

A Conjugate Heat Transfer Model for Autoclave Process Simulation

Yao Sun¹, Hongsen Fang¹, Lu Li² and Dianyun Zhang¹

¹School of Aeronautics and Astronautics, Purdue University, West Lafayette IN 47906, USA

²Convergent Science Inc., Madison, WI, USA

Abstract. Autoclave processing of thermoset composites demands precise temperature and pressure control to achieve proper resin flow, consolidation, and cure. Manufacturer-recommended cure cycles embed conservative safety margins that can limit manufacturing throughput. In prior work, a full-scale autoclave conjugate heat transfer (CHT) model was developed in ConvergeCFD, verified against thermocouple measurements under a modified IM7-8552 cure cycle, and used in a parametric study of air velocity and heating rate on mold thermal response. The present work extends that validated thermal framework by integrating resin cure kinetics through a user-defined volumetric heat-generation source, so that Degree of Cure (DoC) evolution and exothermic heat release from resin curing are resolved within the now-improved CHT solution. The cure-kinetics implementation is first verified numerically against three independent reference solutions: an adaptive ODE integrator, an operator-split fourth-order Runge–Kutta scheme, and an ABAQUS UMATHT subroutine on an adiabatic single-element benchmark. The solutions are highly consistent at the converged state. The coupled model is then applied to predict the spatially and temporally resolved temperature and DoC fields for IM7-8552 across the autoclave geometry. The simulation reproduces convective thermal lag during the heating ramps and an exotherm-driven temperature excess of the part above the circulating air during the final hold and predicts a vitrification-limited DoC of approximately 85% at the end of the modeled cycle. Experimental validation of the predicted cure response via Differential Scanning Calorimetry and mechanical testing of various coupons, together with kinetic-parameter refinement is identified as the next step toward a comprehensive, physics-based process-optimization capability.

Keywords: Autoclave, CFD Simulation, Conjugate Heat Transfer, Cure Kinetics, Degree of Cure, Composites Manufacturing

1 Introduction

Autoclave processing remains the dominant route for manufacturing high-performance aerospace composites, combining elevated temperature, pressure, and vacuum to consolidate laminates to high fiber volume fraction while suppressing porosity. The quality of the final part is governed by the coupled thermal, chemical, and

mechanical history experienced during the cure cycle, which is strongly influenced by airflow behavior, part placement, and tooling thermal mass. These factors introduce spatial and temporal variability in convective heat transfer that becomes especially severe in large or densely loaded autoclaves.

Local temperature deviations are consequential because they alter the timing and progression of the cure reaction throughout the laminate. Asynchronous curing promotes defects such as resin-rich zones, voids, deconsolidation, and ply wrinkling [1], particularly in thick sections and at geometric features. Residual stress and part distortion likewise originate from mismatched gelation and vitrification across the part. As Xu et al. [2] emphasize, cure cycles are long and tooling is massive, so the interplay of thermal, chemical, and mechanical histories ultimately dictates part quality and shape fidelity.

Despite its industrial importance, comprehensive simulation of autoclave processing remains difficult. Most finite element analysis (FEA) thermal workflows impose a constant or spatially averaged heat transfer coefficient (HTC) at the part surface, neglecting turbulence, recirculation, and flow shadowing produced by the actual load configuration [3–5]. Resolving the three-dimensional air-to-tool heat transfer instead requires computational fluid dynamics (CFD) capable of capturing turbulent flow over complex geometry, typically through Reynolds-averaged closures such as k - ϵ or k - ω SST. In-situ validation is itself challenging: embedding thermocouples in tooling or mapping the flow with calorimetry can perturb the flow field, and the number of measurement locations is also limited [3].

Recent work has established the foundations of flow-aware autoclave modeling. Zhu et al. [4] validated CFD predictions of turbulent recirculation inside autoclave chambers and showed that asymmetric circulation produces measurable thermal gradients across components. Weber et al. [5] developed an efficient procedure to convert CFD-derived velocity fields into spatially varying HTC boundary conditions for thermal FEA. Lightfoot et al. [1] attributed ply wrinkling to interply shear arising from tool-part thermal-expansion mismatch during cure. Building on resolved flow fields, parametric and optimization studies have targeted manufacturing improvement: Tang et al. [6] reported a multi-objective optimization of cure profiles, and Fisher et al. [7] quantified how heat-transfer-coefficient variations affect the predicted cure, while Rangapuram et al. [8] and Zhu et al. [9] demonstrated close agreement between validated autoclave models and measured thermal data.

The present work integrates and extends two prior efforts by the authors. A conjugate heat transfer (CHT) CFD model of the autoclave processing was developed in ConvergeCFD, verified against thermocouple measurements under the modified IM7-8552 cure cycle, and used to quantify the effects of heating rate and air velocity on mold thermal response [12]. In parallel, a finite-element process-optimization framework based on the Cure Hardening Instantaneously Linear Elastic (CHILE) constitutive model and a multi-reaction cure-kinetics description was developed for cure-cycle discovery [13] drawing on the integrated multiscale modeling framework of Enos [14]. These two efforts remain disconnected: the validated CHT model is purely convective and carries no internal heat generation, while the cure-coupled FEA relies on prescribed or empirically averaged convective boundaries rather than a resolved

autoclave flow field. Global sensitivity analysis confirms that the convective heat transfer coefficient is the dominant influence on mold surface temperature [15], reinforcing the value of resolving convection directly.

