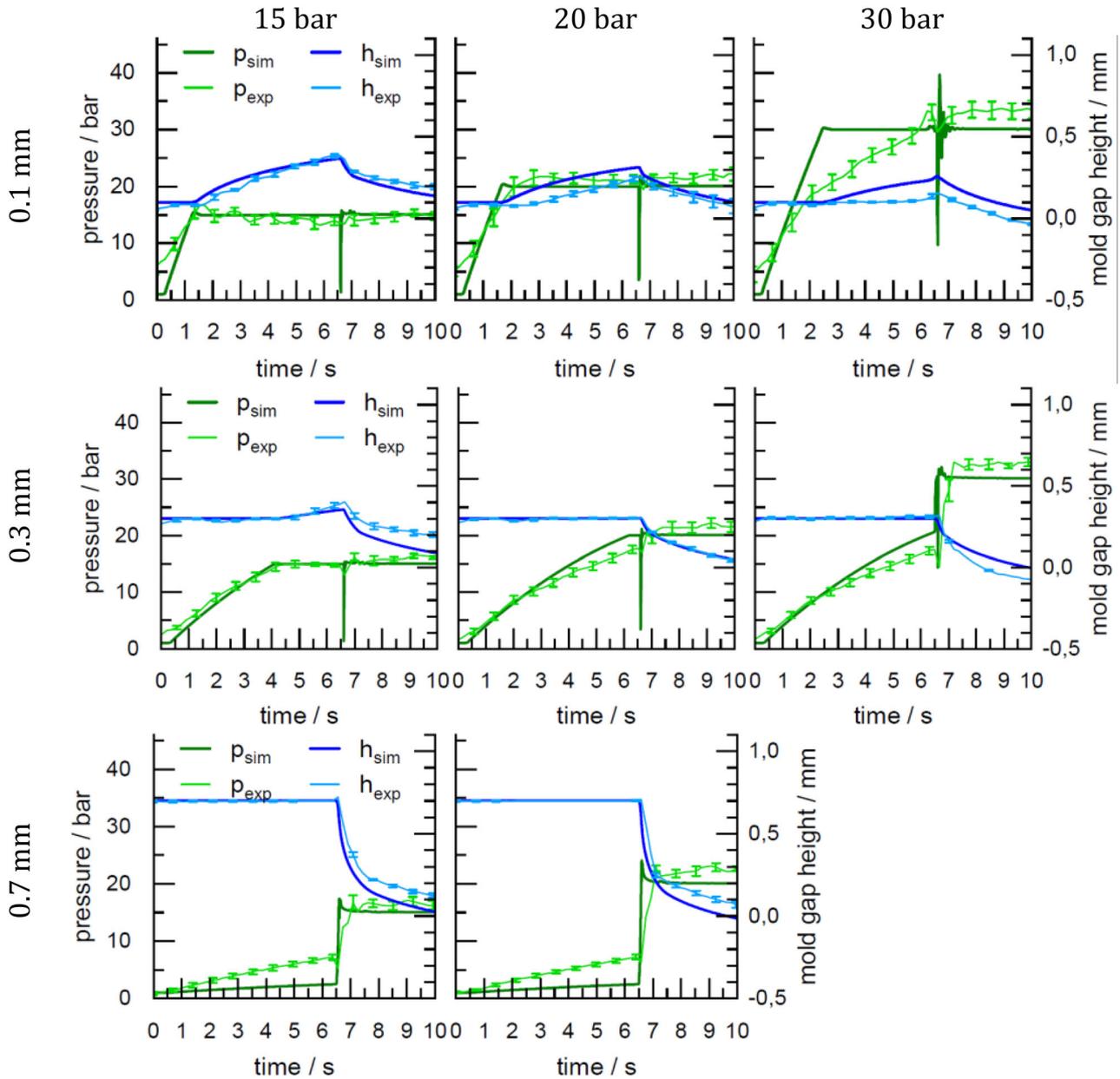


Figure 8. Pressure and mold gap height comparison for the investigated parameter combinations; the graphs show the results of the simulations and experiments.