This work closes that gap by integrating resin cure kinetics into the validated CHT CFD framework through a user-defined volumetric heat-generation source, so that the reaction exotherm enters the energy equation and couples back into the laminate temperature history. The cure-kinetics integration is verified numerically against independent solvers before application, and the coupled model is used to predict degree-of-cure and temperature evolution for IM7-8552 across the autoclave geometry. No experimental cure data are yet available for the coupled simulation; experimental validation of the predicted cure response is identified as the next step. The objective is a single, physics-based autoclave model that resolves both the turbulent thermal environment and the in-situ cure response, providing the foundation for cure-cycle refinement and, ultimately, closed-loop process optimization.

2 CFD Methodology

2.1 Autoclave System at Purdue University

The autoclave used in this study is a Baron Blakeslee BAC 35 with updated control system, maintained and operated by Purdue University's Composite Manufacturing and Simulation Center (CMSC). It is a forced-convection vessel under PID temperature control. The circulation fan draws air through a rear-mounted heating unit and drives it between the processing chamber and the outer enclosure wall, feeding the chamber from the front. The system is rated to 600 °F and 120 psi, spanning the processing envelope of most prepreg systems.

The cylindrical part processing chamber measures 36.75 in. in diameter by 60 in. in length. Six vacuum ports enable vacuum control, and five K-type thermocouple ports provide multi-point temperature acquisition during operation. A fixed steel support structure carries removable aluminum shelving trays for configurable part placement, and a library of flat and contoured aluminum tools are available for processing under prescribed conditions.



Fig. 1. BAC 35 Autoclave at Purdue University.

2.2 Autoclave Processing and Modified Cure Cycle.

Airflow characters, including flow pattern and temperature history inside the vessel directly govern cure uniformity and final part quality. Flow recirculation zones shaped by internal baffles, shelves, and part geometry can create regions of reduced turbulence and poor circulation, which drive non-uniform temperature distribution. Variation of flow characteristics may produce uneven Degree of Cure (DoC), inter-laminar voids, and unfavorable deformation. Resolving these spatially varying temperature and flow fields supplies the high-resolution thermal histories required for downstream analysis of cure kinetics, residual stress, and deformation.

The cure recipe used here begins with autoclave pressure ramping from 0 to 30 psi over 10 minutes, followed by a one-hour hold, while a vacuum is applied to the bagged preform; the autoclave pressure is then raised to 100 psi. The thermal profile heats at 5 °F/min from room temperature 380K, holds for 60 minutes, heats at the same rate to 450K, and holds for 120 minutes. Vacuum is relaxed after the first thermal hold, circulating air is cooled with autoclave pressure vented at the onset of cooling. This modified cycle departs from the standard Hexcel MRCC [11] in accordance with facility operating recommendations while preserving part quality.

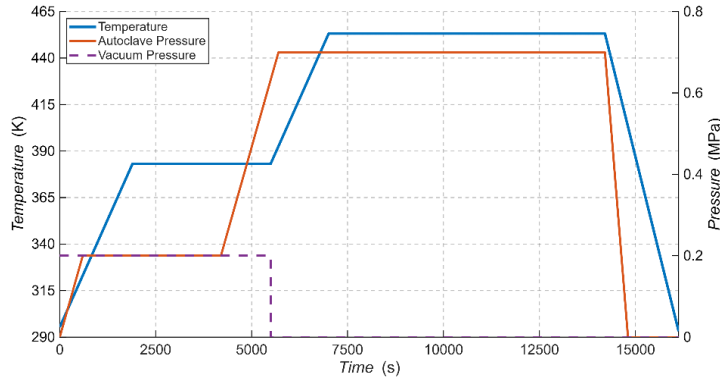


Fig. 2. Modified IM7-8552 Cure Cycle (Temperature, Autoclave Pressure, and Vacuum).

2.3 Conjugate Heat Transfer CFD Setup

The flow field and thermal history are obtained by solving the full transient Navier–Stokes equations in ConvergeCFD [10], with additional transport equations for turbulence closure. This CFD framework was verified against autoclave thermocouple measurements and exercised in a heating-rate and air-velocity parametric study in prior work [12]. Conservation of mass, momentum, and energy is expressed in Equations (1)–(3):

$$\frac{\partial \rho}{\partial t} + \frac{\partial u_i}{\partial x} = S \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_i} + S_i \quad (2)$$

$$\frac{\partial(\rho e)}{\partial t} + \frac{\partial(\rho e u_j)}{\partial x_j} = -P \frac{\partial u_j}{\partial x_j} + \frac{\partial}{\partial x_j} \left(K \frac{\partial T}{\partial x_j} \right) + \sigma_{ij} \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left(\rho \sum_m D_m h_m \frac{\partial Y_m}{\partial x_j} \right) + S \quad (3)$$

where u_i is the i -th velocity component, ρ the fluid density, S the general source term, P the pressure, and Y_m the mass fraction of species m ; e is the specific internal energy, K the thermal conductivity, σ_{ij} the viscous-stress tensor, D_m the mass diffusivity of species m , and h_m its specific enthalpy. The energy source term S in Eq. (3) is the entry point for the cure exotherm introduced in Section 3.

A full-scale autoclave, mold and part CAD model were built in ABAQUS CAE using shell elements and exported as a STEP file for import into ConvergeCFD. A 27 in. $\times$ 30 in. $\times$ 1/4 in. solid shelf was created natively to support an L-shaped mold positioned at the shelf center, 10 in. from the inlet plane of the processing chamber. The part used for the study is a 10 in. $\times$ 10 in. IM7-8552 prepreg with quasi-isotropic layup of $[-45, 0, 45, 90]_{3s}$, comprising 24 plies with resin content of 35% by mass and a nominal cured thickness of 3 mm. The composite preform was attached to the mold assuming perfect contact. The computational domain was partitioned into six functional regions for independent boundary definition: circulating air, heat exchanger, fan enclosure, aluminum mold, composite part and aluminum shelf.

The mold and shelf were made of Aluminum 6061-T6, and the composite part was modeled as a homogeneous solid with effective thermal properties homogenized from the IM7 fiber and 8552 resin using Rule of Mixture (RoM). The properties of both materials are listed in Table 1.

Table 1. Implemented Material Properties.

Material	Density (kg/m ³)	Heat capacity (J/(kg·K))	Heat conductivity (W/(m·K))
IM7/8552 composite	1577	827	0.43
Aluminum 6061-T6	2700	896	167

A transient Conjugate Heat Transfer (CHT) model with gas–solid temperature coupling was used. The fluid was treated as a compressible gas with SST k – ω turbulence closure, selected for its established performance in wall-bounded and recirculating flows [4], and pressure–velocity coupling was handled by the PISO solver. Autoclave operation was imposed through a source–sink formulation: an energy source in the heat-exchanger region raised the air temperature while a momentum source in the fan-enclosure region drove circulation. Another heat source from composite curing was also imposed. All chamber walls were treated as adiabatic. A structured Cartesian mesh with a 0.25 m base cell size was adaptably refined locally by zones (factor of 2^3 to 2^7), ensuring result resolution while saving computational resources. Air-temperature control was implemented with a User Defined Function (UDF) utilizing PID logic, and pressure effects on material properties and heat transfer were neglected as their influence on thermal response is minimal under the operating conditions considered.

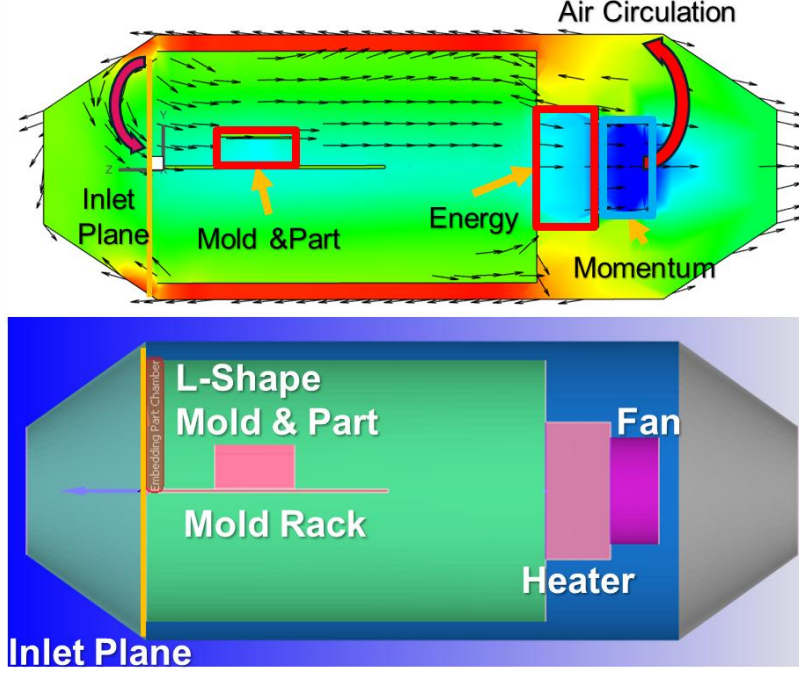


Fig. 3. ConvergeCFD Autoclave Geometry, Region and Air Flow Illustration.

2.4 Cure Kinetics Model

The curing state of the composite part is described by the Degree of Cure (DoC, ϕ), defined as the fraction of the total reaction enthalpy released at a given time,

$$\phi(t) = \frac{H(t)}{H_r} \quad (4)$$

where $H(t)$ is the reaction heat released at time t and H_r the total heat of reaction for completely cured resin. The reaction kinetics are expressed as a rate equation, $d\phi/dt = f(\phi, T)$, in which the Rate of Cure depends on the instantaneous Degree of Cure and the temperature. Because the Rate of Cure is proportional to the instantaneous heat-release rate, $d\phi/dt = (1/H_r)(dH/dt)$, it is the quantity obtained directly from differential scanning calorimetry (DSC). The temperature dependence is introduced through Arrhenius rate constants of the form $k(T) = A \exp(-\Delta E/RT)$. The reaction is exothermic, and the reaction heat released is returned to the conjugate-heat-transfer solution as a volumetric source in the energy equation.