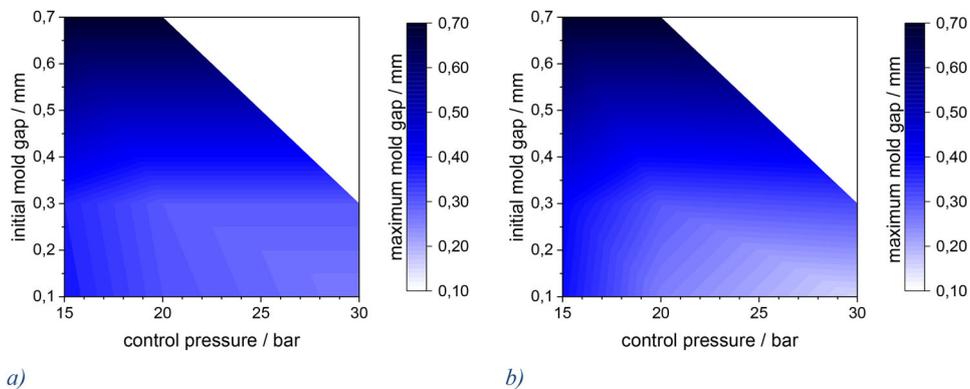


Figure 9. Comparison of maximum mold gap height at the end of the injection; a) simulations and b) experiments.

124 bar at the end of the injection after approximately 5 s. The simulated HP-RTM mold filling times for a constant inlet pressure of 20 bar and 30 bar

are 19.4 s and 11 s, respectively. In the case of 15 bar injection pressure, the simulation stops after 39.2 s without a complete filling of the mold.

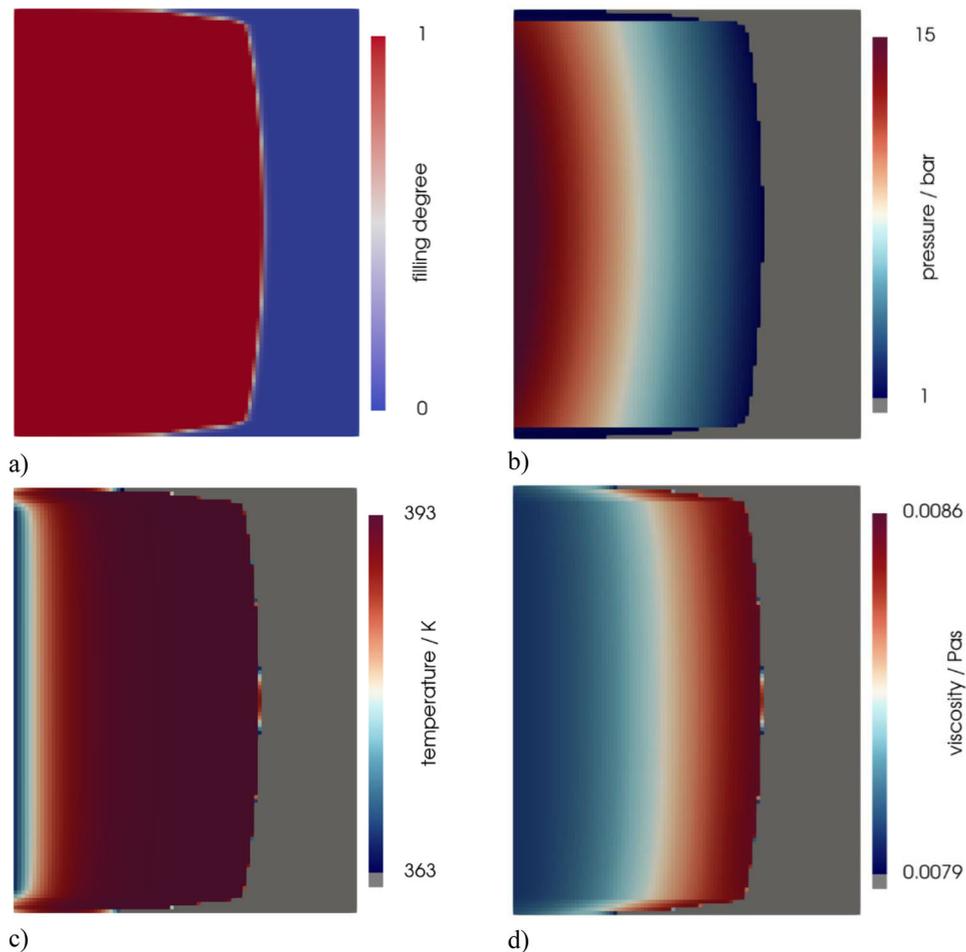


Figure 10. Fields after a simulation time of 5 s, exemplary for the simulation with an initial mold gap height of 0.3 mm and a pressure limit of 15 bar; a) filling grade, b) resin pressure, c) resin temperature and d) resin viscosity.

5. Discussion

The controlling of the pressure was successfully implemented. The experiments show low standard deviations in their pressure and mold gap height data, which indicate a robust process characteristic.