The Rate of Cure (RoC) is represented by an autocatalytic model with a mixed n -th-order term, a seven-parameter expression widely used for epoxy systems because it captures both the n -th-order reaction that dominates at low conversion and the auto-

catalytic acceleration that follows. The conventional form of RoC equation is as follows:

$$\dot{\phi}(\phi, T) = k_1(T) (1 - \phi)^l + k_2(T) \phi^m (1 - \phi)^n \quad (5)$$

where the two rate constants follow the Arrhenius law, $k_i(T) = A_i \exp(-\Delta E_i/RT)$ for $i = 1, 2$. The two Arrhenius pairs, $(A_1, \Delta E_1)$ and $(A_2, \Delta E_2)$, independently set the temperature sensitivity of the two contributions, with exponents l , m , and n determining the conversion dependence of the reaction.

For implementation, the rate law is recast in terms of an ordered parameter vector $a = (a_1, \dots, a_7)$ that maps directly onto the subroutine input,

$$\dot{\phi}(\phi, T, a) = a_1 \exp(-\frac{a_2}{RT}) (1 - \phi)^{a_3} + a_4 \exp(-\frac{a_5}{RT}) \phi^{a_6} (1 - \phi)^{a_7} \quad (6)$$

as equation above to provide a consistent parameter ordering for the ConvergeCFD source UDF and the ABAQUS UMATHT subroutine, both of which read the same vector. The parameters used in the implemented form, characterized for IM7-8552 in [16], are shown in Table 2.

Table 2. IM7-8552 Cure Kinetics Parameters, Implemented Form.

Parameter	Value	Units
a ₁	1.53E+05	s ⁻¹
a ₂	6.65E+04	J/mol
a ₃	0.813	—
a ₄	2.74	—
a ₅	43.1	—
a ₆	-1.5865	—
a ₇	5.456E-03	K ⁻¹
H _r	5.97E+05	J/kg
C _p	1088	J/(kg·K)
ρ _r	1301	kg/m ³

3 Numerical Method and Validation

This section describes the coupling and numerical integration of the cure-kinetics source within the CFD solver and verifies that integration against independent reference solutions on an adiabatic benchmark, for which the coupled temperature–cure response can be determined in closed form. The underlying conjugate-heat-transfer model was validated against autoclave thermocouple measurements and applied in a parametric study in previous work [12].

3.1 Curing Induced Heat Source

The heat released by the reaction is applied to the composite region of the energy equation, Eq. (3), as a volumetric source proportional to the Rate of Cure,

$$S_{cure} = \rho_r H_r \dot{\phi} \quad (7)$$

where ρ_r is the resin density and H_r the total heat of reaction. At each cell and time step the source subroutine evaluates the local temperature and the stored Degree of Cure, integrates Rate of Cure $\dot{\phi}$ to advance Degree of Cure ϕ , and returns S_{cure} to the energy equation. Because the energy equation is solved by ConvergeCFD, the kinetics are advanced in an operator-split manner: within a single CFD time step, the Degree of Cure is integrated by a fourth-order Runge–Kutta (RK4) scheme using fixed size Δt , with the temperature held constant across the RK4 stages. The Degree of Cure, Rate of Cure, incremental heat generation and total heat generation were stored for post-processing.

3.2 Case Study: Adiabatic Neat Resin Curing, $T_0 = 433K$

The coupled implementation is verified against an adiabatic resin-curing benchmark, which admits an exact energy constraint. The benchmark consists of a single 1 mm³ element of neat 8552 resin, treated as perfectly insulated with an initial temperature T_0 and an initial Degree of Cure $\phi_0 = 0.001$, so that the element exchanges no heat with its surroundings and the temperature rises solely through the reaction exotherm. The problem has no spatial dependence and therefore isolates the integration of the kinetics. Under the adiabatic assumption the conduction term in Eq. (3) vanishes and, with the source of Eq. (7), the energy balance reduces to

$$\rho c \frac{dT}{dt} = \rho_r H_r \dot{\phi} \quad (8)$$

Because the entire reaction heat released is retained, the temperature and Degree of Cure are directly coupled, and integration over the complete reaction yields a closed-form temperature rise that is independent of the numerical scheme,

$$\Delta T = \frac{H_r}{c_p} \quad (9)$$

As this value follows directly from the first law and is independent of the discretization, correct RK4 implementation of the coupled solution should land within close vicinity of $T_{final} = 981.7K$, $\Delta T = 548.7 K$. Although the case study does not represent true manufacturing procedure, it still provides good insight from numerical and implementation standpoint.

3.3 Numerical Verification and Result

The coupled DoC and temperature equations are integrated using the fixed-step RK4 scheme with a time step of $\Delta t = 0.15$ s, selected from a time-step sensitivity study that balanced accuracy against computational cost in ABAQUS and ConvergeCFD. The same RK4 algorithm is implemented in ConvergeCFD through a user-defined function (UDF) and in ABAQUS through a UMATHT user subroutine. The ConvergeCFD result is compared with three independent solutions of the same case study: an adaptive ODE45 integration, an operator-split MATLAB RK4 implementation corresponding to the UMATHT scheme, and the ABAQUS UMATHT subroutine, with the adaptive ODE45 solution taken as the reference.

The adiabatic single-element response from ODE45 (reference) and the implemented RK4 is presented in Fig. 4 at $\Delta t = 0.15$ s. The temperature remains nearly constant during the induction period and then rises sharply to the adiabatic plateau at approximately 974 K as the Degree of Cure advances forward. Owing to the strongly nonlinear form of the rate-of-cure expression, the Rate of Cure remains negligible until about 600 s and then peaks at the runaway near 970 s. The temperature-DoC relation is linear with slope H_r/C_p , in agreement with the analytical constraint of Eq. (9), confirming that the coupled implementation conserves energy; the ConvergeCFD solution shows only a small departure at high DoC.

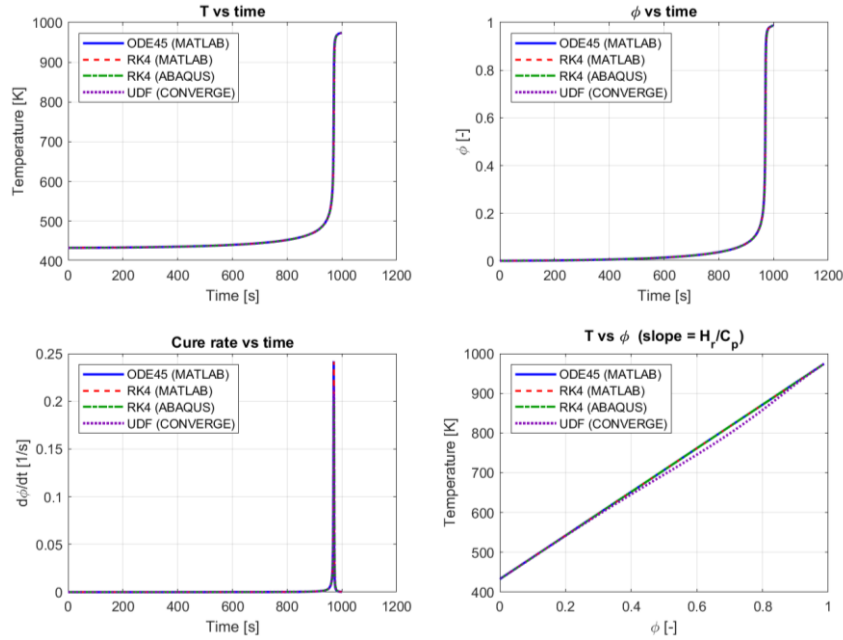


Fig. 4. Temperature, DoC, RoC and Temperature vs DoC Plot With RK4 at $\Delta t = 0.15$ s.

The deviation of each fixed-step solution from the ODE45 reference is shown in Fig. 5. The error is negligible over almost the entire cure and is confined to a brief, localized excursion at the reaction turning point near 970 s, where the temperature error reaches approximately -9% for the MATLAB RK4 and ConvergeCFD UDF solutions and approximately -13% for the ABAQUS UMATHT solution, with correspondingly large but transient excursions in the Degree of Cure and the Rate of Cure that decay within a few seconds. This excursion does not represent an accumulation of integration error, rather, it arises from the combination of the discrete instants at which ConvergeCFD samples and reports the solution and the strongly exponential character of the rate-of-cure equation. Near the runaway the Arrhenius-controlled rate increases almost vertically in time, so that a small offset between the fixed sampling instants of a solver and the continuously adapting reference produces a large instantaneous relative difference. Because the excursion is restricted to the steep peak and does not alter the converged state, the solutions agree to six significant figures at the asymptote with no effect on the final Degree of Cure. These results confirm that the cure-kinetics source is integrated correctly and consistently across MATLAB, ABAQUS, and ConvergeCFD, supporting its use in the full autoclave model.