The pressure in the experiments at the beginning of the injection is higher than 1 bar for the cases of a low initial mold gap height (Figure 8, first row), which is explained by the compaction pressure of the preform. When the upper mold is closed to its initial mold gap height before the injection starts, the preform compaction leads to a pressure increase recorded by the sensor. This also explains the lower initial pressure in the experiments for higher initial mold gap heights (Figure 8, second and third row). Subsequently, when the preform is infiltrated, the compression resistance of the preform decreases due to lubrication with the resin, as was shown by previous studies [24,25]. The relative difference of the pressure values therefore decreases with ongoing infiltration and, furthermore, with increasing fluid pressure. To further develop the experiments and simulations, the compensation of the preform compression pressure as proposed by Fauster *et al.* [25] is one possible option.

The experiments and simulations show that already for small mold gap heights, the pressure increase during injection drops significantly, which is explained by the increase of permeability.

When comparing simulations and experiments, the pressure devolution and the mold gap heights always show the same trend (cf. Figure 9). For higher pressures and higher initial mold gap heights, the mold gap increases less during injection or even completely vanishes (cf. Figure 9 and Figure 8). The difference in pressure devolution for high mold gap heights (cf. Figure 8, third row) can be explained by the permeability uncertainty for low fiber volume fractions. Subsequently, the lower simulated injection pressure leads to a faster simulated compression in those two cases, as the flow resistance in the simulations is lower than in the experiments.

Even for the highest mold gap heights of 0.7 mm the fiber volume fraction is still 0.472. Based on this fact and based on the recorded pressure increase in Stage 1, an in-plane flow is most likely for all experiments. In further investigations, we plan to apply PC-RTM to larger parts, which leads to larger mold gap heights. In this case, a pure in-plane flow cannot be guaranteed but instead a resin flow between the

preform and the cavity wall followed by a through-thickness resin flow can occur, where in addition hydrodynamic pressure arises [26] and has to be considered when measuring the process pressure.

In the cases with the highest investigated control pressure of 30 *bar*, we can observe a deviation of the pressure increase in Stage 1, which subsequently leads to a larger predicted mold gap height. In this experimental set-up a notable resin leakage at the fiber clamping or even an elastic deformation of the tool cannot be excluded, which was also visible in previous experiments [7] and in conclusion leads to the significantly slower pressure increase during the injection. For a more accurate analysis of these effects, a detailed investigation of the resin flow through the elastic fiber clamping and the deformation of the tool is required.

The HP-RTM simulations show that either the pressure value is very high or the mold filling time is very high compared to PC-RTM. In the simulation case of a constant inlet pressure of 15 *bar*, the resin cures and its viscosity increases over 500 *mPas* (cf. Figure 7) before the mold is completely filled.

6. Conclusions

The simulations and experiments show the same general behavior that is typical for PC-RTM:

- In the injection stage (Stage 1), the pressure increase is slower for large initial mold gaps heights than for small mold gap heights.
- Higher control pressure values lead to a smaller increase in mold gap height during pressure controlled injection (Stage 2).
- In the compression stage (Stage 3), the mold gap height decreases faster for higher pressure control values.

We show that PC-RTM offers the possibility for a fast manufacturing at a controlled maximum cavity pressure. In future, this enables for example the integration of lightweight low-density foam cores inside the preform for a rapid manufacturing of intrinsic sandwich components. It can also decrease the investment costs for the manufacturer because of the lower fluid pressure and following lower hydraulic clamping force needed when comparing the process to HP-RTM. While HP-RTM has the fastest filling time but also very high pressures, when no pressure limit is set, especially for lower control pressures PC-RTM enables the manufacturing where the mold cannot be filled completely in HP-RTM due to premature curing of the resin.

The simulation of PC-RTM is based on a further development of a CRTM simulation method. By

implementing a PID-controller to control the compression velocity of the upper mold wall depending on the fluid pressure in the simulation domain, PC-RTM can be modeled. In comparison to the experiments, the simulations show the same principal behavior. The different stages of PC-RTM can be predicted correctly. However, the pressure and mold gap height devolution during the filling is very sensitive to tool geometry, process and material parameters. Further investigations are needed, to analyze the influence of e.g. the permeability, viscosity, temperature and tool geometry parameters like the sealing or fiber clamping systems.

In future investigations, PC-RTM can also be used to manufacture more complex parts and sandwich parts containing polymer foam cores to analyze its influence on the part quality when compared to HP-RTM.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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