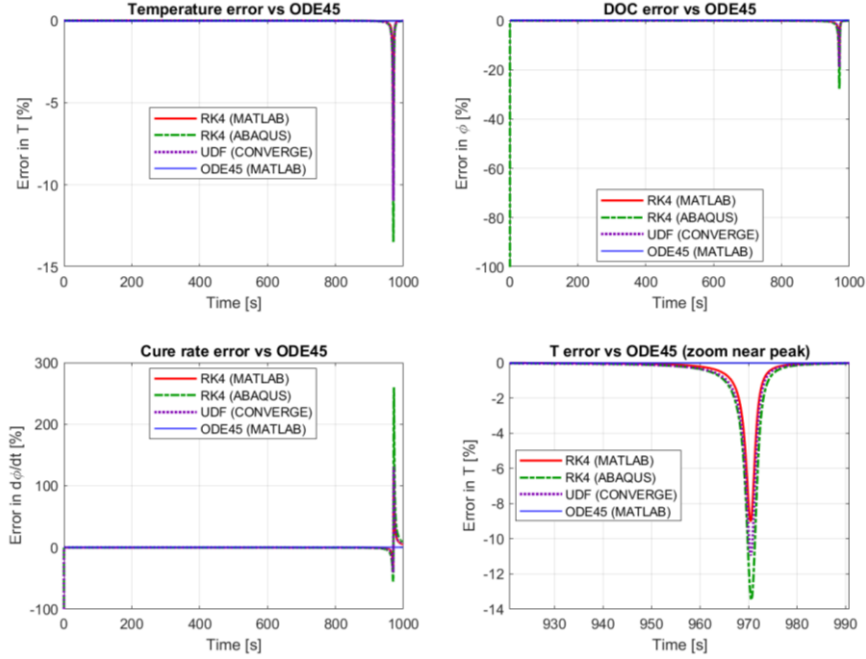


Fig. 5. Error Analysis: ODE45 (Reference) vs RK4, $\Delta t = 0.15s$

4 CFD Simulation Results

4.1 Simulated Temperature History

Over the complete cure cycle, the predicted mean temperature of the circulating air, the aluminum mold, and the composite part over the complete cure cycle as well as temperature band across the part are shown in Fig. 6. The air follows the prescribed two-step profile, heating at 5 °F/min to the first hold near 380 K, holding for 60 minutes, heating again to the final hold near 450 K, and holding for 120 minutes. During each heating ramp the mold and part lag the air because their thermal mass is heated through the convection from air. The thermal lag is largest early in the first ramp and decreases as the parts approach the air temperature. At both holds the mold and part converge to the air temperature, confirming that the convective environment governs the thermal history away from the reaction.

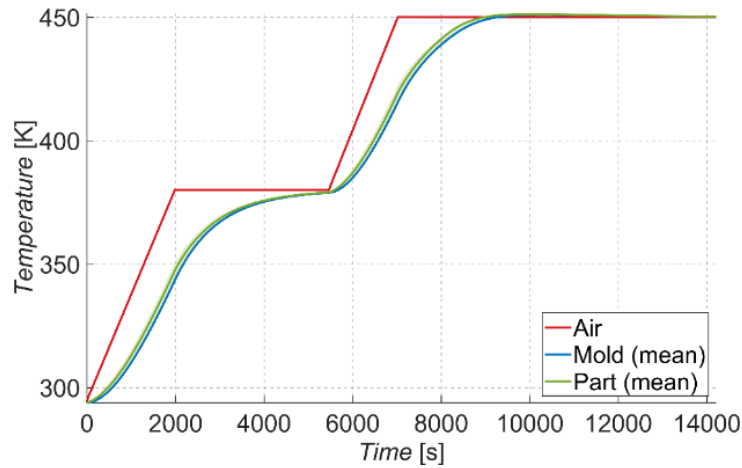


Fig. 6. Temperature History of Air, Mold and Part for IM7-8552 MRCC.

Late in the cycle, the reaction exotherm reverses the sign of the part-to-air temperature difference, which is the signature of the coupled solution. Relative to the circulating air shown in Fig. 7, both the part and the mold lag strongly during the ramps, with magnitude of 33 K (part) and 37 K (mold) early in the first ramp, with a similar pattern on the second. This lag is largest during heating because the air strictly follows the prescribed target while the part and mold can only absorb energy by surface convection. Near 9000s the trend reverses: as the Rate of Cure climbs, the exotherm drives a rapidly raising air temperature and the part and mold move above the air, peaking roughly 1.2 K higher. This crossover is direct evidence that the resin exotherm, not the autoclave controller, sets the peak part temperature during the final hold, the behavior convective-only model cannot reproduce.

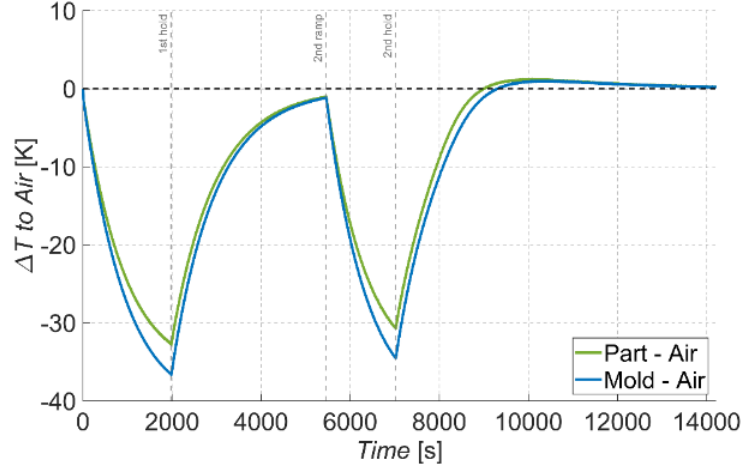


Fig. 7. Temperature Difference Comparison of Part, Mold vs Air Throughout Curing Process.

4.2 Degree of Cure and Reaction Rate Evolution.

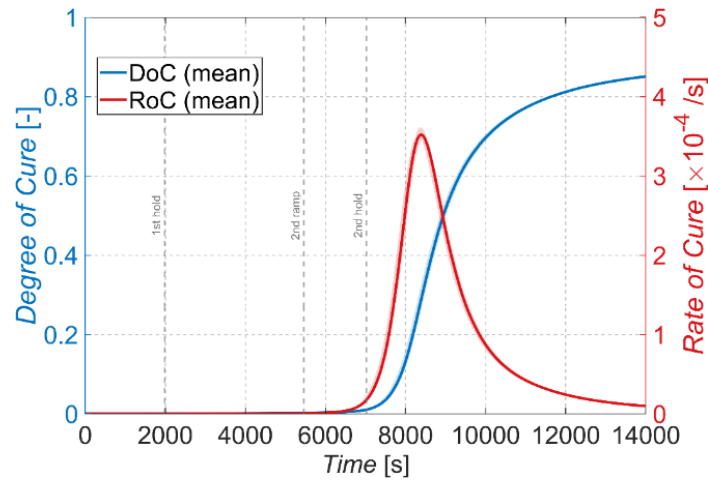


Fig. 8. Predicted Degree of Cure and Reaction Rate for IM7-8552 over Cure Cycle.

As shown on Fig. 8, the Degree of Cure and the Rate of Cure evolve together, both remain negligible until about 6000 s. The second hold begins at 7020 s, the Rate of Cure peaks near 8620 s and then decays, and the Degree of Cure rises monotonically to about 85% by the end of the cycle. The shaded bands give the minimum-to-maximum spread across the part, which is small for this thin (3 mm cured) laminate, indicating a nearly uniform reaction front. A complete 8552 cure reaches a higher ultimate conversion, so the kinetic-parameter refinement is expected to raise the predicted final Degree of Cure and improve model fidelity.

4.3 Through-Thickness Temperature Difference

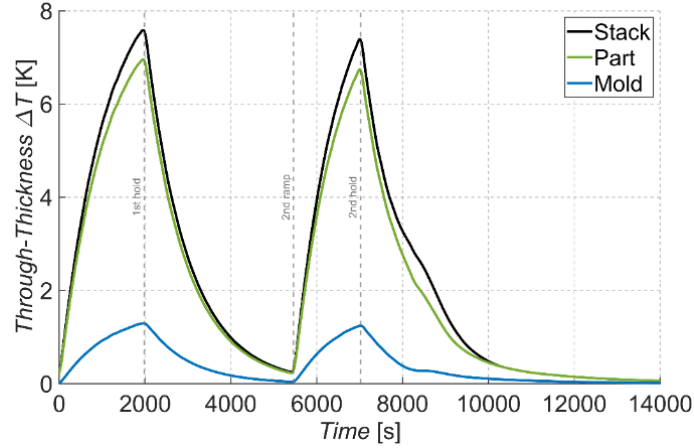


Fig. 9. Through-Thickness Temperature Difference of Part, Mold and Part-Mold Stack.

The through-thickness temperature difference (instantaneous min-to-max spread of the part, the mold, and the combined stack is reported in Fig. 9, while the underlying spatial field appears in Fig. 10. The heat map of the part-mold stack was probed at characteristic instants extracted from the three-dimensional solution. The contours resolve the tool-to-part temperature difference and any in-plane non-uniformity produced by the autoclave flow field.

The gradient through the thin part is consistently mild, within 1.7K throughout. The largest part-mold stack temperature difference occurs at the start of each hold, peaking around 7.5 K, and is dominated by the large thermal mass of the aluminum mold. All gradients converge to zero as time proceed during holds, showing that the dominant through-thickness gradient in this configuration is a convective transient rather than a reaction effect. Near 8400 s, where the resin exotherm peaks, the stack gradient rises and slows the convergence toward uniformity.

For a thin part used in this study, the through-thickness non-uniformity is governed mainly by rapid temperature ramp rate. In thicker laminates the same gradients would scale up and the reaction contribution would become more significant.

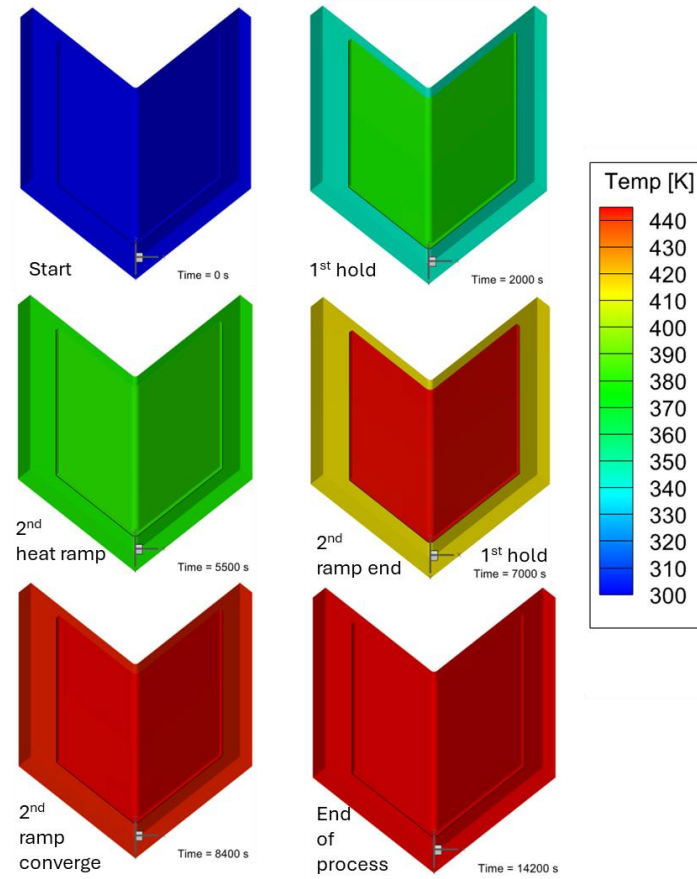


Fig. 10. Heat Map of Part-Mold Stack at Characteristic Timestep.

5 Conclusion

Current work integrates resin cure kinetics into the conjugate-heat-transfer CFD model of autoclave processing that had previously been validated for convective heat transfer alone. The reaction exotherm is introduced into the energy equation as a user-defined volumetric source, with the degree of cure advanced cell-by-cell by a fixed-step fourth-order Runge-Kutta scheme. The coupling was first verified on an adiabatic single-element benchmark, for which the temperature-cure response is known in closed form. ConvergeCFD, a MATLAB RK4 scheme, and an ABAQUS UMATHT subroutine agreed with the ODE45 reference at the converged state, differing only in a brief transient at the reaction runaway that did not affect the final Degree of Cure.

With verified cure kinetics function applied to the full autoclave, the model reproduces the convective thermal history established in prior work, in which the mold and part lag the circulating air during the heating ramps and converge to it at the holds. The contribution of the cure coupling becomes evident in the final hold, where exothermic heat generation raises the part temperature approximately 1.2 K above the circulating air. This crossover indicates that the resin exotherm, rather than the autoclave controller, governs the peak part temperature in that phase, a response that a convective-only model cannot capture. The largest through-thickness gradient, around 7.5 K, occurs at the beginning of heat ramps rather than at the exotherm and is governed by the thermal mass of the aluminum mold, identifying it as a convective transient.

The modeled cure cycle drives the laminate to a Degree of Cure of 85%, close to but short of full conversion, indicating that the kinetic parameters require refinement before the predicted cure can be regarded as quantitatively reliable. The result is a single, physics-based representation of the autoclave that resolves the turbulent thermal environment and the in-situ cure response within a common framework. Future work will validate the predicted cure response through differential scanning calorimetry and coupon testing and refine the kinetic parameters so that the predicted final conversion matches the measured value.

References

1. Lightfoot, J. S., Wisnom, M. R., Potter, K. "A new mechanism for the formation of ply wrinkles due to shear between plies." *Composites Part A*, 49 (2013): 139–147.
2. Xu, Y., Zhao, Z., Shrestha, K., et al. "A coupled data-physics computational framework for temperature, residual stress, and distortion modeling in autoclave process of composite materials." *Composites Part A*, 183 (2024): 108218.
3. Slesinger, N., Shimizu, T., Arafath, A. R. A., Poursartip, A. "Heat Transfer Coefficient Distribution Inside an Autoclave." *ICCM-17* (2009).
4. Zhu, J., Frerich, T., Herrmann, A. S. "CFD modeling and validation of heat transfer inside an autoclave based on a mesh independency study." *J. Compos. Mater.*, 55(18) (2021): 2469–2487.
5. Weber, T. A., Arent, J.-C., et al. "A fast method for the generation of boundary conditions for thermal autoclave simulation." *Composites Part A*, 88 (2016): 216–225.
6. Tang, W. Y., Xu, Y. J., Hui, X. Y., Zhang, W. C. "Multi-Objective Optimization of Curing Profile for Autoclave Processed Composites: Simultaneous Control of Curing Time and Process-Induced Defects." *Polymers*, 14(14) (2022): 2815.
7. Fisher, A., Levy, A., Kratz, J. "Effects of heat transfer coefficient variations on composite curing." *J. Compos. Mater.*, 57 (2023): 363–376.
8. Rangapuram, M., Dasari, S. K., Abutunis, A., et al. "Experimental and numerical investigation of heat evolution inside the autoclave for composite manufactur-

- ing." *Composites and Advanced Materials*, 33 (2024): 1–10. DOI:10.1177/26349833241273506.
9. Zhu, J., Frerich, T., Dimassi, A., Koerdt, M., Herrmann, A. S. "Experimental validation of a quasi-transient coupling approach for the modeling of heat transfer in autoclave processing." *J. Compos. Mater.*, 56(9) (2022): 797–810.
 10. Richards, K. J., Senecal, P. K., Pomraning, E. "CONVERGE 4." (2024).
 11. Hexcel Corporation. "HexPly 8552 Epoxy Matrix Product Data Sheet." (2020).
 12. Sun, Y., Li, L., Zhang, D. "Autoclave Process Modeling: CFD Simulation with Experimental Verification and Parametric Study." *Proc. ASME Aerospace Structures, Structural Dynamics, and Materials Conference (SSDM2026)*, Long Beach, CA, Paper SSDM2026-183392 (2026).
 13. Sun, Y., Enos, R. S., Li, L., Zhang, D. "An Advanced Optimization Framework for Enhanced Autoclave Processing." *Proc. American Society for Composites, 40th Technical Conference* (2025).
 14. Enos, R. S. "An Integrated Physics-Based Multiscale Modeling Framework for Advancing Thermoset Composites Manufacturing Processes." PhD thesis, Purdue University, West Lafayette, IN (2024). DOI:10.25394/PGS.28057928.v1.
 15. He, J., Zhan, L., Yang, Y., Xu, Y. "Global Sensitivity Analysis of Factors Influencing the Surface Temperature of Mold during Autoclave Processing." *Polymers*, 16(5) (2024): 705. DOI:10.3390/polym16050705.
 16. Shahkarami, A., Van Ee, D., Poursartip, A. "Material Characterization for Processing: Hexcel 8552 — Material Model Development." Technical Report, NIAR, Wichita State University (2009).